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ÚSTAV AUTOMOBILNÍHO A DOPRAVNÍHO INŽENÝRSTVÍ

COMPARISON OF THE ACCURACY AND COMPLEXITY OF SELECTED 3D SCANNING METHODS

POROVNÁNÍ PŘESNOSTI A PRACNOSTI VYBRANÝCH METOD 3D SKENOVÁNÍ

BACHELOR'S THESIS

BAKALÁŘSKÁ PRÁCE

AUTHOR

AUTOR PRÁCE

Sviatlana Yarmalinskaya

SUPERVISOR

VEDOUCÍ PRÁCE

Ing. Václav Otipka, Ph.D.

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Bachelor's Thesis Assignment

Institute: Institute of Automotive Engineering
Student: **Sviatlana Yarmalinskaya**
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Supervisor: **Ing. Václav Otipka, Ph.D.**
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As provided for by the Act No. 111/98 Coll. on higher education institutions and the BUT Study and Examination Regulations, the director of the Institute hereby assigns the following topic of Bachelor's Thesis:

Comparison of the Accuracy and Complexity of Selected 3D Scanning Methods

Brief Description:

The bachelor's thesis is focused on the comparison of professional 3D scanning methods used at Institute of Automotive Engineering, as well as their comparison with selected alternative and more accessible tools, such as methods based on photogrammetry. The thesis includes a description of the operating principles of selected 3D scanning methods, a literature review in the field of scanner accuracy evaluation, the design of a methodology for subsequent comparison of the applied methods, and the selection of suitable test specimens for scanning.

Bachelor's Thesis goals:

Conduct a literature review in the field of 3D scanning methods.

Propose a methodology for comparing the accuracy and efficiency of individual 3D scanning methods.

Perform 3D scanning using selected methods on test specimens based on the proposed methodology.

Provide a critical evaluation of the applied approaches, including their limitations and suitability for use in gearbox applications.

Recommended bibliography:

CONFALONE, Gary C.; SMITS, John a KINNARE, Thomas. 3D scanning for advanced manufacturing, design, and construction. Additive manufacturing skills in practice series. Hoboken, New Jersey, 2023. ISBN 978-1-119-75851-8.

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Director of the Institute

doc. Ing. Jiří Hlinka, Ph.D.
FME dean

ABSTRACT

Optical 3D scanning is widely applied in mechanical engineering for the digitization of physical components, particularly in reverse engineering, quality control, and technical documentation of existing parts. The suitability of a scanning method for an industrial application is determined not only by measurement accuracy, but also by surface coverage, mesh quality, operational complexity, acquisition time, and post-processing requirements. This thesis compares selected professional structured-light and laser triangulation systems with more accessible and consumer-grade methods, including iPhone LiDAR and photogrammetry. The experimental comparison is performed under laboratory conditions using representative automotive components, namely a steering knuckle and a car wheel. The results indicate that professional optical scanners provide the most reliable data for accurate reverse engineering of mechanical components. Semi-professional scanning methods may be applicable for less demanding geometry acquisition, while smartphone-based approaches are mainly suitable for approximate shape and scale capture and visual documentation.

KEYWORDS

3D scanning, optical 3D scanning, structured-light scanning, laser triangulation, LiDAR, photogrammetry, mesh quality, surface deviation, automotive components, reverse engineering

ABSTRAKT

Optické 3D skenování je široce využíváno ve strojírenství pro digitalizaci fyzických součástí, zejména v oblasti reverzního inženýrství, kontroly kvality a technické dokumentace existujících dílů. Vhodnost skenovací metody pro průmyslovou aplikaci není určena pouze přesností měření, ale také pokrytím povrchu, kvalitou sítě, provozní náročností, dobou akvizice dat a požadavky na následné zpracování. Tato práce porovnává vybrané profesionální systémy založené na strukturovaném světle a laserové triangulaci s dostupnějšími a spotřebitelskými metodami, včetně iPhone LiDAR a fotogrammetrie. Experimentální porovnání je provedeno v laboratorních podmínkách na reprezentativních automobilových součástech, konkrétně na těhlici kola a automobilovém kole. Výsledky ukazují, že profesionální optické skenery poskytují nejspolehlivější data pro přesné reverzní inženýrství mechanických součástí. Poloprofesionální skenovací metody mohou být použitelné pro méně náročnou akvizici geometrie, zatímco metody založené na chytrém telefonu jsou vhodné především pro přibližné zachycení tvaru a měřítka a pro vizuální dokumentaci.

KLÍČOVÁ SLOVA

3D skenování, optické 3D skenování, skenování strukturovaným světlem, laserová triangulace, LiDAR, fotogrammetrie, kvalita sítě, odchylka povrchu, automobilové komponenty, reverzní inženýrství.

ROZŠÍŘENÝ ABSTRAKT

Digitalizace fyzických objektů představuje v současném strojírenství důležitý nástroj pro získávání geometrických dat reálných součástí. Umožňuje převést reálný objekt do digitální podoby, která může být dále využita pro reverzní inženýrství, kontrolu kvality, rozměrovou analýzu nebo přípravu dat pro aditivní výrobu. Význam 3D skenování roste především v případech, kdy není k dispozici CAD model, takže pokud je potřeba ověřit skutečný stav vyráběné nebo provozované součásti, případně když má být existující geometrie upravena nebo znovu vyrobena.

Hlavní výhodou 3D skenování je schopnost rychle zachytit i tvarově složité objekty. Na rozdíl od tradičních měřicích metod, umožňuje 3D skenování získat rozsáhlá plošná data. 3D skenování není založeno pouze na jedné univerzální technologii. Existuje mnoho typů skenerů, které se liší především principem měření, dosažitelnou přesností, rozlišením, rychlostí snímání, náročností obsluhy a pořizovací cenou.

Profesionální průmyslové skenery, například systémy se strukturovaným světlem nebo laserovou triangulací, jsou určeny pro přesnější technické a metrologické aplikace. Vedle profesionálních systémů jsou stále dostupnější také méně nákladné alternativy. Patří mezi ně hobby 3D skenery, chytré telefony s integrovaným LiDAR senzorem nebo fotogrammetrie založená na sadě fotografií pořízených dostupnými fotoaparáty, které jsou dnes již běžnou součástí chytrých telefonů. Tyto metody jsou výrazně dostupnější a obvykle jednodušší na použití. Jejich využitelnost pro technické aplikace však závisí na tom, zda dokážou poskytnout dostatečně přesná, úplná a kvalitní data pro konkrétní účel. Praktická volba vhodné skenovací metody nemůže být založena pouze na deklarované přesnosti zařízení, ale pro technické použití je důležité také to, zda výsledný digitalizovaný model obsahuje mezery, šum, artefakty nebo deformace, které mohou omezit její využití při tvorbě CAD modelu nebo při porovnání s referenční geometrií.

Práce je zaměřena na optické 3D skenování, protože tento typ měření umožňuje bezkontaktní získávání geometrie povrchu a je běžně využíván v technické praxi. Vybrané optické metody skenování jsou hodnoceny z hlediska jejich přesnosti, dostupnosti, přenositelnosti a provozní náročnosti. Hlavní pozornost je věnována využitelnosti těchto metod pro reverzní inženýrství v oblasti automobilových součástí a dílů souvisejících s aplikacemi v oblasti převodových ústrojí. Porovnávány jsou profesionální systémy používané na Ústavu automobilního a dopravního inženýrství a dostupnější alternativní metody. Smyslem porovnání je posoudit, za jakých podmínek mohou méně nákladné metody nahradit nebo doplnit profesionální skenery a kde jsou jejich technická omezení příliš významná.

Popis řešení práce

V teoretické části jsou popsány základní principy využívané v rámci optických skenovacích metod. Jedná se, zejména o strukturované světlo, laserovou triangulaci a technologii LiDAR. Kvalitu získaných dat pomocí 3D skenování ovlivňuje celá řada faktorů. Patří mezi ně vlastnosti světelného zdroje, vlnová délka, způsob výpočtu hloubky, geometrie snímaného objektu, stav povrchu, okolní osvětlení, teplota, vibrace a způsob práce obsluhy. Optické skenery potřebují, aby se dostatečné množství světla odrazilo zpět do snímacího systému. Matné a difuzní povrchy jsou proto obecně vhodnější než povrchy lesklé, tmavé, průhledné nebo poloprůhledné. Významná omezení vznikají také u hlubokých otvorů, úzkých drážek a ostrých hran, kde může být povrch částečně nebo úplně skrytý z pohledu projektoru nebo kamer.

V práci jsou porovnávány metody s rozdílnou úrovní technické úrovně. Profesionální úroveň reprezentuje strukturovaný optický skener ZEISS ATOS Q a ruční laserový skener ZEISS T-SCAN Hawk 2. Tyto systémy jsou určeny pro metrologické použití a umožňují nejpřesnější zaznamenání geometrie. Jako dostupnější alternativy jsou zařazeny také skenery Creality CR-Scan Raptor a EinScan Pro HD. Zástupce nejdostupnější technologie představuje iPhone LiDAR spolu s fotogrammetrií realizovanou za pomoci využití běžného chytrého telefonu. Zařazení těchto metod umožňuje porovnat nejen přesnost, ale také praktickou náročnost, rychlost a vhodnost pro různé typy technických úloh.

V metodice srovnání jednotlivých metod bylo cíleno primárně pro oblast reverzního inženýrství. Pro experimentální porovnání byly zvoleny dvě automobilové součásti: těhlice kola a automobilové kolo. Těhlice představuje tvarově složitý díl s kombinací funkčních ploch, otvorů, zaoblení, přechodových ploch a obtížně přístupných oblastí. Automobilové kolo doplňuje porovnání o větší rotačně symetrickou součást s otvory, hranami a odlišnými povrchovými vlastnostmi. Tyto díly byly vybrány tak, aby prověřily schopnost jednotlivých metod zachytit funkční geometrii, celkový tvar, menší detaily i rozsáhlejší povrchové oblasti. Skenování bylo provedeno v laboratorních podmínkách. Před měřením byly díly podle potřeb technologii skenování připraveny. U lesklých povrchů byl nanesen matovací nástřik, a pro některé skenery na díly byly umístěny referenční značky vhodné velikosti, které umožnily vzájemné zarovnání jednotlivých skenů.

Jako referenční systém byl použit 3D skener ZEISS ATOS Q, který má z porovnávaných zařízení nejvyšší metrologickou úroveň a poskytuje vysokou hustotu skenovaných bodů. Výsledné sítě z ostatních skenerů byly porovnávány s referenčními daty v softwaru ZEISS INSPECT. Hodnocení bylo založeno na povrchových odchylkách, úplnosti zachycení geometrie, kvalitě polygonální sítě, přítomnosti děr a artefaktů, schopnosti zachytit funkční plochy a celkové náročnosti pracovního postupu. Součástí hodnocení byl také čas potřebný k přípravě, vlastnímu skenování a následnému zpracování dat. Při hodnocení tak nebyla posuzována pouze geometrická odchylka od referenčního modelu. Pro praktické použití je důležité také to, zda jsou získaná data dále reálně využitelná. Polygonální síť může mít přijatelnou lokální odchylku, ale pokud obsahuje rozsáhlé mezery, deformace nebo ztracené funkční prvky, může být její využití pro reverzní inženýrství omezené. Důraz byl kladen na to, zda daná metoda dokáže poskytnout použitelný digitální model pro reverzní inženýrství.

Zhodnocení výsledků

Tato práce porovnává přesnost a komplexnost několika optických metod 3D skenování pro aplikace reverzního inženýrství, od průmyslových metrologických systémů až po spotřebitelská zařízení. Získané výsledky potvrdily, že výkonnost skeneru silně závisí nejen na samotném principu měření, ale také na vztahu mezi rozlišením skeneru, měřicím objemem, dostupností geometrie a optickými vlastnostmi skenovaného povrchu.

Teoretický předpoklad, že průmyslové metrologické skenery překonají poloprofesionální a nejdostupnější systémy v rozměrové přesnosti a kvalitě rekonstrukce, byl potvrzen. Výsledky však zároveň ukázaly, že samotná nominální přesnost skeneru nestačí k zajištění úspěšné rekonstrukce všech geometrických prvků, a proto by neměla být používána jako jediné výběrové kritérium. Schopnost skeneru zachytit drobné geometrické detaily, jako jsou zkosení, rádiusy, zaoblení nebo obrobené hrany, závisí na několika faktorech, včetně zdroje projekce, například LED nebo laseru, hustoty bodů a měřicího objemu. Volba skeneru by proto měla vycházet také z požadovaného rozlišení geometrických prvků, zejména pokud je nutné přesně rekonstruovat drobné geometrické detaily. Všechny hodnocené metody vykazovaly systematickou tendenci zaoblovat ostré vnější hrany a ztrácet zaoblení s malým poloměrem.

Praktickým důsledkem je, že pouze ZEISS ATOS Q vytvořil síť, z níž bylo možné rekonstruovat zkosený profil čepu s technicky použitelnou věrností. Zkosení v oblasti dosedací plochy náboje kola o délce větší než 4 mm byla dobře zachycena všemi skenery kromě iPhone LiDAR a fotogrammetrie, což potvrzuje existenci minimální hranice rozlišitelné velikosti prvku.

Měřicí objem ve vztahu k velikosti součásti se ukázal jako kritický faktor zejména u spotřebitelských a poloprofesionálních skenerů. Kvůli menšímu zornému poli (FOV) vyžadoval Creality CR-Scan Raptor při skenování kola značný počet dodatečných referenčních značek a opakovaných skenovacích průchodů. Přesto k úplnému pokrytí ráfku a nebyl zaznamenán ani centrační otvor kola. Tím se prokázalo, že tento skener je vhodnější pro součásti velikostně srovnatelné s těhlicí kola, kde jeho výsledky byly srovnatelné se skenerem EinScan Pro HD.

EinScan Pro HD sice umožnil jednodušší získání dat, než Creality CR-Scan Raptor, ale projevil se u něj jiný typ selhání. Bílý LED zdroj strukturovaného světla se ukázal jako citlivější na mírně odrazivý povrch vnitřní části kola než modrá LED u ATOS Q. EinScan v ručním režimu vytvořil síť kola s většími mezerami na ráfcích než skener Creality Raptor. Na vnitřní části kola bylo pozorováno širší rozložení odchylek bodů, což může souviset s driftem skenu při ručním režimu. Na základě těchto výsledků lze předpokládat, že skener EinScan se strukturovaným světlem pracoval v ručním režimu méně efektivně než ve stacionárním režimu. Výsledky mohou rovněž naznačovat vyšší citlivost na světelné podmínky a odrazy povrchu, pravděpodobně v důsledku použití bílého strukturovaného světla namísto modrého strukturovaného světla.

Nejdostupnější metody hodnocené v tomto porovnání nesplnily požadavky na rozměrovou přesnost pro reverzní inženýrství mechanických součástí. iPhone 16 LiDAR vykázal odchylky přibližně $\pm 2,5$ mm těhlicí a ± 11 mm na kole. Výsledné síť vykazovaly významné tvarové deformace, zejména na rotačně symetrických plochách, což je činilo nevhodnými pro následnou rekonstrukci CAD modelů. Neočekávaným zjištěním bylo, že fotogrammetrie vykazovala výhodu na geometricky složitých plochách svislého čepu, kde její přesnost ± 1 mm byla lepší než $\pm 2,5$ mm u iPhone LiDAR, a také ve schopnosti rozlišit obrysy zkosení náboje kola. Fotogrammetrie však nepřekonala iPhone LiDAR konzistentně na vnitřní části kola a na čepu, kde odlesky způsobily úplné selhání rekonstrukce, zatímco iPhone LiDAR v těchto oblastech nasnímal povrch alespoň částečně. Na základě výsledků dosažených v této práci je však nutné konstatovat, že ani jedna z těchto nejdostupnějších metod se nejeví jako vhodná pro jakoukoli kvantitativní technickou aplikaci nad rámec hrubého zachycení tvaru s následným správným škálováním při post-processingu.

Z hlediska použitelnosti jednotlivých metod pro oblast převodových ústrojí výsledky ukazují, že volba skeneru musí být založena především na zamýšlené technické úloze. Například pro skenování skříně převodovky se jeví jako vhodný skener ZEISS T-SCAN Hawk a EinScan a to v oblastech vnějších a částečně vnitřních ploch, přičemž ATOS Q je nezbytné využít všude tam, kde je vyžadována rozměrová návaznost. Žádná z optických metod skenování v tomto porovnání není dostatečná pro detailní reverzní inženýrství nebo kontrolu profilů ozubení, ačkoli ATOS Q by mohl být potenciálně schopen zachytit základní profil zubů a počet zubů. U hřídelů by bylo možné pomocí metrologických skenerů ZEISS potenciálně zachytit jejich celkové uspořádání, stupňovité průměry a relativní polohu funkčních prvků.

Je rovněž nutné uvést několik omezení předložené metodiky. Porovnání bylo založeno pouze na dvou reprezentativních automobilových součástech a jako referenční geometrie byl použit sken získaný ze skeneru ZEISS ATOS Q namísto původních CAD modelů. Vnitřní část kola

byla záměrně ponechána bez povrchové úpravy, avšak toto rozhodnutí vneslo do porovnání skenerů další proměnnou. Dále byla pro každou metodu provedena pouze jedna skenovací relace, takže nebylo možné kvantifikovat vliv zkušenosti obsluhy ani opakovatelnost jednotlivých skenů. Budoucí práce by měla zahrnovat opakovaná měření za shodných podmínek, aby bylo možné určit statistickou spolehlivost uvedených hodnot odchylek. Práci by bylo možné dále rozšířit o další experimenty se součástmi s různými průmyslově relevantními povrchy, například korodovanými, lakovanými nebo eloxovanými, a s různými světelnými podmínkami. To by poskytlo ještě komplexnější pochopení praktických omezení optického 3D skenování ve strojírenských aplikacích.

KLÍČOVÁ SLOVA

3D skenování, optické 3D skenování, skenování strukturovaným světlem, laserová triangulace, LiDAR, fotogrammetrie, kvalita sítě, odchylka povrchu, automobilové komponenty, reverzní inženýrství.

BIBLIOGRAPHIC REFERENCE

YARMALINSKAYA, Sviatlana. *Comparison of the Accuracy and Complexity of Selected 3D Scanning Methods*. Online, bachelor's Thesis. Václav OTIPKA (supervisor). Brno: Brno University of Technology, Faculty of Mechanical Engineering, 2026. Available at: <https://www.vut.cz/en/students/final-thesis/detail/173997>.

STATUTORY DECLARATION

In accordance with the guidelines of BUT, I hereby confirm that I have have used generative artificial intelligence tools in the preparation of my final thesis; their use is described in the section Declaration of the use of artificial intelligence and in Appendix 5.

I hereby declare that this thesis is my original work, I created and written it independently under the guidance of Václav Otipka and using listed references.

Brno, 22th May 2026

.....

Sviatlana Yarmalinskaya

DECLARATION OF THE USE OF ARTIFICIAL INTELLIGENCE

During the preparation of this bachelor's thesis, I used generative artificial intelligence tools.

Tools used and their purpose:

- Claude (Anthropic; model/version: Opus 4.6; URL: <https://claude.ai/>), period: 2026-03-01–2026-05-17
Purposes: Language proofreading, stylistic reformulation of my text, translation of English and Czech

AI was used only as a supporting tool without direct insertion of the generated outputs. I critically verified the outputs of generative AI by comparing them with primary sources and literature, revising and modifying them based on my own judgement, checking factual claims in primary sources, and verifying citations and statements in primary sources. I take full responsibility for the content of the thesis.

The prompts were formulated generally and did not contain personal or internal data. More detailed evidence of use, including selected prompts where relevant, is provided in Appendix 5.

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INTRODUCTION

3D scanning has become an important and widely used tool in modern engineering, because it enables the geometry of physical objects to be captured and converted into digital form. The resulting digital model can be used for a wide range of applications, including dimensional inspection, quality control, reverse engineering, wear analysis, and preparation of models for additive manufacturing.

The main advantage of 3D scanning is its ability to capture complex shapes much faster than traditional measurement methods. A wide range of 3D scanning technologies is currently available with different data acquisition and operational methods. Some systems are automated, while others require manual operation. Some are based on contact measurement, whereas others use optical principles. These technologies differ significantly in their measurement principle, accuracy, resolution, acquisition speed, operational complexity, portability, and cost. The selection of a suitable scanning method therefore depends on the intended application. A method suitable for rapid visual documentation or rough reverse engineering may not be sufficient for dimensional inspection of functional surfaces. In contrast, a professional metrology scanner may provide unnecessary accuracy for simple shape acquisition while requiring more time, preparation, and financial resources. For practical use in an engineering environment, it is therefore necessary to compare not only accuracy, but also scanning time, workflow complexity, post-processing effort, surface coverage, and the overall suitability of the obtained model.

This thesis focuses on the comparison of selected optical 3D scanning methods due to their wider availability. Professional 3D scanning systems used at the Institute of Automotive Engineering are compared with more accessible alternatives, including consumer-grade scanning methods. The aim is to evaluate whether these alternative methods can provide results suitable for engineering applications, particularly for reverse engineering of automotive components and parts related to gearbox applications. In addition to measurement accuracy, the thesis also considers the complexity of use, scanning workflow, and post-processing requirements. The purpose of this comparison is to support the selection of a suitable scanning method for a particular part, application, and set of scanning requirements.

1 KEY CONCEPTS OF THE 3D SCANNERS

This chapter establishes fundamental concepts and terminology necessary for understanding 3D scanning technology, covering basic definitions, operating principles, and factors affecting scanning accuracy and data quality across optical scanning systems.

1.1 BASIC DEFINITIONS IN 3D SCANNING

3D scanners are devices that capture an object's geometry and produce a digital model of it. Depending on the system, they may also capture color or texture.

The working principle of a scanner is determined by how it captures geometry. Based on the method of detecting surface points, 3D scanners can be divided into three main groups:

- Optical (non-contact) systems emit electromagnetic (EM) waves, usually in visible or infrared spectrum, onto an object and register reflected rays to determine surface point coordinates.
- Contact systems use a tactile probe to acquire geometry by physically tracing the surface and capturing a series of 2D profiles, while the position and orientation of the scanner head are monitored. Both parts of the system are used to produce a precise 3D data set of all points measured. [1]
- Hybrid systems combine contact probing with optical scanning. For example, a robotic arm can carry both a tactile probe and an optical device, allowing switching between precision measurements and high-speed surface capture without repositioning the system.

To ensure a meaningful comparison, all devices examined in this thesis belong to the same group - optical 3D scanners. This allows differences in accuracy and complexity to be attributed to the scanning method itself rather than to fundamentally different measurement principles.

All optical 3D scanners operate on the same general measurement principle. They acquire surface geometry by analyzing how light interacts with the object. The scanned part is fixed in a place to limit the movement. Ideally the full 360° of the surface is observable, if not the object is then repositioned and captured again. Depending on the underlying technology, the system projects LED light or a laser beam in specific patterns onto the surface. Those patterns are deformed by the object's geometry and are reflected back to the scanner to compute width, height and depth. Lastly scanner's software uses all of the acquired data to produce a 3D model of the scanned part. It is typically in the form of a point cloud or a polygonal mesh.

Point cloud is a dataset generated by 3D scanning equipment (*Fig. 1*). It is a 3D image composed of a multitude of small dots. Each dot represents the x, y, z coordinate of a distinct point on a scanned surface. Points are given either a grayscale or color value for ease of visual recognition. A single scan typically contains more than a million surface points. [1]

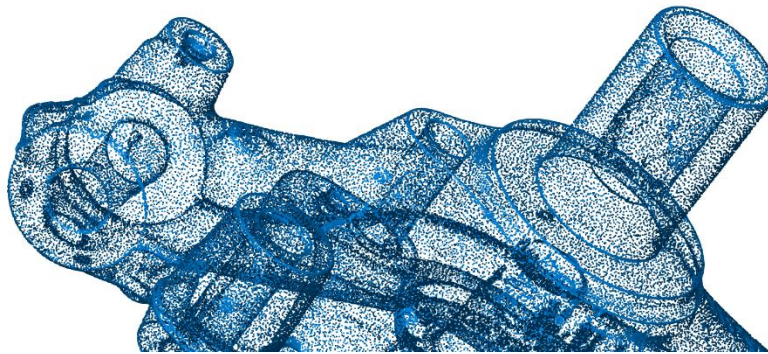


Fig. 1 Point cloud of a steering knuckle in ZEISS INSPECT software

Polygonal mesh is a dataset created by 3D scanning equipment to represent a solid 3D surface (Fig. 2). It is formed by connecting groups of three or more points from the point cloud into polygons. These polygons create the planes and edges that define the object's shape. The result is a collection of many small, interconnected surface elements, usually triangles or other polygonal shapes. The outcome is usually in STL or OBJ format. [1]

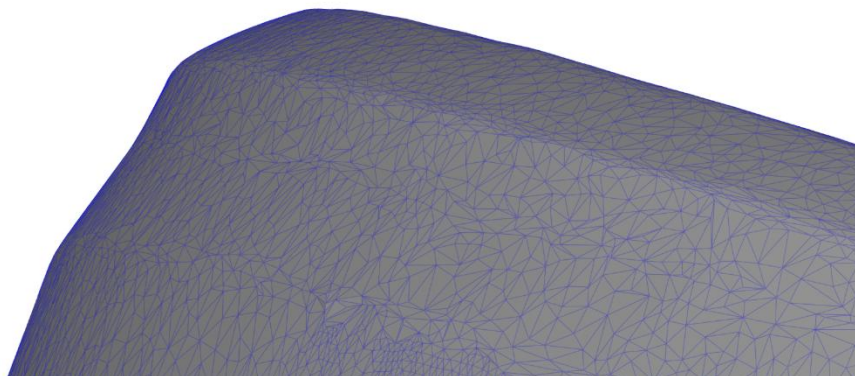


Fig. 2 Polygonal mesh in ZEISS INSPECT software

Raw point cloud or mesh produced by the scanner is typically not the final deliverable. The scan data is exported to dedicated software for further processing. For dimensional inspection, meshes are imported into metrology software such as ZEISS INSPECT, where they are compared to Computer-Aided Design (CAD) models. For reverse engineering, meshes are processed in tools such as Geomagic Design X or CATIA to reconstruct CAD surfaces. It is the most time-consuming and important step. For rapid prototyping, the mesh may be exported directly in STL format for 3D printing, often after minor repairs such as closing holes or smoothing artifacts.

Optical 3D scanners form a broad family of devices, so classification by light source is useful for narrowing the scope of this thesis. The choice of principle largely determines the achievable accuracy and measurement range. These aspects are explained in detail in Section 1.2 and 1.3. The main categories of optical 3D scanners are:

- Structured-light scanners (SLS) have an LED light source and project fringes or grids onto the object and use one or two cameras to compute depth by mathematical

method called triangulation (see Section 1.2). They offer high point density and are widely used in industrial metrology. Price ranges from mid to high depending on the target application.

- Laser scanners project a laser line or points onto the object and observe its displacement with a camera, also computing depth using triangulation (see section 1.2). They achieve high accuracy and are well suited for automated industrial use. They are typically in the mid-to-high price range.
- LiDAR (Light Detection and Ranging) scanners emit pulses of infrared light and measure the time each pulse takes to return from the surface, calculating distance directly. They range from low-cost consumer-grade sensors integrated into smartphones to high-cost professional systems used in construction, surveying, and geosciences. Accuracy varies widely across this range, but is generally lower than that of structured-light and laser scanners.
- Photogrammetry reconstructs 3D geometry from multiple overlapping 2D photographs using software with feature-matching algorithms. Photographs could be taken on a smartphone as well as a professional camera, depending on the requirements. It is commonly found in low-cost applications, including smartphone augmented-reality systems.

In addition to the main features, the form factor of the scanner affects its practical use. This distinction determines portability, repeatability, and the types of objects that can be scanned efficiently:

- Handheld optical scanners integrate both projector and detector of the light into a compact device that operator moves around during scanning.
- Stationary optical scanners mount both the projector and detector on a fixed base. The scanned object is often placed on a turntable (rotary stage), or the scanner's head position is changed manually during scanning.
- Hybrid optical scanners could be used both handheld and stationary.

1.2 LIGHT SOURCES AND DEPTH CALCULATION IN OPTICAL 3D SCANNERS

The type of light source determines key properties of the projected pattern, such as coherence, wavelength, and beam geometry, which in turn affect the scanner's resolution, noise characteristics, and suitability for different surface types. Optical scanners characterized by the type of light source:

- Coherent light sources, usually LASERs (Light Amplification by Stimulated Emission of Radiation). These devices produce monochromatic, highly coherent, highly collimated beams of light with high energy density, in a visible or infrared spectrum.
- Non-coherent light sources such as LED (Light-Emitting Diode) based devices. They emit non-coherent EM waves in a narrow band (typically 20–30 nm wide), not a single wavelength, and usually are in a visible spectrum.

Unique limitations that each source imposes are described on the example of scanners used in this thesis: Structured-light and LiDAR with non-coherent light sources in sections 2.3 and 4.3 respectively, LASER in section 3.4.

While the light source defines what is projected onto the object, the depth calculation method determines how the reflected signal is used to compute three-dimensional coordinates. Different

computation methods are suited for different measurement ranges and accuracy requirements. Optical scanners characterized by the method of calculating point coordinates:

- Time-of-flight devices measure the time it takes for a pulse of light to reflect off a target and return to the transmitter. For example, LiDAR scanner in iPhone used in this thesis. They can capture data over hundreds of meters, but have worse accuracy on small distances compared to other methods.
- Phase-shifting devices emit a constant laser/light beam which is set in multiple phases. The phase shift of the retuning beam is recorded by the system to calculate the distance traveled. Phase-based units have a shorter range than time-of-flight units. Their strength lies in providing a faster scanning time and denser array of points returned. [1]
- Triangulation in optical 3D scanning is a geometric method that determines the 3D coordinates of a surface point by forming a triangle between a light projector, the object point, and sensor, which are separated by a known distance. The scanner captures the pattern of projected light as it deforms across the surface, and from the known geometric constants computes depth for each measured point [2]. For example, ZEISS ATOS Q structured-light scanner and ZEISS T-SCAN HAWK a laser triangulation scanner.

1.3 WAVELENGTH AND ACCURACY OF OPTICAL 3D SCANNERS

The light sources described in section 1.2 can emit electromagnetic waves in different parts of the electromagnetic spectrum, depending on the application and required accuracy. The most common wavelength bands are:

- Visible-light scanners use wavelength around 380-750 nm, which is visible to the human eye.
- Infrared scanners operate at wavelengths above the visible range.

Before describing the relationship between wavelength and accuracy of the scanners, it is important to define what is meant by measurement accuracy.

“Measurement accuracy is closeness of agreement between a measured quantity value and a true quantity value of a measurand” [3]. For example, industrial structured-light scanners can achieve measurement accuracy on the order of 0.01–0.05 mm, while consumer-grade devices such as smartphone LiDAR typically operate with accuracy in the range of 1–10 mm [1].

Dependence of accuracy on wavelength. Shorter wavelengths provide higher accuracy, and longer wavelengths sacrifice this resolution, but offer better performance over longer ranges and lower sensitivity to ambient visible light [1]. It is explained by diffraction of light. The smallest distance between two surface features that the scanner can still distinguish (spatial resolution) is limited by diffraction. The minimum resolvable feature size is approximately:

$$d \approx \frac{\lambda}{2 \cdot NA}, \quad (1)$$

where λ is the wavelength and NA is the numerical aperture (how much light a system can gather) of the imaging optics. Shorter wavelengths therefore resolve finer details. As an example, blue light (~450 nm) can distinguish features roughly twice as small as near-infrared (~940 nm) for the same optical system [1][4]. In LED-based scanners, shorter wavelengths also produce sharper fringe patterns, improving the precision.

Ambient light is a fundamental limitation of optical scanners, because the sensor cannot fully distinguish the projected pattern from environmental light. Three main factors determine how strongly ambient light interferes with the measurement: intensity, wavelength and the camera's light filtering. As an example, structured-light scanners (SLS) reconstruct depth of the points from projected pattern brightness variations [4]. The higher the contrast between the projected and ambient light at the sensor, the more reliably the data could be read. Direct sunlight is typically much brighter than the projected pattern, therefore SLS are not suitable for outdoor conditions – projected pattern is barely or not visible. Laser scanners on the other hand with higher light intensity could tolerate stronger ambient conditions. Wavelength determines whether the projector competes with the brightest parts of the ambient light spectrum. When projector and ambient sources overlap spectrally, both reach the sensor, and the unwanted component creates noise that reduces effective contrast. Infrared-based systems generally perform better in uncontrolled lighting conditions and artificial light contains limited IR radiation [5]. Among visible-light scanners, blue-light sources perform better than white-light under typical indoor warm-lit conditions, since there's less light in blue wavelengths. Lastly, a bandpass filter mounted in front of the camera transmits only wavelengths close to the projector's emission band. A blue LED source camera would capture a band of light of approx. 450–470 nm and block the rest, which significantly reduces the amount of noise. For these reasons, ambient lighting must be controlled during scanning. Natural light is typically blocked. Artificial lighting is kept diffuse and moderate in intensity to avoid sensor saturation, reduced pattern contrast, and sharp cast shadows on the scanned surface.

Material Absorption and Wavelength. Absorption characteristics of the scanned object vary widely across the electromagnetic spectrum and depend on the material's molecular structure and pigment composition. Dark or carbon-rich materials may absorb strongly in specific visible or infrared bands, diminishing the amount of reflected light available for measurement and potentially introducing noise or reconstruction gaps [1]. Temporary surface coating might be required.

1.4 THE EFFECT OF SURFACE AND GEOMETRIC PROPERTIES OF THE SCANNED OBJECTS

The limitations described in this section apply to all optical 3D scanners regardless of the measurement principle. They arise from how projected light interacts with the object's surface finish and geometry, and they directly affect what each scanner can and cannot measure.

Surface properties are an important factor. For any optical scanner to measure a surface point, enough of the projected light must reflect toward the camera sensor. How much light returns and in what direction depends on the surface finish. Ideal surface finishes could be divided in two extremes [1]:

- Diffuse surfaces scatter reflected light approximately equally in all directions (*Fig. 3*). Matte and rough finishes behave this way. These are ideal for scanning because the camera receives a usable signal regardless of its viewing angle.
- Specular (mirror-like) surfaces reflect light in a single concentrated direction (*Fig. 3*). Glossy, polished, or metallic finishes behave this way. Very little light reaches the camera unless it happens to be positioned exactly in the reflection path.

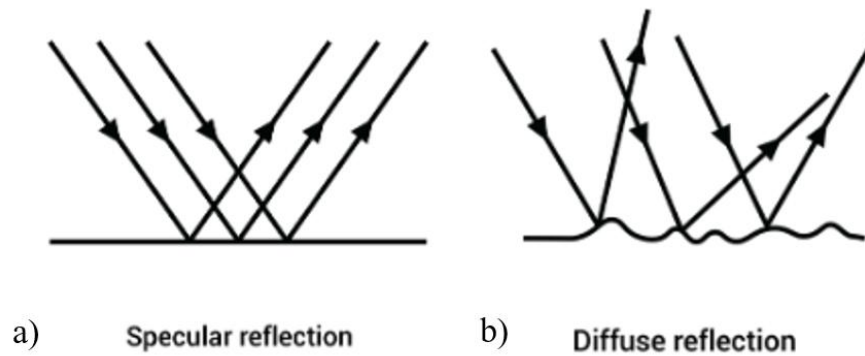


Fig. 3 Types of reflection: a) specular reflection; b) diffuse reflection [1]

Real surfaces exhibit a combination of both behaviors. A machined metal part, for example, may have diffuse regions where the tool marks scatter light and specular regions on polished faces.

Highly specular surfaces cause the scanner to receive either no signal (gaps in the point cloud) or an oversaturated signal that distorts the fringe pattern, producing artifacts such as ripple noise or depth spikes. Transparent and translucent materials present a similar problem, where light passes through rather than reflecting [1]. In practice, these surfaces are treated with a temporary matte coating before scanning. Common options include titanium dioxide powder (coating thickness below 1 μm), developer spray for penetrant testing ($\sim 5\text{--}6\ \mu\text{m}$), or sublimating sprays such as AESUB that evaporate after scanning and require no cleaning [6]. The coating creates a uniform diffuse layer that reflects reliably at any angle. The trade-off is that any coating adds material to the true surface, introducing a small systematic dimensional error proportional to the coating thickness [6].

Geometric limitations are one of the biggest factors for optical scanners. Even on surfaces with good reflective properties, the geometry of the object itself can prevent accurate measurement. The key factor is the angle at which the projected light strikes the surface relative to the camera's viewing direction. Two angles define this relationship at every surface point [1]:

- Angle of incidence – the angle between the incoming light ray and the local surface normal (Fig. 4).
- Detection angle – the angle between the reflected ray reaching the camera and the local surface normal (Fig. 4).

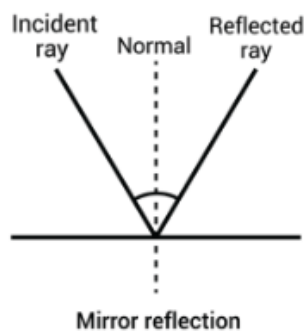


Fig. 4 Angle of incidence and reflected ray [1]

As the angle of incidence increases, projected dots stretch into ovals and lines thicken. This deformation reduces precision. The best measurement quality is achieved when the light strikes perpendicular to the surface (angle of incidence = 0°). This is especially relevant for handheld scanners such as the T-SCAN Hawk described in this thesis, where the operator directly controls the scanning angle and must consciously maintain near-perpendicular orientation [1].

Three specific geometric situations cause systematic errors:

- Sharp external edges split the projected beam. As a result, only a fraction of light reflects back, causing the system to register the point at an incorrect depth, typically farther from the scanner than the true surface [1].
- Internal edges cause light to reflect from two adjacent surfaces simultaneously. The detector averages the two returns and records a point above the actual surface, closer to the scanner than the true geometry [1].
- Line-of-sight occlusion occurs when surrounding geometry blocks either the projected light from reaching a surface area or the reflected light from reaching the camera [1]. The result is missing data (voids) in the point cloud. Deep cavities, undercuts, and closely spaced features are typical causes.

1.5 OTHER ENVIRONMENT RELATED ISSUES AFFECTING SCANNING

3D scanning results are affected by environmental factors such as vibrations, temperature, humidity and ambient light (see section 1.3). All measurements in the practical part are done under the controlled environment conditions, that are specified in Chapter 7. Although it is impossible to compare in this work different methods that manufacturers use to minimize effects from certain factors, most significantly affecting scanning are:

- Vibration of the setup degrades measurement. Scanners/objects must be at rest during acquisition. Some systems include stabilizing features. [1]
- Temperature of both scanner and the scanned object is one of the biggest factors. Geometrical properties of scanned parts are normally referenced to a standard temperature of 20°C , therefore scanner, object and environment should be allowed to reach thermal equilibrium or corrected for thermal expansion.

1.6 INDUSTRIAL APPLICATIONS AND RESULTING SCANNER REQUIREMENTS

In order to meaningfully compare 3D scanners in this thesis, it is first necessary to establish what the scanning output should achieve. It allows to determine which technical parameters and features matter most. Four representative application areas from mechanical engineering were selected for this purpose, each placing distinct demands on the scanning system. The requirements derived below draw on published studies and international standards, and they form the basis for both the comparison matrix and the selection of test parts used in the practical part. In every case, the scanners must be evaluated under conditions representative of the actual measurement task, rather than relying solely on manufacturer specifications.

Dimensional inspection and quality control requires the tightest metrological performance. The scanner measurement uncertainty must be a small fraction of the part tolerance being verified, ideally one-fifth or less, following the principle of ISO 14253-1 [7]. For a typical machined part tolerance of $\pm 0.1\text{ mm}$, the scanner should demonstrate uncertainty below 0.02 mm on a calibrated artefact. Performance must be verified per VDI/VDE 2634 or ISO 10360-13 for

traceability [8; 9]. The scanner must be evaluated against the specific GD&T tolerance types present on the part (size, form, position), since sensors that perform well on one tolerance type may show larger errors on another [10][11]. Demonstrated accuracy on representative surface finishes (not only on calibration artefacts) is essential, as optical scanners show degraded performance on rough, dark, or reflective surfaces [12; 13].

Wear analysis prioritizes repeatability over absolute accuracy, because the method compares successive scans of the same object to detect progressive geometry changes. The scan-to-scan repeatability must be smaller than the smallest wear increment to be detected, typically below 0.05 mm for tooling applications [14; 15]. The scanner must support volumetric comparison (material loss and material gain) by registering successive scans to a common coordinate system. Accessibility to the measurement location is critical, since wear is often measured on tools that are difficult to reposition, favoring portable scanners. Robustness to shop-floor conditions (temperature, vibration, surface contamination) is also required [16; 17].

Reverse engineering demands as much surface coverage as possible and sufficient point density. The main purpose of the resulting meshes is to help reconstruct CAD models in the post-processing. The scanner accuracy must exceed the required tolerance of the final model, and point density must resolve the smallest relevant features such as fillets, chamfers, and thin walls [18][1][19]. The scanning strategy and operator skill have been shown to affect accuracy as much as the hardware itself [20][19].

Rapid prototyping requires accuracy matched to the additive manufacturing process tolerance. For stereolithography (SLA) verification (process tolerance approximately ± 0.15 mm), scanner uncertainty should be below 0.05 mm; for selective laser sintering (SLS) (± 0.3 mm), below 0.1 mm; for fused deposition modeling (FDM) (± 0.5 to 1.0 mm), below 0.2 mm [21; 22]. The scanner must perform reliably on additive manufactured surface textures including layer lines, partially sintered powder, and translucent resins, which differ from conventional machined surfaces [23; 24]. For scan-to-print workflows, the output mesh must be watertight and of a resolution matched to the printer's minimum feature size. Over-resolved meshes needlessly increase file size and slicing time, whereas under-resolved meshes introduce faceting artifacts below the printer's capability.

2 WORKING PRINCIPLES OF ZEISS ATOS Q

ZEISS ATOS Q is a structured-light scanner manufactured by ZEISS (*Fig. 5*). It is designed for high-precision industrial metrology applications such as dimensional inspection, quality control and wear analysis. In addition, it is well suited for reverse engineering of small removable parts, although its capabilities exceed the requirements for rapid prototyping. The system consists of a projector and two cameras, a powerful desktop PC or laptop, a stand to mount the sensor on. Although ATOS Q is mounted on a stand during measurement, it is classified by the manufacturer as a mobile system because it can be relocated between measurement sites. For automated multi-view acquisition of small parts, the system can be combined with a motorized rotary table (*Fig. 5*). ATOS Q projects precise fringe patterns (alternating light and dark stripes) onto the surface of the object, which are captured by two cameras. The projection uses narrow-band blue LED light (see Section 1.3), allowing ambient light interference to be filtered out during image acquisition [25]. The technical principles underlying this measurement process are described in the following sections.

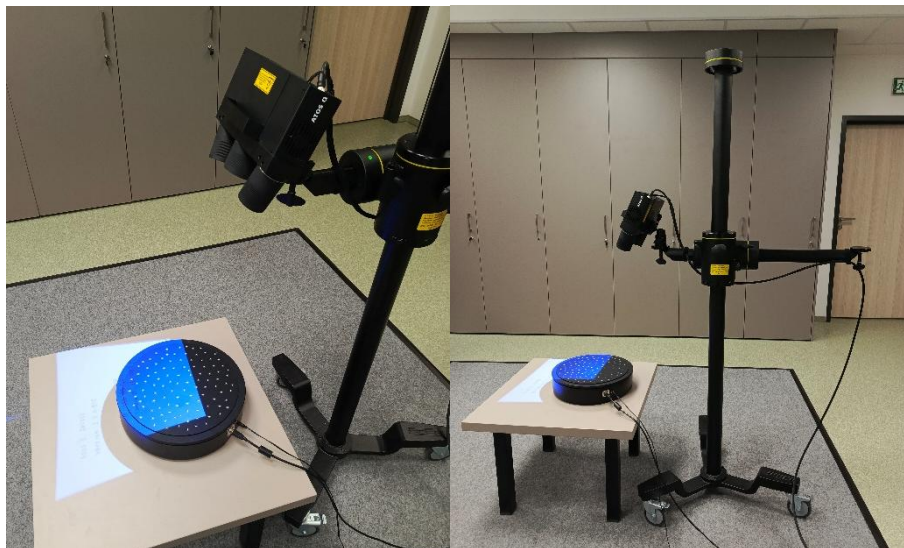


Fig. 5 ZEISS ATOS Q scanner

2.1 STRUCTURED-LIGHT SCANNING AND TRIANGULATION PRINCIPLE

Structured-light scanning gets its name from the organized patterns of light, such as stripes, grids or dots, projected onto an object's surface. It is an optical measurement method based on the triangulation principle.

ZEISS ATOS Q computes 3D surface coordinates using the triangulation principle. The sensor head contains a central digital projector and two cameras arranged in a fixed configuration, separated by a known baseline distance (*Fig. 6a*). During scanning, the projector emits a rapid sequence of fringe patterns onto the object's surface in both vertical and horizontal directions. Both cameras simultaneously capture images of the deformed patterns from different viewing angles (*Fig. 6b*).

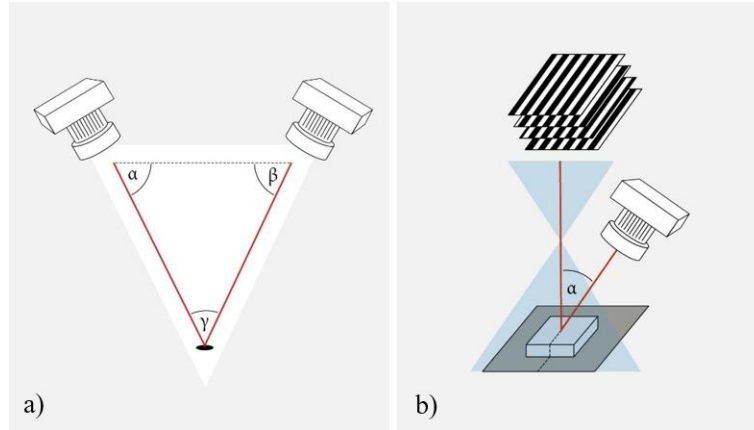


Fig. 6 Triangulation principle of the ATOS Q: a) stereo camera configuration, b) fringe projection setup [41]

The 3D coordinate computation relies on the stereo disparity principle. Cameras measure pixel positions. A point in 3D space lands on a specific pixel (u, v) on each camera sensor. When both cameras observe the same surface point, it appears at pixel u_L in the left camera and u_R in the right camera. The difference is called disparity: $d = u_L - u_R$. This horizontal pixel shift is related to the depth of the surface point by the equation:

$$Z = \frac{f \cdot b}{d}, \quad (1)$$

where Z is the depth, f is the camera focal length, b is the baseline distance, and d is the disparity [26]. Once the depth Z is determined, the remaining coordinates X and Y are calculated from the pixel positions and the known camera parameters [26].

The projected fringe patterns are used to establish which pixel in the left camera corresponds to which pixel in the right camera. When a striped pattern is projected onto a surface, each camera pixel records a specific brightness value (Fig. 7). On a flat surface the stripes appear evenly spaced, but wherever the surface has depth variation, the stripes shift - and this shift encodes the local height. By projecting several phase-shifted versions of the pattern and recording how the brightness changes at each pixel, the system computes a unique value (called the phase) for that point on the surface. Patterns at multiple frequencies are combined so that every pixel across the field of view receives a unique identifier [27]. Because the projector is digital, the projection consists of many discrete pixels and can generate many different fringe patterns in both vertical and horizontal directions, providing significantly more information than an analog projector, whose fringes run in one direction only [28]. This dense, unambiguous encoding allows the two cameras to be matched with sub-pixel precision.

202	211	144	81	101
173	185	227	88	123
92	164	177	225	149
42	99	162	180	232
35	45	95	182	230

Fig. 7 Simplified example of the pixel brightness values in the ZEISS ATOS Q scanner [30]

2.2 PARAMETERS OF ZEISS ATOS Q

Before comparing ZEISS ATOS Q with the other scanners evaluated in this thesis, it is necessary to understand how its key parameters influence measurement results. Unlike handheld or mobile scanners where the operator freely controls the scanning distance and angle, ATOS Q operates within a precisely defined measuring volume that determines the achievable point density, spatial resolution, and measurement accuracy for each scan. The choice of measuring volume therefore directly affects which application the scanner is suited for. A small volume with fine point spacing is needed for dimensional inspection of tight-tolerance parts, while a larger volume may be sufficient for reverse engineering (see Section 1.6) [25][29]. The key technical parameters of ATOS Q are summarized in *Tab. 1*.

Tab. 1 Technical parameters of ZEISS ATOS Q [25]

Technical Parameters	ATOS Q 12M
Light Source	LED
Points per scan	12 million
Measuring area [mm ²]	100 × 70 – 500 × 370
Point spacing [mm]	0.03 – 0.12
Working distance [mm]	490
Measuring volumes	100, 170, 270, 350, 500
Cable length [m]	10

The fixed working distance of 490 mm defines the optimal measurement plane (*Fig. 8*), the flat plane at which the fringe pattern is sharpest, and the calibration is most accurate. Points closer to or farther from this plane are still measured, but with slightly reduced accuracy (*Fig. 9*).

During setup, the scanner is positioned so that the center of the scanned object sits approximately at this distance from the sensor head. Since real parts have depth, different features of the part protrude at different distances, not every surface point lies exactly at 490 mm. This is accounted for by the measuring volume.

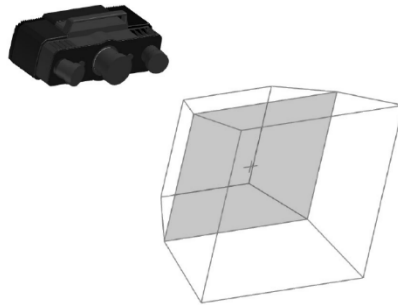


Fig. 8 Optimal measurement plane and measurement volume [30]

The measuring volume (MV) is the three-dimensional space that the scanner captures in a single acquisition (*Fig. 8*). Changing the measuring volume in ATOS Q is done by swapping the lens kit on the scanner. For example, MV 270 ($270 \times 200 \times 200$) covers $255 \times 185 \times 180$ mm in length, width and depth [30]. Points anywhere within this depth range are measured, though accuracy decreases toward the edges. A smaller volume such as MV 100 concentrates the sensor's pixel resolution on a smaller area, yielding higher point density and accuracy. A larger volume such as MV 500 covers more surface area but with lower point density, since the camera sensor always has the same number of pixels - 12 million (*Tab. 1*). The trade-off between coverage and resolution is inherent to all camera-based triangulation systems [1; 25; 29]. It is important to differentiate measuring volume from the field of view (FOV). The latter refers only to the two-dimensional area visible to the cameras at the working distance [29].

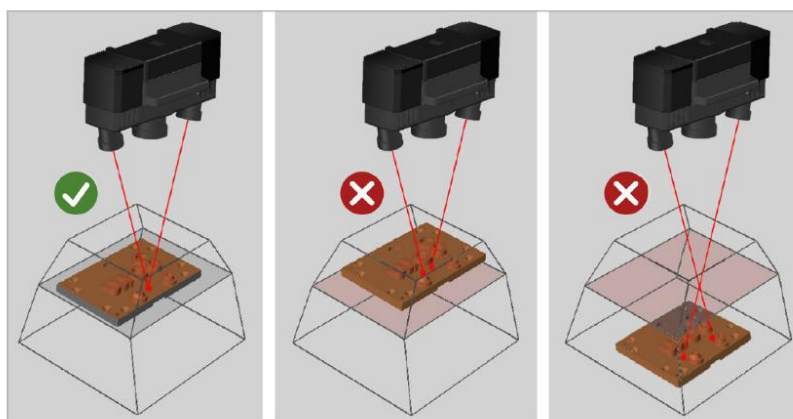


Fig. 9 Scanner positioned at optimal and non-optimal measuring distances [30]

2.3 LIMITATIONS AND SOURCES OF ERROR

ATOS Q uses narrow-band blue LED light (wavelength approximately 450–470 nm) as its illumination source. The shorter wavelength of blue light provides higher spatial resolution

compared to infrared-based systems (see Section 1.3) and is generally well suited for the indoor illumination. LED source does not provide enough light intensity for the outdoor use.

ATOS Q achieves high accuracy within its calibrated measuring volume, but several limitations become apparent when compared to handheld and consumer-grade scanners. The most fundamental constraint is the fixed measuring volume. Each lens kit defines a specific field of view and working distance (490 mm), meaning the scanner cannot adapt to varying part sizes without physically swapping lenses and recalibrating. Parts larger than the selected measuring volume require multiple measurement series, which introduce alignment uncertainty that accumulates in the final mesh. This lack of portability is the primary practical disadvantage relative to the T-SCAN Hawk and consumer-grade methods [25; 20].

Surface reflectivity and material properties impose significant constraints. Mirror-like, transparent, or translucent surfaces cannot be reliably measured without temporary anti-reflective coating, which adds a finite thickness to the measured geometry (systematic error). Dark or colored surfaces, particularly red materials, reduce fringe contrast and degrade accuracy. Semi-transparent polymers such as SLA resins cause subsurface light scattering that distorts depth measurements. In practice, most industrial parts require surface preparation before scanning with the ATOS Q, adding time and introducing coating-thickness uncertainty that is particularly problematic for high-tolerance dimensional inspection [1; 23].

Geometric accessibility is limited by stereo camera configuration. Deep cavities, narrow slots, undercuts, and internal channels may be occluded from one or both cameras, producing gaps in the point cloud. External edges can cause fringe aliasing (incorrect depth values), and internal edges produce averaged readings above the true surface [1].

Environmental sensitivity and workflow rigidity present additional disadvantages in comparison. ATOS Q requires a vibration-free setup, thermal equilibration of both the scanner and the part, and controlled ambient lighting. The calibration procedure is multi-step and time-consuming and must be repeated whenever the measuring volume is changed. Scan time per part is relatively long because the system acquires one field of view per exposure and requires repositioning between views. Jacobs et al. (2023) showed that reducing scan positions from 15 to 5 doubled the standard deviation of the measurements, confirming that the ATOS Q demands a careful, time-intensive scanning strategy to achieve its specified accuracy [25; 20].

3 WORKING PRINCIPLES OF ZEISS T-SCAN HAWK 2

ZEISS T-SCAN Hawk 2 is a handheld blue laser triangulation scanner designed for portable 3D measurement (*Fig. 10*). Unlike stationary systems, it allows the operator to move freely around the object, making it suitable for scanning large parts, objects in fixed installations, or geometries that are difficult to reposition onto a turntable. The scanner weighs less than 1 kg and connects to a laptop via a lightweight 10 m cable [31]. The following sections describe the laser triangulation principle used by T-SCAN Hawk and how it differs from the structured-light approach of ATOS Q, the tracking system that replaces the fixed measuring volume, the key technical parameters, and the practical limitations relevant to the comparison in this thesis.



Fig. 10 ZEISS T-SCAN hawk 2 scanner

3.1 LASER TRIANGULATION PRINCIPLE

ZEISS T-SCAN Hawk 2 uses laser triangulation as its measurement method, which differs from ZEISS ATOS Q structured-light approach in both the illumination strategy and the data acquisition mode. Instead of projecting a rapid sequence of fringe patterns in a single capture, T-SCAN Hawk projects narrow blue laser crosses onto the object surface for the whole duration of scanning. The scanning process is therefore continuous, which attributes to faster capture time than that of ATOS Q. In addition to the blue measurement lasers, a smaller red laser cross is projected onto the surface to help find the optimal measuring distance. The scanner contains two integrated cameras in a stereo configuration similar to ATOS Q (see Section 2.1) that capture the projected pattern from slightly different viewpoints. The laser crosses deform across the surface geometry, and each camera records the position of the deformed line on its sensor. The system computes the 3D coordinates of points along each line using the known geometric relationship between two cameras and the surface point [2; 31].

The triangulation geometry of T-SCAN Hawk 2 is based on the two-camera baseline, which follows the principle of ATOS Q (see Section 2.1). The difference is that the relation between the cameras' views is established by narrow blue laser lines instead of fringe patterns. The blue laser crosses function as a high contrast structured cue that makes corresponding points easy to identify in both camera images. This principle allows the system to operate with continuous projection rather than a sequence of phase-shifted patterns [30].

3.2 TRACKING AND COORDINATE SYSTEM

ZEISS T-SCAN Hawk 2 must continuously determine its position and orientation in space. This is achieved by detecting reference point markers placed on or around the part prior to scanning. Before scanning the reference point field is created. In this mode scanner doesn't project patterns but is moved around as the cameras identify visible reference markers and create a point field. In the scanning stage the system tracks its position by identifying at least three reference points from that field. New markers could be added during scanning, as long as three known are visible. The system can orient each new scan sweep relative to all previous data. This approach replaces the fixed measuring volume of ATOS Q with a dynamically expanding coordinate system that grows with each new scan pass [31].

Alternatively, the scanner can operate without reference markers by relying on geometric feature matching (markerless mode). In this mode, the software matches overlapping surface geometry between sweeps to maintain registration. This is faster to set up and works best on parts with sufficient geometric variation. Large flat or featureless surfaces may cause tracking loss [31].

3.3 PARAMETERS OF ZEISS T-SCAN HAWK

The key parameters of T-SCAN Hawk are summarized in *Tab. 2*. Unlike ATOS Q, where the measuring volume is selected by swapping lens kits, T-SCAN Hawk does not have a fixed measuring volume. Its effective measurement range is determined by the scanning distance maintained by the operator and the distribution of reference markers that define the global coordinate system.

Tab. 2 Technical parameters of ZEISS T-SCAN Hawk 2 [31]

Technical Parameters	ZEISS T-SCAN Hawk 2
Laser class (IEC 60825-1:2014)	Class 2 (eye-safe)
Point spacing [mm]	0.05-10
Scan area [mm]	Up to 600 x 550
Volumetric accuracy	0.02 mm + 0.015 mm/m
Weight	< 1kg
Cable	10m (ultra-light)

T-SCAN Hawk has a fixed measuring volume and a flexible depth of field. During scanning set up the preferred resolution (point spacing) is picked in the software. It defines how much depth of the measuring volume can be used (*Fig. 11*)[30]. The system derives a range of working distances from this (*Tab. 3*). T-SCAN Hawk incorporates a radar that continuously measures the scanner-to-object distance and projects a red laser cross to help identify it. When scanner head is closer to the surface, horizontal cross line moves up and when further, moves down (*Fig. 11*). As soon as red laser lines stop intersecting, the scanner is outside the working range. This feature helps create continuous measurements without checking software indications, significantly improving scan time. T-SCAN Hawk operates in a flexible range,

unlike ATOS Q with a fixed optimal working distance, allowing scanning surfaces at varying depths with no need to recalibrate or change lenses. The practical benefit is that complex geometries with significant depth variation can be captured in a single continuous scan session [31].

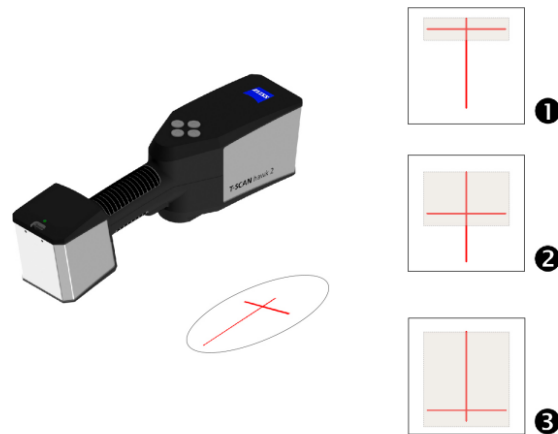


Fig. 11 ZEISS T-SCAN Hawk 2 usable depth of the measuring volume from 30% to a 100% depending on the set resolution [30]

Volumetric accuracy is specified as $0.02 \text{ mm} + 0.015 \text{ mm/m}$, which consists of a fixed base accuracy component and a distance-dependent component that accumulates with the size of the measurement volume [31]. For example, scanning within a 1 m volume gives a maximum expected error of $0.02 + 0.015 \times 1 = 0.035 \text{ mm}$. For a 3 m volume: $0.02 + 0.015 \times 3 = 0.065 \text{ mm}$. This linear error growth contrasts with ATOS Q, where accuracy is fixed for a given measuring volume and does not degrade with part size within that volume.

Tab. 3 ZEISS T-SCAN Hawk measuring areas [30]

Number of the measuring area	Resolution [mm]	Working distance [mm]	Scan area [mm]
1	0.05-0.19	240-330	300 x 300
2	0.20-0.49	240-480	450 x 430
3	0.50-10.00	240-700	610 x 560

The deep pocket scanning capability uses a single blue laser line mode that concentrates the measurement beam into a narrow strip [31]. Because the laser line can project into confined spaces where a wide fringe pattern would be partially occluded, T-SCAN Hawk can reach into cavities, narrow grooves, and recessed features that ATOS Q cannot access with its stereo camera configuration. The scanner head is compact (under 1 kg) and can be physically maneuvered into tight spaces. This capability is particularly relevant for wear analysis on forging dies with deep impressions and for reverse engineering of parts with internal features.

3.4 LIMITATIONS AND SOURCES OF ERROR

T-SCAN Hawk shares the fundamental surface-interaction limitations of all optical scanners (see Section 1.4), but is more susceptible to specular reflection and subsurface scattering effects than ATOS Q (see Section 3.1). The blue laser light used by T-SCAN Hawk operates at approximately 450 nm wavelength, providing the same advantages of shorter wavelength as ATOS Q blue LED: higher spatial resolution compared to infrared systems and the ability to filter out ambient light interference through narrow-band optical filtering on the cameras. However, because the illumination is a coherent laser source rather than an incoherent LED, T-SCAN Hawk is susceptible to speckle noise, a granular interference pattern caused by coherent light reflecting from rough surfaces [32]. The scanner mitigates this through multiple laser crosses and averaging algorithms, but the effect cannot be eliminated entirely, particularly on very rough or grainy surfaces [28][32].

In a single acquisition, the point density achievable with T-SCAN Hawk is lower than with ATOS Q, because laser-line triangulation samples the surface along projected lines rather than across the full field of view simultaneously. Although the handheld scanner can accumulate high overall density through sustained sweeping, coverage tends to be less uniform, and fine surface details (small fillets, shallow engravings, subtle curvatures) may be resolved less faithfully in regions the operator swept quickly.

Meana et al. (2024) showed that laser triangulation sensors produce less accurate points near the edges of spherical surfaces, where the laser beam hits the surface at nearly tangential angle. These outliers need to be filtered out, and the optimal filter setting depends on both the sensor and the scanned material [12].

T-SCAN Hawk introduces more operator-dependent error sources than stationary scanners. The scanner accuracy depends on maintaining correct working distance, appropriate scanning speed and near-perpendicular scan angle. The exposure time must be matched to the standoff distance to minimize errors [33]. Although environmental sensitivity is lower than ATOS Q (no vibration-free setup required), the reference point field must remain stable throughout the scan, and any movement of markers between passes introduces registration error into the final mesh [31].

4 WORKING PRINCIPLES OF IPHONE LIDAR

The Apple iPhone (models 12 Pro and later) integrates a LiDAR sensor (see Section 1.1) on its rear camera module. Originally designed for augmented reality applications, LiDAR can also be used for 3D scanning through third-party applications such as Polycam, 3D Scanner App, or Scaniverse. This makes the iPhone the most accessible and lowest-cost option among the three scanners compared in this thesis.

4.1 TIME-OF-FLIGHT PRINCIPLE

The iPhone's LiDAR operates on the time-of-flight (ToF) principle and consists of an infrared light emitter and a receiver. The source contains 64 vertical-cavity surface-emitting laser (VCSEL) cells, and the 64 laser pulses are multiplied by a 3×3 diffraction optical element (DOE) into 576 pulses (*Fig. 12*). These reflect off the target and are detected by a single-photon avalanche diode (SPAD), which measures the round-trip travel time of each pulse [34]. The 576 depth points are then fused with RGB data from the wide-angle lens to generate a denser depth map. According to Krausková et al. (2025), the resulting depth map has a resolution of 256×192 pixels (roughly 49,000 points per frame) and can be produced at frame rates of up to 60 Hz depending on the scanning application [35]. The depth Z for each point is computed from the relationship:

$$Z = \frac{c \cdot t}{2}, \quad (3)$$

where c is the speed of light and t is the measured time of flight of the emitted ray. Unlike triangulation-based systems, ToF does not require a baseline between projector and detector, which makes it inherently more compact but also limits its achievable depth resolution at close range [34].

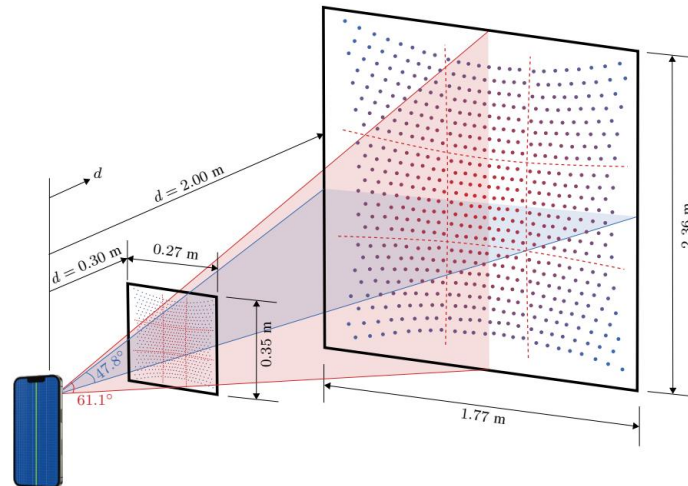


Fig. 12 The 3×3 grid of 64 laser emitters each is defined by the dashed red lines [34]

4.2 PARAMETERS OF IPHONE LIDAR

Apple does not publish formal metrology specifications for the iPhone LiDAR scanner. The parameters relevant to comparison were taken from independent evaluations and cited accordingly.

The iPhone's LiDAR scanner has a specified range of approximately 0.2–5 m. Published evaluation reports absolute accuracy of approximately ± 1 cm for objects with side length greater than 10 cm, with precision degrading for smaller objects [36]. The sensor is factory-calibrated, leading to non-adjustable measuring volume, no calibration procedure, no control over calibration quality and the accuracy is not traceable to any metrology standard. The quality of the 3D output depends heavily on the scanning application used, since each implements different SLAM algorithms [37].

A critical aspect of iPhone LiDAR scanning is the use of SLAM (Simultaneous Localisation and Mapping) for 3D reconstruction. Unlike the ATOS Q and T-SCAN Hawk, which use physical reference markers or calibrated geometric relationships to determine scanner position, the iPhone relies on a software algorithm that combines LiDAR depth data with visual-inertial odometry (VIO estimates local position, orientation and velocity) from the cameras and the inertial measurement unit (IMU containing gyroscope and accelerometer). As the scanner is moved around an object, the SLAM algorithm continuously estimates the device position by matching current observations to a map built from previous frames. This approach eliminates the need for reference markers or calibration but introduces drift error. Inaccuracies accumulate over time and distance, producing a progressive distortion of the 3D model. SLAM drift is visible as split surfaces, displacement errors, and surface duplication at locations where scan paths overlap [37; 38].

4.3 LIMITATIONS AND SOURCES OF ERROR

For dimensional inspection and wear analysis iPhone LiDAR is fundamentally unsuitable. Luetzenburg et al. (2021) established an absolute accuracy of approximately ± 1 cm for objects larger than 10 cm and showed that both accuracy and precision degrade for smaller objects. The limit of detection for objects is around 5 cm [36]. Tondo et al. (2023) further identified an optimal working distance of 0.30-2.00 m, with significant noise degradation outside this range [34].

The point cloud density is approximately 49000 points per frame, with each application for scanning slightly affecting the number [35]. When compared to 12 million for the ATOS Q it's producing a much worse spatial resolution, that cannot capture fine geometric features such as fillets, chamfers, threads, or small holes. The infrared wavelength (approx. 940 nm) provides roughly half the spatial resolution of blue light (approx. 450 nm) for equivalent optics. iPhone LiDAR could be used outdoors, although the sensor is still susceptible to interference from direct sunlight and the accuracy decreases in poorly illuminated conditions [34]. LiDAR has difficulty with highly absorptive (dark black) and highly reflective surfaces [34; 36].

SLAM drift is the characteristic error source that fundamentally limits the iPhone for all engineering applications. As the device moves during scanning, errors accumulate progressively, producing global distortion of the model. Askar et al. (2023) observed split surfaces and displacement errors that varied significantly between scanning applications

running on the same hardware, demonstrating that software processing affects results as much as the sensor itself [37]. This means the iPhone LiDAR cannot produce metrologically traceable measurements for mechanical parts under any conditions.

For reverse engineering and rapid prototyping iPhone LiDAR can produce usable results only for geometrically simple objects where centimetre-level accuracy is acceptable, such as rough form-factor mockups or large-scale spatial documentation. The coarse mesh resolution means small features are smoothed over or lost entirely. For scan-to-print workflows, a printed reproduction will differ from the original by approximately ± 10 mm in every dimension, acceptable only for the roughest conceptual prototyping [36]. For print verification, the scanner cannot distinguish between a correctly printed part and one with gross dimensional errors, since the measurement noise dominates over any printing deviation for all common AM processes (FDM ± 0.50 mm, SLS ± 0.30 mm, SLA ± 0.15 mm) [21].

5 Comparison matrix and scanned parts

In the following chapter predictions of the scanners' performance are estimated and the test parts are selected. The predicted values serve as predictions to be validated in the practical part. The comparison (*Tab. 1* *Tab. 4*) is derived from the four application areas defined in Section 1.6. and presumes the performance of each scanner across those areas, based on the technical specifications and limitations identified in Chapters 2, 3, and 4.

Tab. 4 Comparison matrix

Application	Parameter	ATOS Q	T-SCAN Hawk	iPhone 16 LiDAR
Dimensional inspection	Accuracy on calibrated reference [mm]	0.01-0.03	0.02 + 0.015/m	Approx. 10
	Point density [pts/cm ²]	Very High	High	Very low
	GD&T capability (size/form/position)	Full	Full	None
Wear analysis	Scan-to-scan repeatability	Excellent	Good (operator dependent)	Poor
	Volumetric deviation capability	Yes (ZEISS INSPECT)	Yes (ZEISS INSPECT)	Limited (app-dependent)
	Accessibility to measurement location	Low (stationary)	High (handheld, wired)	Very High (handheld, wireless)
Reverse engineering	Surface coverage completeness [%]	85-95 (occlusion limits)	90-95	70-90 (SLAM gaps)
	Resolution (Point spacing) [mm]	0.03-0.15 (MV-dependent)	0.05-10 (adjustable in software)	Unknown
	Mesh quality (watertight, defect-free)	Very High	High	Low
Rapid prototyping	Accuracy vs. SLA tolerance (± 0.15 mm)	Exceeds (10x margin)	Meets (3-5x margin)	Fails (noise > tolerance)
	Performance on AM surface textures	Good (may need coating)	Good (subsurface risk on resin)	Unknown
	STL mesh suitability for printing	Exceeds (needs simplification)	Good (adequate density)	Poor (coarse, defects)

Based on the predicted performance in the matrix (*Tab. 4*), the following test parts are selected to validate the theoretical comparison. Each part targets specific parameters where the three scanners are expected to differ most significantly, ensuring that the practical measurements can confirm or refute the predictions above.

Direct validation of the accuracy row of the dimensional inspection category

Calibrated gauge block or reference standard. This part tests absolute dimensional accuracy against a known reference value. ATOS Q is predicted to achieve deviations below 0.03 mm, T-SCAN Hawk below 0.05 mm, and iPhone LiDAR deviations of several millimeters.

Validation of geometric accessibility and minimum resolvable feature size

Component with deep pockets, undercuts, and fine geometric features, such as small radii, thin walls, and sharp edges. This part tests the ability of each scanner to capture difficult-to-access geometry and small details. T-SCAN Hawk is predicted to achieve the best surface coverage due to its handheld operation and deep-pocket scanning mode, while ATOS Q is expected to show occlusion gaps in deeper areas. iPhone LiDAR is expected to fail in resolving small geometric features.

Validation of sensitivity to surface properties

Component with mixed surface finishes, including matte, glossy, dark, and translucent regions. This part tests how different optical scanning methods respond to surface reflectivity, absorption, and translucency. All scanners are expected to be affected by specular reflections, while T-SCAN Hawk may show errors caused by subsurface penetration on translucent materials, and iPhone LiDAR is expected to lose signal on dark surfaces.

Validation of rapid prototyping inspection capability

3D-printed test specimen with known CAD geometry, such as an SLA or FDM printed object with holes, cylinders, flat surfaces, and curved features of different sizes. This part tests the ability of each scanner to verify additively manufactured geometry by comparing the acquired scan with the original CAD model. It also evaluates mesh quality and suitability for scan-to-print workflows.

Validation of reverse engineering workflow

Complex automotive component requiring full surface coverage. This part tests surface coverage completeness, mesh quality, scan time, and the practical effort required to produce a complete digital model. T-SCAN Hawk is predicted to achieve faster full coverage, while ATOS Q is expected to provide higher point density per scan. iPhone LiDAR is expected to show SLAM drift artefacts on complex geometry.

Two test parts were selected for the practical comparison: a steering knuckle (rear axle left, cast aluminum) and a car wheel (*Fig. 13*). The steering knuckle combines features that challenge all scanners simultaneously: functional surfaces on all sides (ball joint taper, wheel bearing bore, brake caliper mount, tie rod attachment), freeform transitions between features, and deep pockets that test geometric accessibility. The car wheel complements this selection by providing a large-diameter rotationally symmetric geometry with both matte and glossy surface regions, fine details (bolt holes, valve hole, spoke edges), and a size that requires multi-scan registration

for ATOS Q while remaining within a single scan session for T-SCAN Hawk. Together, these two parts expose the key differences predicted by the comparison matrix. ATOS Q is expected to have an advantage in point density and accuracy on accessible flat surfaces, T-SCAN Hawk should excel in surface coverage on complex geometries through handheld freedom, and the iPhone LiDAR should show inability to resolve fine features and its SLAM drift on large objects.

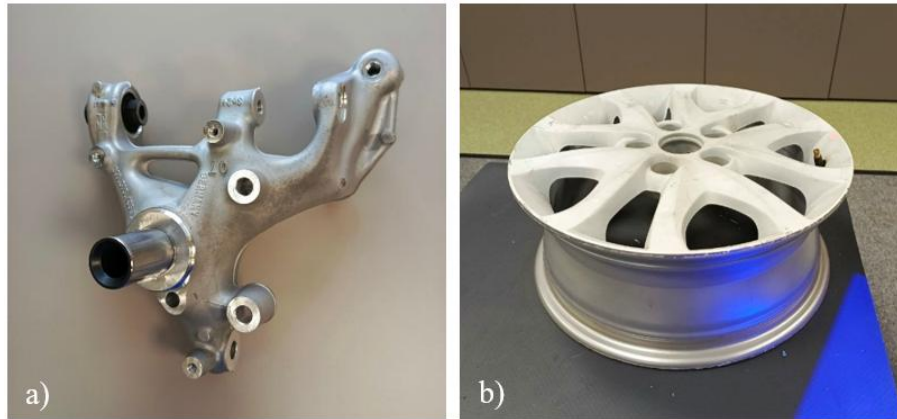


Fig. 13 Test parts: (a) steering knuckle; (b) car wheel

6 TESTING METHODOLOGY

In the practical part additional scanners are included for a broader comparison. As a more accessible alternative to ZEISS ATOS Q, the white structured-light scanner EinScan Pro HD is selected. Similarly, for ZEISS T-SCAN Hawk 2, a more accessible device is represented by the blue laser scanner Creality CR-Scan Raptor. Photogrammetry with Android camera is considered as another consumer-grade scanning method, alongside iPhone LiDAR.

Based on the comparison matrix, the practical part of this thesis focuses on the reverse engineering application area. This choice reflects the primary requirements of the laboratory at the Institute of Automotive Engineering, where 3D scanning is most frequently used for digitizing existing components for CAD modelling, design modification, and documentation. Reverse engineering also provides the most comprehensive comparison, as it tests all scanners across multiple evaluation criteria simultaneously.

The main evaluation criterion is based on a surface-to-surface comparison of the 3D models produced by each scanner. It quantitatively expresses the deviation of each mesh to the reference model in millimeters. Since CAD models of the selected parts are not available, ZEISS ATOS Q is used as the reference system. This is due to its highest metrological grade among the evaluated scanners and the fact that its structured-light measurement principle is the most established in industrial metrology. Comparison is done in ZEISS INSPECT Optical 3D pro software, where meshes from all scanners are imported in STL format. Fully repaired meshes from ZEISS ATOS Q serve as the reference dataset and are converted to CAD models using ZEISS INSPECT mesh-to-CAD tool (Section 8.3). to enable the use surface-to-CAD comparison tool. Meshes of compared scanners then are aligned to the ATOS Q CAD model using best-fit registration. Surface deviations are analyzed using color-coded deviation maps.

For a valid mesh comparison, it is necessary to define which surfaces of the test parts are used as the basis for accuracy evaluation. Reverse engineering of mechanical components prioritizes functional surfaces that define the part's fit, together with the overall external geometry that affects clearance and assembly. Therefore, quantitative deviation analysis is limited to these functional regions, while the remaining surfaces, being geometrically complex, are evaluated only for mesh defects and surface coverage completeness. Surface coverage is determined by importing a fully repaired ATOS Q mesh in STL format into software Creo Parametric and measuring its total surface area. This value is taken as 100% coverage, although in practice it does not represent absolute completeness. The corresponding meshes from the other scanners are imported in their untreated state, retaining all the mesh defects and gaps, with only reference markers holes filled, since they don't contain any meaningful data.

Surface-to-surface dictation is calculated using surface comparison on CAD function in ZEISS INSPECT software. Only functional surfaces that were completely captured by the ATOS Q system were quantitatively evaluated. For the steering knuckle, the evaluated surfaces included the spindle, mounting faces, and suspension attachment surfaces. For the wheel, the evaluated features included the central bore, lug hole seats, and hub mounting surface. In addition to geometric accuracy, the selected scanners areas compared based on technical parameters and operational complexity. These include setup time, scanning duration and the time required for post-processing. The complexity of the scanning workflow and software usage is described in the individual sections for each scanner and summarized in the final comparison. Together, these parameters provide a more nuanced basis for selecting an appropriate scanner under specific conditions. All the results are presented in Chapter 14.

7 PART PREPARATION AND SCANNING CONDITIONS

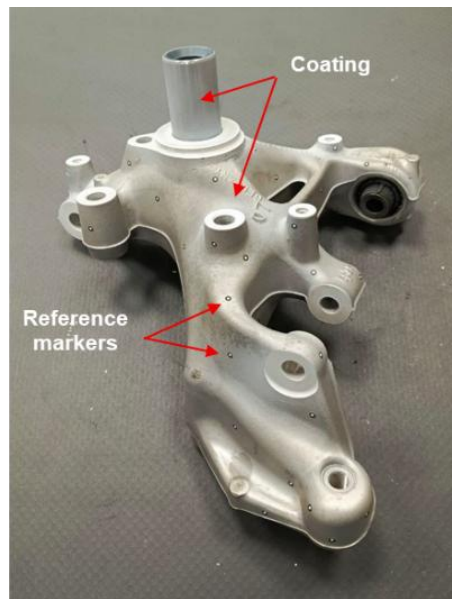


Fig. 14 Steering knuckle with coating and reference markers

All scanning sessions were conducted under controlled laboratory conditions at the Institute of Automotive Engineering. The ambient temperature was maintained within the range of 24 ± 2 [°C]. All scanners were allowed to reach thermal equilibrium for at least 20 minutes before calibration and scanning. Artificial lighting in the laboratory was kept constant and indirect. Direct sunlight was excluded by covering windows.



Fig. 15 Car wheel with reference markers

Before scanning, both test parts required surface preparation. Glossy and reflective surfaces of the steering knuckle are coated with a thin layer of anti-reflective matting spray (*Fig. 14*). For

this purpose, titanium oxide TiO_2 (titanium powder suspended in ethanol) is used. Car wheel is not coated as it has small enough reflective areas in the places that aren't sufficient for comparison. White 1.5 mm reference markers are placed on both parts only for ZEISS scanners (*Fig. 14; Fig. 15*). The marker size is chosen to suit both ATOS Q and T-Scan HAWK measuring volume and resolution. The marker layout is arranged to ensure that at least three markers are visible from every scanning position [30]. For Creality CR-SCAN Raptor and EinScan Pro HD white markers are later replaced by reflex 3.0 mm reference markers in the same places. Additionally, Creality scanner required placing markers on the table during wheel scanning, because measuring area was too small to keep tracking at certain angles. The iPhone LiDAR and photogrammetry do not use physical markers, but require surface coating.

8 SCANNING WITH ZEISS ATOS Q

ZEISS ATOS Q scanning complexity is more demanding and time-consuming compared with handheld or consumer-grade scanning methods. Effective use of the system ideally requires operator training and familiarity with ZEISS workflow, because it involves lens selection, multi-step calibration, surface preparation, object positioning, and repeated acquisition from suitable angles. Despite the complexity, the practical use of ZEISS ATOS Q system was highly effective and enabled the acquisition of high-quality mesh data even when operated by an inexperienced user following ZEISS workflow guidelines.

Among the evaluated scanning methods, ZEISS ATOS Q provided the highest metrological accuracy and the most reliable reconstruction quality. The resulting scans captured functional surfaces, fillets, chamfers, and the overall geometry with high fidelity, producing dense and consistent polygonal meshes. Due to this superior accuracy and mesh quality, the ATOS Q results were used as the reference data for comparison with the other scanning methods.

8.1 CALIBRATION

Full calibration procedure for ZEISS ATOS Q needs to be done every time the lens for the different measurement volume is changed. It follows six sequential steps.

First, for sufficient scanning of both parts, the MV 270 lens configuration is selected with 1.5 mm reference markers. The sensor was positioned facing perpendicularly a flat surface of the laboratory floor at the ideal working distance of 490 mm. Laser pointers (mounted between the cameras and the projector) were adjusted so that their beams converge at this distance. The laser pointers themselves do not affect measurement, as their red wavelength is invisible to the blue-light-filtered cameras.[30]

Second, the camera focus was adjusted. Both camera apertures were opened fully to produce the shallowest possible depth of field, and the focus of each camera was then set to be sharpest at the ideal measuring distance.[30]

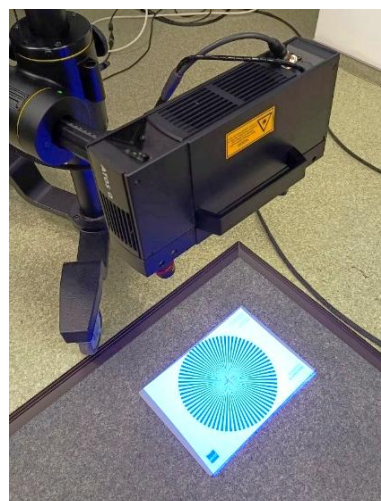


Fig. 16 ZEISS ATOS Q fringe pattern calibration

Third, the projector focus was adjusted so that the fringe patterns were as sharp as possible at the same working distance (*Fig. 16*). The cameras evaluate the sharpness of the projected fringes during this step, so the camera focus must be set first.[30]

Fourth, both camera apertures are closed down to the correct setting for the selected measuring volume, which defines the usable depth range over which the fringe patterns remain sufficiently resolved.[30]

Fifth, the actual sensor calibration was performed (*Fig. 17*). The sensor was pointed toward a certified calibration plate whose dimensions correspond to the selected measuring volume. Then the current ambient temperature was manually entered. The software uses this temperature value to compensate for thermal deformation of the calibration object relative to the reference state in which it was originally certified. A series of measurements of the calibration plate in multiple prescribed orientations was performed, guided by the software. The result displayed two green check marks, the calibration was successful.[30]

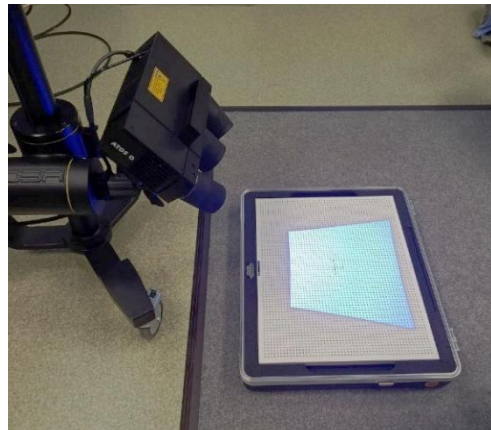


Fig. 17 ZEISS ATOS Q sensor calibration

8.2 SCANNING WORKFLOW

ATOS Q scanning workflow consists of four main phases: preparation of the measuring part, positioning, data acquisition, and finalization. The entire process is managed through ZEISS INSPECT Optical 3D software, which provides guided workflows, real-time feedback, and self-monitoring capabilities.

In the preparation and positioning phases, the sensor head was positioned at approximately the ideal working distance of 490 mm. The distance was verified using both the laser pointers and the software's distance indicator, which projected a pattern and displayed the measured distance on screen [30]. The scanning template was configured with the highest quality settings, measurement temperature at the time of scanning and exposure time was set to automatic. Only one measurement series was used for each part to ensure the least amount of error.

During data acquisition, the ATOS Q system captures reference points on the part and assigns each a unique identifier. For subsequent scans, the scanner must detect at least three previously identified reference points to ensure proper alignment. Both parts were positioned to maximize the number of reference points captured during the initial scan. ATOS Q workflow also allows the addition of new reference points during the scanning session. This functionality was utilized

due to an insufficient number of markers placed during the preparation phase. The outcome of the acquisition phase is point cloud.

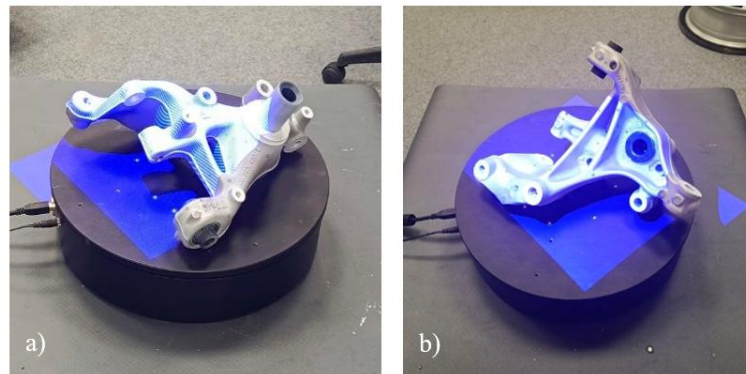


Fig. 18 Steering knuckle on the rotary table: (a) initial position; (b) flipped position

The steering knuckle was placed on the automated rotary table (*Fig. 18a*), with 12° rotation increments set in the software. The sensor head was adjusted to a near perpendicular angle to the surface of the steering knuckle. After manual initiation of the first scan, the scanner automatically scanned the part at each increment until a full 360° pass was complete. The part was then flipped to expose the opposite side and scanned using the same parameters (*Fig. 18b*). Finally, the scanner head was manually repositioned to acquire a scan of the deep cavity. System's self-monitoring features continuously checked for vibration during a scan, calibration status, ambient light changes, temperature drift, transformation errors, and missing reference points [30].

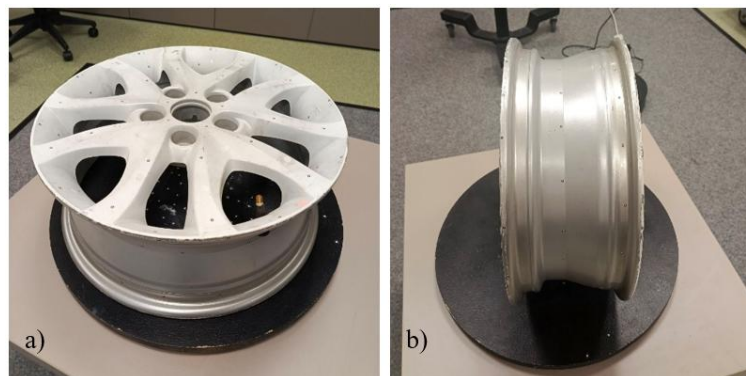


Fig. 19 Car wheel positioning: (a) initial positioning; (b) transitional positioning

The preparation phase of the steering knuckle, including reference point placement, coating, and positioning, took approximately 1 hour. The full scan was completed in under 30 minutes and could ideally be performed even faster by a skilled operator, as the selected measuring volume was well suited to the size of the steering knuckle. The main challenges were selecting appropriate scanner head angles and ensuring that the scanner always had enough reference points from the previous scan. The holes could not be scanned completely due to occlusion.

Scanning workflow of the car wheel required more steps than the steering knuckle. Due to its size, it could not be positioned on the rotary table. The wheel placed with its rotational axis perpendicular to the table surface (*Fig. 19a*) and manually rotated in approximately the same angular increments as the steering knuckle. Each scan was initiated manually and its quality controlled in the software. After scanning spokes, lug holes and central bore, scanner's head

was repositioned to scan barrel of the wheel, and increments repeated. For the inside of the wheel a few transitional scans were captured using reference points on the rim (*Fig. 15*). The wheel was repositioned as shown in the *Fig. 19b* and fixed still. Reference points on the rim were scanned to transition to the other side of the wheel (*Fig. 15*). After that the wheel was placed upside down from the initial position, incremental scans repeated. In total more than 70 scans were performed, which is comparable to the steering knuckle scan.

Preparation phase of the car wheel took nearly 2 hours without coating, including only reference points placement and positioning. Challenges were primarily associated with the large dimensions of the wheel relative to the small size (1.5 mm) of the reference markers. It complicated their accurate placement to ensure a robust and continuous scanning workflow. Complete scan was accomplished in 1 hour. Main contributing factor to the complexity of scanning was repeated repositioning of the wheel and scanner head, while ensuring appropriate working distance and optimal scanning angles.

8.3 RESULTS

In the finalization phase, the acquired raw point cloud must be polygonized into a mesh. For this purpose, the polygonization function in ZEISS INSPECT software was used with the maximum quality settings, while holes and reference markers were left unfilled (*Fig. 21a*). The mesh processing took approximately 2 hours in total. The software was intuitive and easy to use, and it performed the required function effectively.

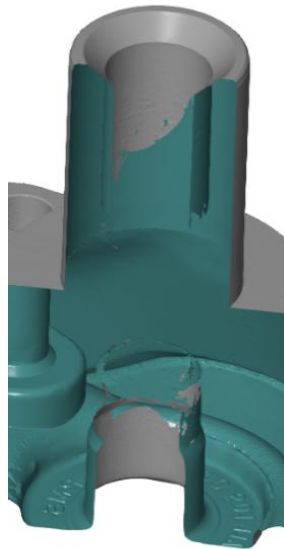


Fig. 20 ZEISS ATOS Q section of the steering knuckle's mesh with gaps in the bore of the spindle

Post-processing of the steering knuckle mesh included removal of the scanned table surface (background), closure of mesh discontinuities caused by reference markers, noise filtering, and repair of poorly captured regions. Due to occlusion effects, the scanner showed limited capability in capturing hole geometries, resulting in visible gaps in the mesh. ATOS Q's incomplete bore mesh is shown in (*Fig. 20*). All critical geometric features, including chamfers, fillets, functional planar and cylindrical surfaces, were accurately captured and did not require

further correction. The resulting mesh contains 8 960 738 points and had a total surface area of 89 265 323 mm², measured in Creo software (see Chapter 6).

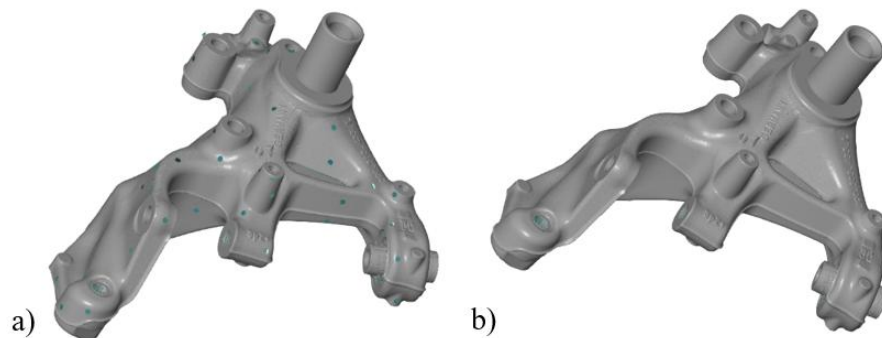


Fig. 21 ZEISS ATOS Q mesh of the steering knuckle: (a) untreated mesh; (b) mesh after post-processing.

Post-processing of the wheel mesh followed a similar procedure to that used for the steering knuckle, although it required more extensive repair due to a greater number of mesh gaps caused by the uncoated surface of the wheel (*Fig. 22a*). These defects were not on the functional surfaces and are therefore repaired only to improve the quality of the reference model. The central bore and lug holes were captured almost completely, because they were accessible for the angled scanner cameras to capture accurately. The wheel geometry consisted primarily of conical and cylindrical surfaces, as well as fillets, which exhibited minimal mesh inaccuracies. The resulting mesh contained 61 623 773 points and had a total surface area of 480 073 402 mm², as measured in Creo Parametric (see Chapter 6).

Fully repaired meshes were converted into CAD geometry using the mesh-to-CAD functionality in ZEISS software. These CAD models serve solely as reference geometry and are not included in the surface-to-surface deviation evaluation (see Chapter 6).

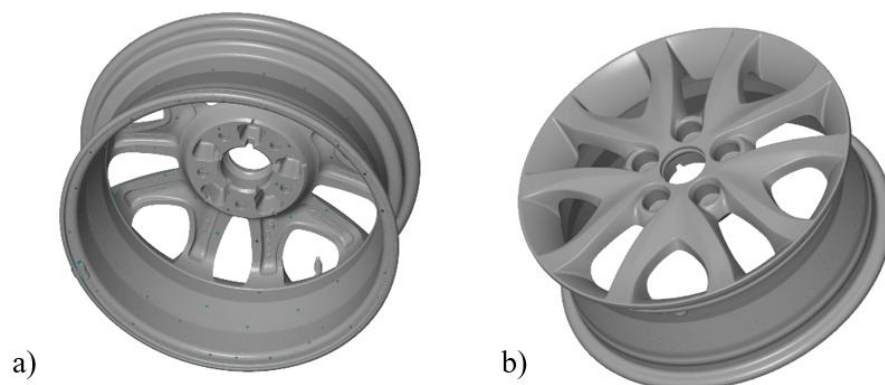


Fig. 22 ZEISS ATOS Q mesh of the car wheel: (a) untreated mesh; (b) mesh after post-processing.

9 SCANNING WITH ZEISS T-SCAN HAWK 2

On the tested parts, ZEISS T-SCAN Hawk 2 produced results that were very close to the ATOS Q reference data. The overall geometry and main functional surfaces were captured with high accuracy, and the generated polygonal meshes exhibited a high level of completeness and required only minimal post-processing. However, the scanner did not resolve small geometric features with the same level of detail as the ATOS Q, especially in areas containing fine chamfers, small radii, and sharp transitions.

ZEISS T-SCAN Hawk 2 in comparison with the stationary ATOS Q system, its use is more flexible because the operator can move freely around the scanned object and continuously capture surfaces from different angles. The workflow is less dependent on a fixed measuring volume, since the scanner operates within an adjustable working range and uses reference markers or geometry tracking to maintain its position. However, the method is still operator-dependent. Correct scanning distance, scanning speed, angle of incidence, and stable reference marker visibility must be maintained throughout the measurement. Therefore, although the setup is generally faster and more flexible than ATOS Q, good results still require careful handling and practical experience.

9.1 CALIBRATION

T-SCAN Hawk calibration is designed to be fast and field-portable, unlike the ATOS Q, which requires a multi-step procedure (see Section 8.1). The T-SCAN offers two calibration options, and the faster one was selected for this work. HyperScale recalibration is a one-shot procedure that re-establishes the scanner's geometric calibration from a single measurement position. It allows to compensate for thermal drift before each measurement without performing a full calibration [33]. The procedure uses a HyperScale scale bar (*Fig. 23*), which is held horizontally in front of the sensor at the optimum measuring distance. The scanner detects the reference markers along the bar and the software re-scales the system based on the certified bar length. This procedure takes less than 2 minutes to complete and was performed once for the steering knuckle and once for the wheel.



Fig. 23 T-SCAN Hawk 2 with HyperScale scale calibration bar

9.2 SCANNING WORKFLOW

Preparation phase of the scanned parts is described in Chapter 7. Before data acquisition, the scanning template was configured to a resolution of 0.2 mm, which restricts the usable measuring volume to a working distance of 240–480 mm and a scan area of 450×430 mm [30]. The optimum standoff was maintained using a red laser cross (*Fig. 11*) projected onto the part, which indicates the position within the depth of field.

Data acquisition is started by scanning the reference markers, allowing the system to create a reference point field. After that, the background plane is scanned. Additional markers are placed on the table to define the position of plane, that could later be automatically deleted in the software. This was an advantage compared to the ATOS Q workflow, which resulted in less post-processing time.

During scanning, the scanner head was moved in an arched, “umbrella-like” motion around the part, as recommended in the instructions [30]. The whole scanning procedure is controlled using the trigger buttons on the front of the scanner. T-SCAN Hawk 2 projects diagonal intersecting laser lines, which allows faster surface coverage and scanning from more angles. The system also tracks the sensor position in real time, indicating it with red laser cross (*Fig. 11*), making it easier to keep the scanner in the correct position.

For both the wheel and the steering knuckle, the scanning procedure consisted of two measurement series, unlike the single measurement series used with the ATOS Q. This eliminated the need for transitional scans. After capturing one side, the part was flipped, the markers on the supporting plane were re-acquired to transfer the coordinate system, and the other side was scanned. The two acquired point clouds were then combined into one using a dedicated function in ZEISS software.

During acquisition, the deep pocket function was activated for both parts to improve the scanning of holes. Despite the absence of a rotary table, the complete acquisition took approximately 40 minutes for the wheel and 25–30 minutes for the steering knuckle. However, since the scans were performed by an inexperienced operator, several additional attempts were needed to complete the full workflow. As a result, the total time required was approximately 3 hours.

9.3 POST-PROCESSING

After the scanning process is finished, two measurement series are merged into one point cloud and then polygonised. For this function maximum quality settings are used, holes and reference markers are left unfilled. Scanned table, defined in the acquisition as a background plane, is automatically removed by software. Mesh processing required approximately 2 hours. The software was intuitive and responsive, and it performed the required functions effectively.

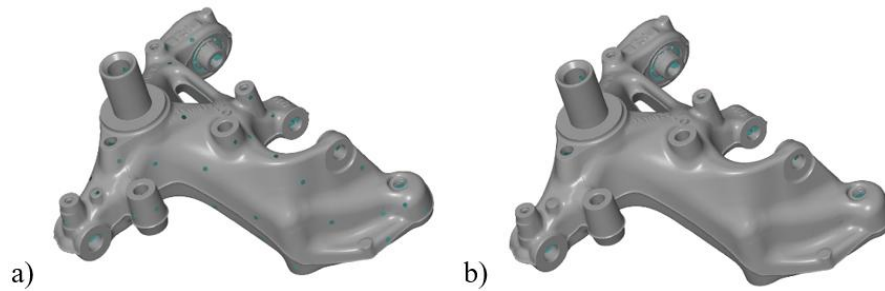


Fig. 24 T-SCAN Hawk 2 mesh of the steering knuckle: (a) untreated mesh; (b) mesh after post-processing.

The untreated mesh of the steering knuckle required only minor post-processing, mainly filling the gaps left by reference markers and removing noise around the part. Even with the deep scan function activated, the scanner showed similar limitations to the ATOS Q when capturing holes. Central bore of the spindle was maximally captured to nearly 20 mm depth (*Fig. 25*). Chamfers, fillets, and functional surfaces were fully captured and did not require additional treatment.

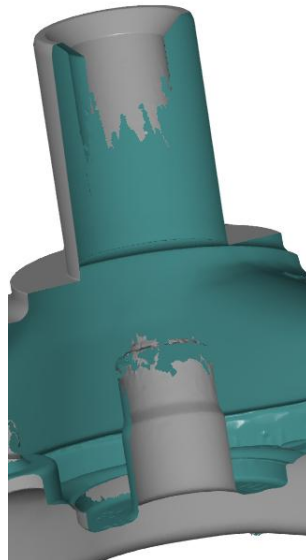


Fig. 25 T-SCAN Hawk 2 section of the steering knuckle's mesh with gaps in the bore of the spindle

Post-processing of the wheel was similar, but required more work compared to the steering knuckle, as the mesh contained more gaps due to the uncoated surface (*Fig. 26*). These defects were not located in the functional areas of the wheel. They were repaired, but they were not included in the comparison. Central bore and lug holes were captured almost entirely and required only minor repair. The barrel of the wheel had small gaps in the mesh because the laser was more sensitive to the slightly reflective surface than the ATOS Q.

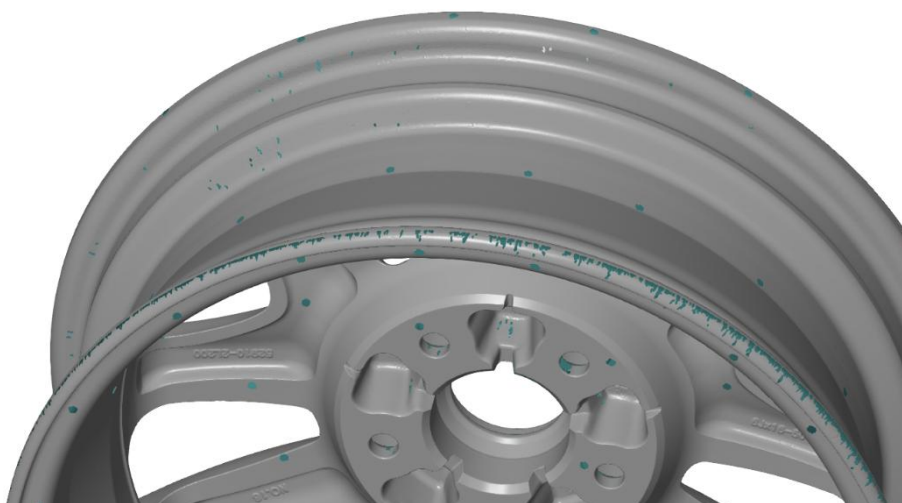


Fig. 26 T-SCAN Hawk 2 mesh of the steering knuckle untreated mesh

9.4 RESULTS

Surface deviation of the steering knuckle's spindle is ± 0.05 mm. External and internal edges caused the scanner to register points at an incorrect depth (see Section 1.4) with the maximum of $+0.10$ mm on the fillet between the spindle and the mounting surface (*Fig. 27a*). This deviation is also visible in the section view of the model (*Fig. 27b*), where the fillet captured by the T-SCAN Hawk 2 has a larger radius than the reference model. This indicates lower accuracy in this area. External fillets showed similar behavior, with deviations ranging from -0.05 to -0.09 mm on all functional surfaces (*Fig. 27a*; *Fig. 28*). Chamfers of the spindle had showed the same tendency at the edges. Functional surfaces on both top and bottom have small deviations of 0.00 to $+0.02$ mm (see Appendix 1, *Fig. 45*).

The car wheel surface deviation is ± 0.05 mm (*Fig. 28*), similar to the steering knuckle. Sharp edges showed deviations between -0.03 and -0.05 mm, while the flat functional surface of the hub had deviations of 0.00 to $+0.02$ mm. These results follow the same trend as those observed on the steering knuckle. The lug holes showed a maximum deviation of $+0.06$ mm, which could be attributed to an insufficient scanning technique. The rim surface was captured with higher variation, ranging from -0.05 mm to $+0.05$ mm. This was possibly caused by slight surface reflectivity and the higher sensitivity of the laser to reflective surfaces. However, most of the rim surface was still captured close to the ATOS Q reference, with an average deviation of 0.01 mm (see Appendix 2, *Fig. 46*).

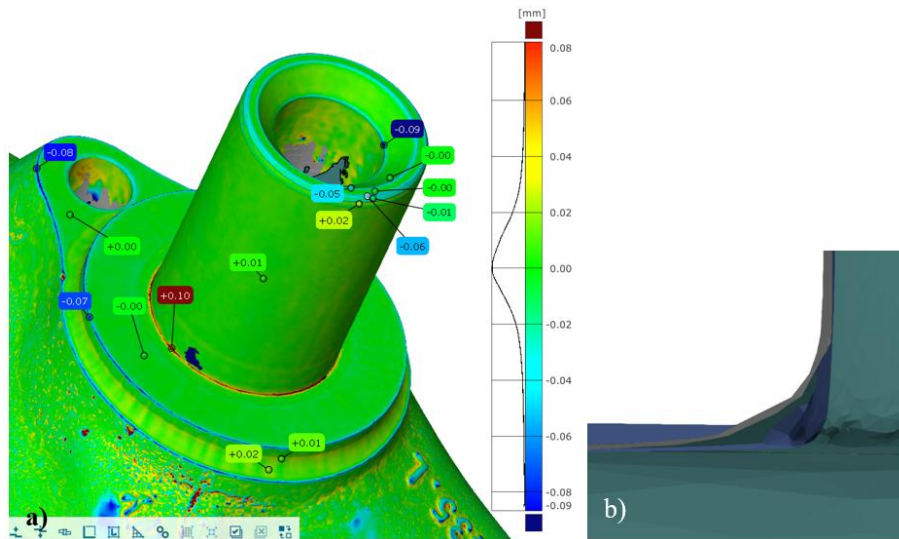


Fig. 27 T-SCAN Hawk 2 spindle surface deviations: (a) surface deviations; (b) fillet scanned by T-SCAN Hawk 2 and ATOS Q

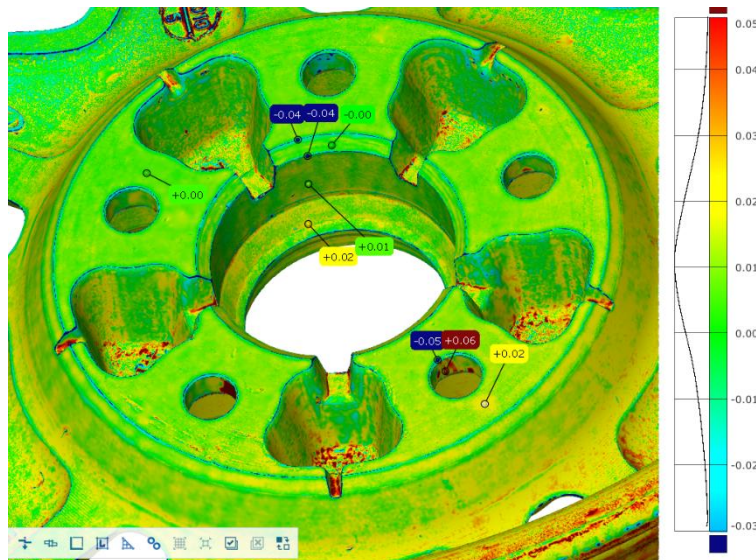


Fig. 28 T-SCAN Hawk 2 wheel hub surface deviations

Overall, ZEISS T-SCAN Hawk 2 captured the parts within its specified accuracy. Higher deviations were mainly observed on sharp machined edges. The cast shape was captured accurately, with only a few outliers in non-critical areas caused by post-processing.

10 SCANNING WITH IPHONE 16 LIDAR

The iPhone 16 LiDAR represents the most accessible and user-friendly scanning method evaluated in this thesis. In contrast to metrological scanners, it does not require calibration, reference markers, or a complex setup procedure. The scanning process is performed directly through a mobile application, which makes the method fast, portable, and simple to operate even without previous scanning experience. The final result depends strongly on the scanning application, device movement, lighting conditions and scanned surface properties. Therefore, although the iPhone LiDAR offers the easiest workflow, its technical reliability is limited compared with professional optical scanners.

iPhone 16 LiDAR showed limited dimensional accuracy compared with the professional scanning methods. The acquired data can therefore be used mainly for understanding the general shape and scale of the scanned object, not for detailed reverse engineering or quantitative evaluation. The scanning outcome also depends strongly on the application used for data acquisition and processing, while this thesis evaluates only one selected application - Scaniverse.

10.1 SCANNING WORKFLOW

The workflow is guided by the selected scanning application. In this case, Scaniverse Pro was used. The application allows the user to choose a scanning mode depending on the size of the part: small, medium, or large. For the steering knuckle, the small mode was selected. For the wheel, the medium mode was used, because the small mode caused too many shape errors in the mesh.

For the steering knuckle, the scanning depth was set to 0.4 m. This setting blurs the background outside the depth of field and uses an augmented reality feature to show which areas still need to be scanned. The software did not provide clear instructions on how the part should be scanned, so several scanning techniques were tested, and the method with the best result was selected. During scanning, the best results were achieved by performing one continuous 360-degree scan around the object, without repeating areas or pausing the scan. The steering knuckle was tested in different positions, including being suspended in the air. However, the best results were achieved when the top and bottom sides were scanned separately. This approach complicated the comparison, as the two sides could not be merged into one complete model within the time frame of this thesis. For the wheel, the scanning depth was set to 2.5 m, and the same scanning movement was used. The wheel was captured while positioned on its side (*Fig. 19b*). All models were polygonized directly in Scaniverse. They were then exported in STL format for comparison and in OBJ format for texture visualization.

10.2 POST-PROCESSING

Produced meshes were exported in both STL and OBJ formats. The OBJ format also included textures (*Fig. 29a,b*). The hub area of the wheel followed only general shape with high dimensional inaccuracies. Fillets and chamfers were not captured (*Fig. 29c*). The circular shape of lug the holes and central bore was not accurately captured. Meshes needed to be scaled x100 times to match scans from atos. The meshes had to be scaled by a factor of 100 to match the scans from the ATOS system. This was done in the free third-party software CloudCompare.

The wheel mesh contained significant gaps due to reflections. Similarly, the spindle area of the steering knuckle had a deformed region (see Appendix A3, Fig. 47).



Fig. 29 iPhone LiDAR mesh: (a) steering knuckle with texture; (b) car wheel with texture; (c) car wheel's hub mesh

Post-processing required deleting the scanned background and applying noise filtering. Minor mesh defects were repaired automatically by the Scaniverse software. The models of both the wheel and the steering knuckle could not be properly aligned to the ATOS reference scans due to the limited quality and completeness of the models. Therefore, 3-point alignment was used. This influenced the results, so they should not be considered precise, but rather only approximate.

10.3 RESULTS

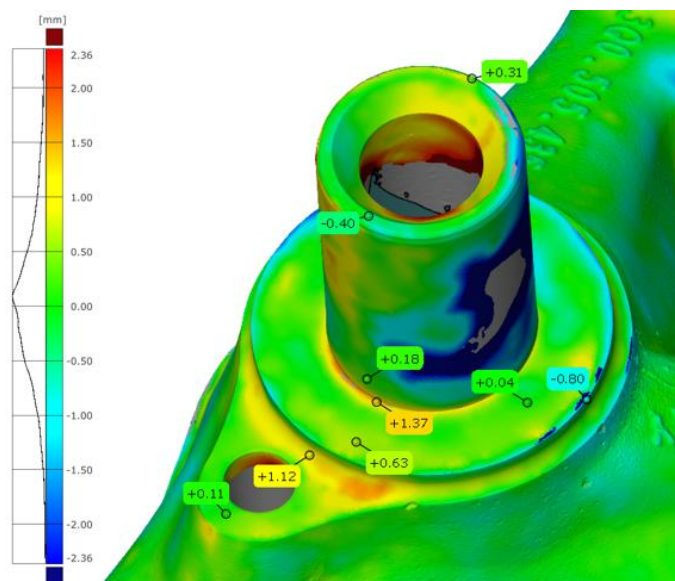


Fig. 30 iPhone LiDAR steering knuckle spindle's surface deviations

The results followed the theory described in Section 4.3. The wheel showed deviations above 11 mm (Fig. 31), while the steering knuckle of approximately 2-5 mm. Significant shape distortions were observed in both models. Grey regions indicate deviations greater than 5 mm on the steering knuckle (Fig. 30) and greater than 15 mm on the wheel. The cast body of the steering knuckle was captured reasonably well, although the deviations had a large variance, meaning that the surface appeared uneven. In general, this area was closer to the reference model, with deviations ranging from -0.05 mm to +1 mm.

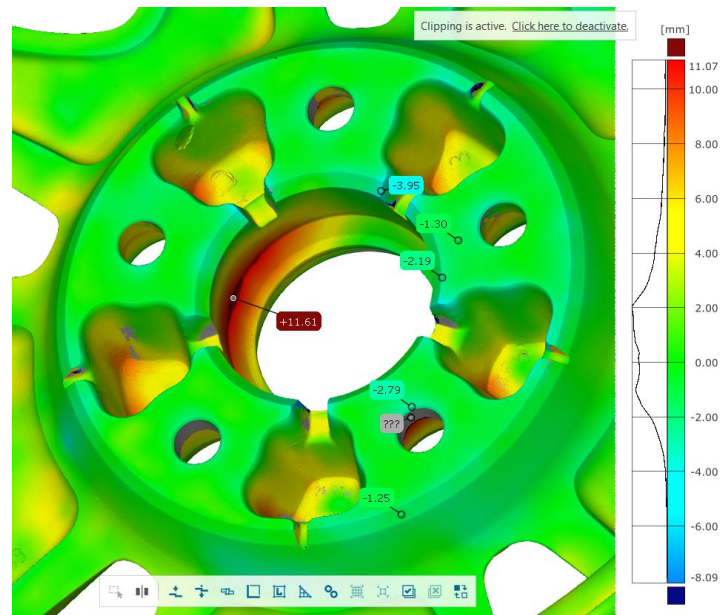


Fig. 31 iPhone LiDAR car wheel's hub surface deviations

The rim area of the car wheel was captured with deviations greater than 11 mm in some regions (see Appendix 3, *Fig. 48*), which means that it could not be reconstructed accurately in CAD. The conical and cylindrical surfaces of the barrel were generally captured, but they showed irregular surface deviations, making further reconstruction unreliable. The hub of the car wheel did not preserve its conical shape, and the central bore lost its cylindrical shape, with deviations greater than 11 mm (*Fig. 31*). The lug holes were only slightly visible.

The analysis shows that the scanner failed to reconstruct flat surfaces accurately, as they appeared uneven and distorted. Holes were not properly captured and were only partially visible. Fillets and chamfers were also not fully visible. Therefore, the reverse engineering process could not be carried out, because the critical surfaces could not be reconstructed with sufficient accuracy. The general dimensions could only be used as an approximate indication of the object's scale.

11 SCANNING WITH CREALITY CR-SCAN RAPTOR

Creality CR-Scan Raptor represents a more accessible scanning method compared with professional metrological systems (*Tab. 5*). Its workflow is simpler than ZEISS ATOS Q, since it does not require calibrated measuring volumes or a complex metrological setup. However, the scanning process still requires careful preparation, especially the placement of reference markers, suitable surface conditions, and stable scanner movement around the part. During the scanning of larger geometry, such as the car wheel, the smaller field of view made the workflow more demanding and required a higher number of scanning passes. Therefore, although the scanner is more accessible, its practical use is still strongly dependent on correct scanning strategy and operator handling.

Creality CR-Scan Raptor produced usable results for less demanding reverse engineering tasks, especially on parts with a size comparable to the steering knuckle. On the tested parts, its results were less accurate and less complete than ZEISS metrological scanners, but still significantly more suitable for technical geometry acquisition than smartphone-based methods. The scanner was less effective on the larger car wheel, where the limited field of view led to incomplete rim coverage and missing geometry in the central hole. Therefore, the method can be considered suitable for approximate engineering use on smaller components, but not as a replacement for metrological scanning where high accuracy, full surface completeness, and reliable capture of small features are required.

Tab. 5 technical characteristics of Creality CR-Scan Raptor [39]

Scanning Mode	7 blue parallel laser lines
Accuracy*	Up to 0.02mm @ 100mm
Point spacing [mm]	0.02-2
Single Capture Range [mm]	270x170 @ 300
Working distance [mm]	150-400
*Accuracy is evaluated in laboratory conditions (measurement object is 100mm sphere pair) and accrual results may be affected by operating environments such as temperature, vibration, and other factors	

11.1 SCANNING WORKFLOW

Setting up the scanner with the wiring and laptop, excluding the application of reference markers described in Chapter 7, was straightforward and took approximately 10 minutes. Creality scanner has its own software CrealityScan which was used during the acquisition part. The Creality scanner has its own software, CrealityScan, which was used during the acquisition phase. A new project was created with the same point distance of 0.2 mm as used for the T-SCAN Hawk. The Creality scanner followed a similar workflow to the T-SCAN Hawk (see Section 9.2). For both the wheel and the steering knuckle, the reference points were scanned first, and the background plane was then defined. The short length of the cable connecting the

scanner to the PC required more careful setup and could be a limitation in less flexible conditions, such as outdoor scanning or scanning larger parts.

For the wheel, the same procedure as with the T-SCAN Hawk was used. The two sides of the wheel were scanned separately and then combined by the software. This handheld laser scanner has a smaller field of view than the ATOS Q, which required more reference points to be added both to the part and to the table. In addition, there was no laser pointer to indicate the correct scanning distance. Instead, this was shown by a small LED on the scanner handle, which blinked in different colors depending on the distance. The software also showed the scan acquisition in real time, including the scanner position and whether the distance was correct. As a result, it was necessary to frequently look between the laptop and the wheel during scanning.

Creality Raptor projects vertical laser lines, which requires slower scanning and repeated passes over the same regions from different angles. Its laser intensity was also lower than that of the T-SCAN Hawk. Under the same lighting conditions, the scanner sometimes did not provide enough contrast, so the lighting had to be reduced slightly. This adjustment was minor and was not expected to significantly influence the results. The full setup and scanning process for the wheel took approximately 3 hours. With previous knowledge of the workflow and its limitations, this time could likely be reduced to around 1.5–2 hours.

The steering knuckle was scanned using a different setup. The part was suspended in the air to allow access to all sides, so only one scan session was required. This took significantly less time than the wheel and required only a few additional markers on the part. However, acquiring the markers before scanning took several attempts, which increased the total scanning time to approximately 50 minutes.

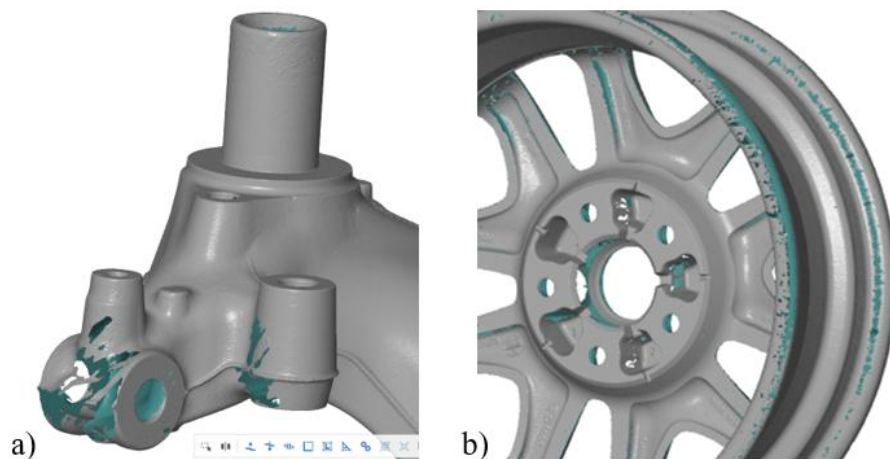


Fig. 32 Creality's untreated mesh: (a) steering knuckle; (b) car wheel

Post-processing involved closing mesh gaps caused by insufficient scanning. These repaired regions were not included in the analysis of the steering knuckle, as they were not located on functional surfaces (*Fig. 32a*). The car wheel had significant gaps on the rim surfaces (*Fig. 32b*) due to the scanner's sensitivity to reflections, smaller field of view, and difficult scanning angles. The central bore was not captured for the same reason, as the scanner was not able to track enough reference points in this area. This issue might be improved with a better tracking

algorithm. Because of this, the central bore could not be included in the comparison. Both models also had holes that were not fully captured.

11.2 RESULTS

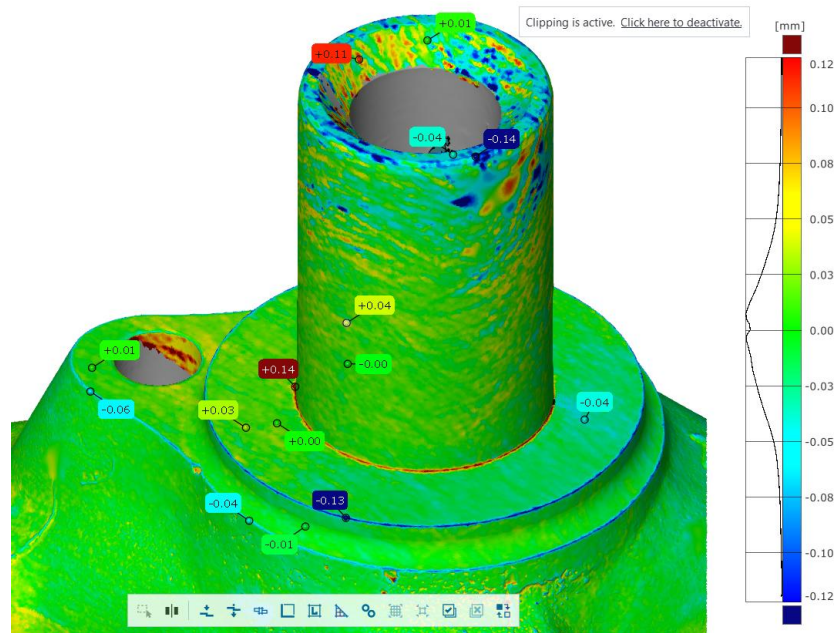


Fig. 33 Creality steering knuckle's spindle surface deviations

Surface deviation analysis of the steering knuckle showed a relatively uniform distribution within ± 0.12 mm (Fig. 33). The car wheel had a wider deviation range, with an overall span of approximately ± 0.18 mm (Fig. 34). Slightly visible grooves appeared on the spindle due to the laser projection method. This area required slower scanning and more repeated passes, which were not fully performed. As a result, the surface showed deviations of up to $+0.11$ mm. Properly scanned functional surfaces on both the steering knuckle and the car wheel showed deviations of approximately ± 0.04 mm.

Sharp edges showed similar behaviour to the results from the T-SCAN Hawk. On the steering knuckle, internal fillets had deviations of up to $+0.14$ mm, while external edges showed deviations down to -0.12 mm. The wheel hub had larger chamfers with more rounded edges, resulting in smaller deviations of approximately -0.05 mm. In comparison, sharper edges of the hub showed deviations of up to -0.17 mm.

The rim areas were poorly captured (see Section 11.1), and therefore could not be fairly compared. These areas showed an average deviation of $+0.08$ mm, with maximum and minimum deviations of $+0.18$ mm and -0.18 mm. Only a few well-scanned regions had deviations of approximately 0.02 mm.

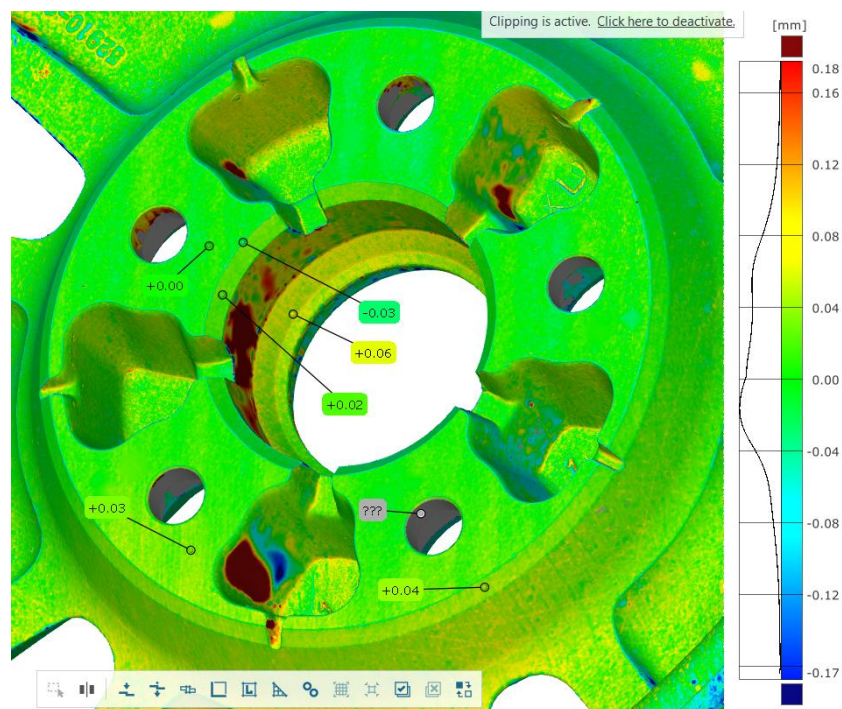


Fig. 34 Creality wheel hub surface deviations

Analysis shows the limitations of the selected measuring volume for the car wheel and the need for an improved scanning algorithm or more careful scanning technique for the steering knuckle. This would likely result in longer scanning time.

12 SCANNING WITH EINSCAN PRO HD

EinScan Pro HD represents a more accessible structured-light scanning method that can be used in both stationary and handheld modes (*Tab. 6*). It produced usable meshes for reverse engineering, especially when the scanned part was suitable for stationary scanning. On the steering knuckle, the deviations were relatively close to the specified scanner accuracy and the point distribution was concentrated within a narrow range. In handheld mode, however, the scanner was more sensitive to the slightly reflective wheel surface, producing larger gaps on the rim areas and wider deviation distribution in the wheel barrel.

Preparation of EinScan Pro HD was relatively quick and combined elements of ZEISS ATOS Q and T-SCAN Hawk workflows, including the application of reference markers, scanner warm-up, and a short software-guided calibration. Compared with the Creality CR-Scan Raptor, the acquisition process was easier and the post-processing was more automated, as the software was able to close many small holes in the mesh. However, the final result still depended on the selected scanning mode, surface condition, and stability of the handheld acquisition.

Tab. 6 Technical characteristics of EinScan Pro HD [40]

Scanning Mode	Handheld HD Scan	Fixed Scan without Turntable
Scan Accuracy	up to 0.045 mm	0.04 mm(single shot accuracy)
Volumetric Accuracy*	0.3 mm/m (Markers Alignment)	
Point Distance	0.2 mm-3 mm	0.24 mm
Single Scan Range	209*160 mm-310*240 mm	
Depth of Field	±100 mm	
Working Distance	510 mm	
Light Source	White LED	
Texture Scan	Yes (with Add-on: Color Pack)	
*Volumetric accuracy refers to the relationship between 3D data accuracy and object size; the accuracy is reduced by 0.3mm per 100cm.		
The conclusion is obtained by measuring the center of sphere under marker alignment.		

12.1 SCANNING WORKFLOW

Preparation for scanning was relatively quick and combined steps from both the T-SCAN Hawk and ATOS Q workflows. The EinScan requires reflective reference markers to be applied to the objects, followed by a 20-minute scanner warm-up and a simple calibration procedure. The

calibration takes approximately 5 minutes and is guided by the software. During this procedure, the reference board is slowly scanned in the handheld mode.

The parts were scanned using different modes to achieve the best possible results. The steering knuckle was scanned in stationary mode, with the rotary table turned manually (not guided by the software), as it was not connected to the software. For the wheel, handheld mode was selected in order to capture the larger volume.

Post-processing required less work than with the Creality scanner and was mostly automated. The software closed many small holes in the mesh, most of them smaller than 1 mm. The steering knuckle had a significant gap on the spindle caused by erased coating. This region was repaired, but it was not included in the evaluation. Even though the scanning process was performed correctly, the untreated mesh contained small spikes and ripples, which were also not evaluated. The central bore of the car wheel was captured completely and was included in the comparison. However, the rim areas of the wheel had major gaps and could not be evaluated (*Fig. 35*).

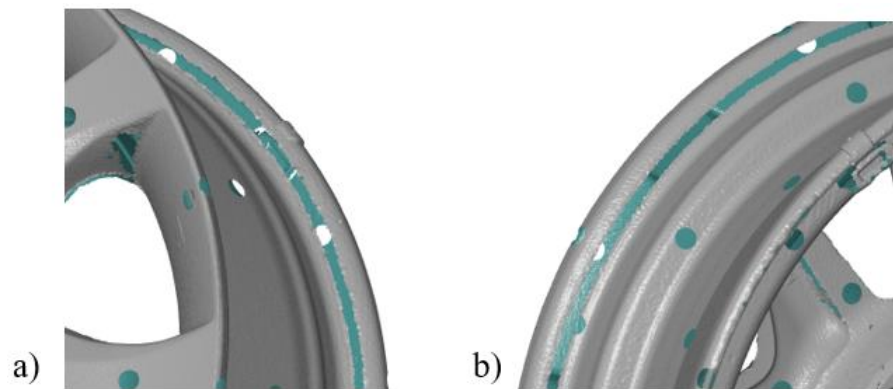


Fig. 35 Creality car wheel untreated mesh: (a) inside rim; (b) outside rim

12.2 RESULTS

The steering knuckle was scanned in stationary scanner mode, which has a specified accuracy of 0.04 mm. The analysis confirms this specification, with a minimum deviation of -0.01 mm on the functional surfaces (*Fig. 36*) and an average of +0.04 mm. Although the scanner uses structured-light technology, it still had difficulties capturing sharp edges. Internal fillets with up to +0.14 mm deviations and external up to -0.14 mm. Overall, the point deviation values were closely distributed, with deviations within approximately ± 0.12 mm.

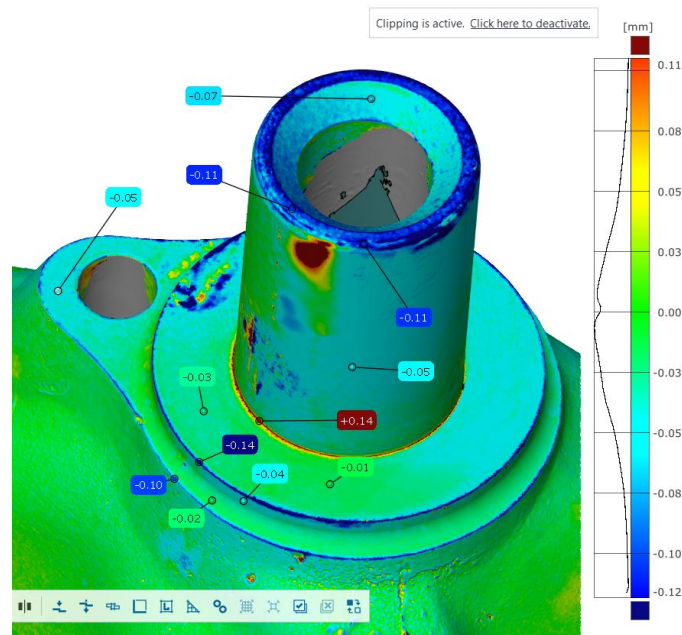


Fig. 36 EinScan steering knuckle spindle surface deviations

The car wheel was scanned in handheld HD mode, which has a stated scan accuracy of up to 0.045 mm and a volumetric accuracy of 0.3 mm/m. Compared to the steering knuckle, the point deviation values were more evenly distributed across the full range, with overall deviations of approximately ± 0.60 mm (*Fig. 37*). The extreme values in the distribution were mainly caused by repaired regions on the rims, which were not fully captured during scanning. The slightly reflective wheel barrel showed higher deviations. One side of the barrel had an average deviation of approximately -0.25 mm, while the opposite side of approximately +0.25 mm. The repaired rim areas showed the highest deviations, with minimum and maximum values of approximately ± 0.60 mm. This behavior was likely caused by drift in handheld mode.

On the functional surfaces of the hub, the point distribution was relatively uniform. The hub had an average of 0.10 mm, with a minimum deviation of -0.04 mm on the outer chamfer and a maximum deviation of +0.23 mm on the mounting surface (Fig. 37). The chamfer edges on the wheel hub did not show the same behavior as the sharper edges on the steering knuckle.

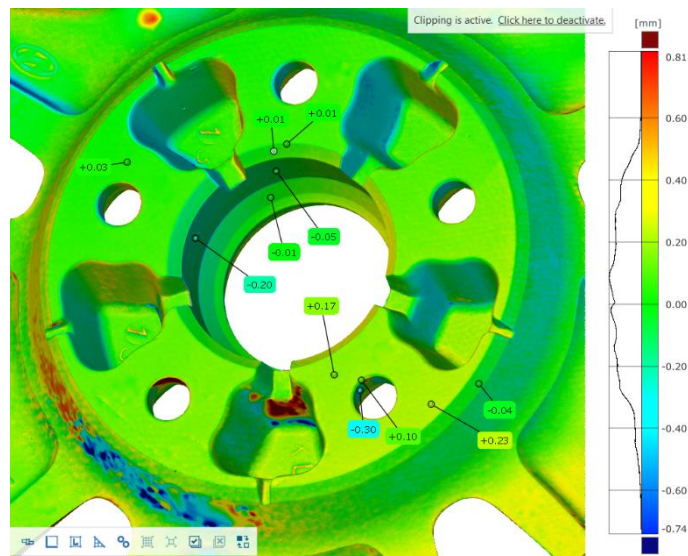


Fig. 37 EinScan car wheel's hub surface deviations

13 SCANNING USING PHOTOGRAMMETRY

Photogrammetry represents one of the most accessible 3D reconstruction methods, since it requires only a set of overlapping photographs and suitable reconstruction software. However, the practical workflow proved to be more demanding than expected. Free third-party software Meshroom was initially tested for mesh generation. Its use was highly hardware-demanding, and the available workflow guidance was not detailed enough for reliable troubleshooting. In most cases, the software failed to generate usable meshes, and the reason for these failures could not be clearly identified due to the lack of sufficiently specific guidelines. The only successfully generated wheel mesh from Meshroom was compared with the result obtained in another free third-party software RealityCapture, which produced a higher-quality reconstruction. In addition RealityCapture also provided a more user-friendly interface. The workflow was easier to control, reconstruction settings were more accessible, and the processing stages were clearer compared with Meshroom. For these reasons, RealityCapture was selected as the preferred photogrammetric reconstruction software in this thesis.

The accuracy of photogrammetry was limited and strongly dependent on image quality, surface texture, lighting conditions, camera parameters, and the reconstruction software used. In this work, the smartphone camera could not be further optimized for the given conditions, which limited the quality of the input photographs and consequently the final reconstruction (*Tab. 7*). The use of a camera system with higher optical resolution, lower image noise, and greater manual control over exposure, focus and aperture would likely improve the quality of the photogrammetric reconstruction, particularly under the given laboratory lighting conditions.

The method was able to capture the general geometry of the scanned parts and, in some areas, produced better local detail than iPhone LiDAR. However, it did not provide consistent or metrologically reliable data for reverse engineering, especially on reflective surfaces, where reconstruction errors and missing geometry occurred. The acquired data can therefore be considered suitable mainly for approximate shape documentation and visual comparison.

Tab. 7 Smartphone camera's parameters for photogrammetry

Focal length	Aperture	Shutter speed	ISO	Exposure	Resolution	DPI
5.249mm	f/1.75	1/125 sec	1250	0	2976x3968	72

13.1 SCANNING WORKFLOW

The steering knuckle was captured from the top and bottom sides separately. The wheel was fixed in position on its side and captured in one setup. Photographs were taken around the parts at approximately 10-degree increments, creating a full 360-degree circle with overlapping images (*Fig. 38*). Each surface region was visible in at least two images. The image sets were then processed in the free software RealityCapture, which generated textured 3D meshes in OBJ format. The meshes were exported with textures (*Fig. 39*) and then scaled in the third-party software CloudCompare. The exporting format is changed to STL for comparison.

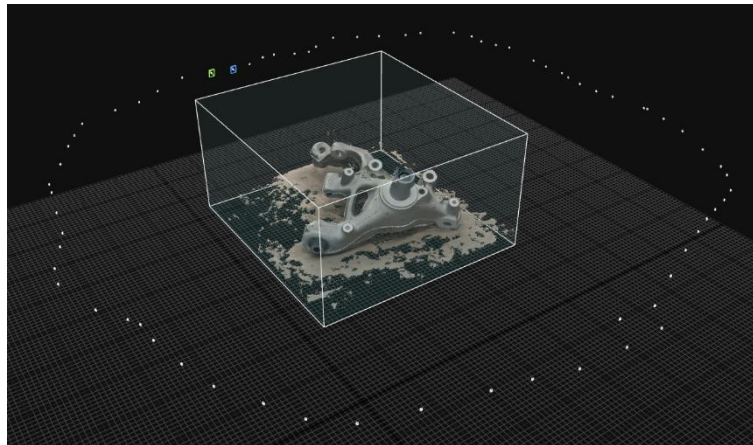


Fig. 38 Photos taken around the steering knuckle in RealityCapture software

The untreated models contained significant ripples and spikes caused by noise. Areas where the camera captured reflections, such as the steering knuckle spindle and the wheel barrel, were not reconstructed properly in the mesh (see Appendix 4, *Fig. 49*). Compared to the iPhone scan, the photogrammetry model captured the outlines of fillets and chamfers on the steering knuckle more clearly. The larger chamfers on the wheel were also captured better, although they were still not accurate enough for reconstruction.

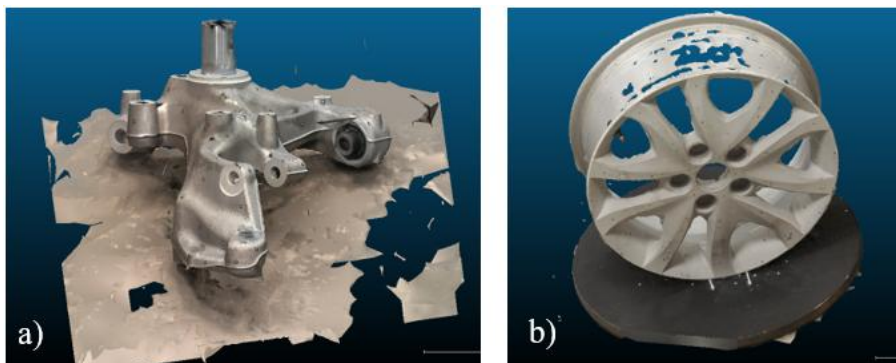


Fig. 39 Photogrammetry textured models: (a) steering knuckle; (b) car wheel

Unlike the iPhone scans, the models of both the wheel and the steering knuckle could be aligned to the reference models. The steering knuckle was aligned using pre-alignment, while the wheel required 3-point alignment followed by a local best-fit alignment on the hub. This alignment method influenced the results, so the comparison should not be considered precise, but rather approximate.

13.2 RESULTS

Photogrammetry produced results comparable to the iPhone LiDAR scan. The overall point distribution showed high variance due to noise (*Fig. 40*; *Fig. 41*). Functional flat and round surfaces showed different behavior. On flat surfaces, the deviations ranged from -0.84 mm to +0.98 mm, with some points being close to the reference at approximately +0.04 mm. Roughly the flat surfaces are visible (*Fig. 40*). On round cylindrical surfaces, the noise caused much larger deviations. As a result, these areas did not accurately represent a round shape, both on

the steering knuckle spindle (see Appendix 4, *Fig. 49a*) and on the wheel barrel (see Appendix 4, *Fig. 49c*). The bottom side of the steering knuckle, including its complex transitions, was reconstructed with an accuracy of approximately 3 mm (see Appendix 4, *Fig. 50*). In the areas that were successfully captured, the top side of the steering knuckle showed deviations of approximately ± 1 mm, with the distribution slightly shifted towards negative values. The bottom side showed deviations of approximately ± 2.5 mm.

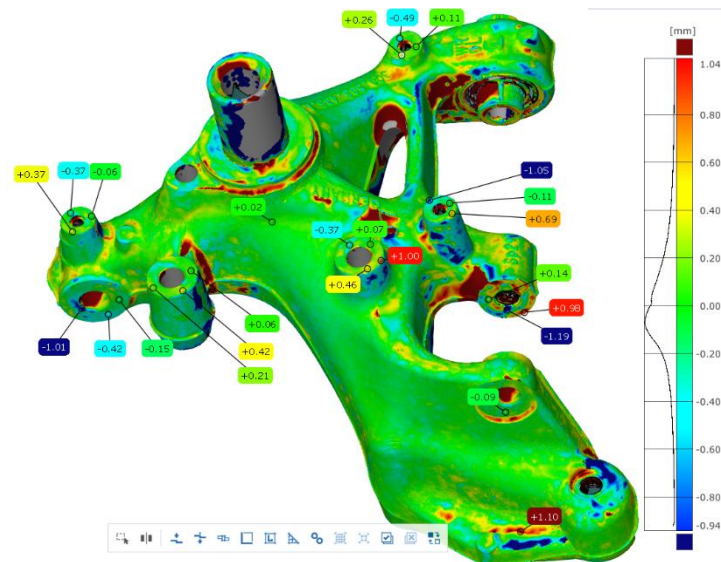


Fig. 41 Photogrammetry steering knuckle functional surfaces deviations

The car wheel hub had a more accurate shape than in the iPhone scan. However, the surface was still uneven, with deviations ranging from -0.01 mm to +1.65 mm (*Fig. 41*). The circumference of the central bore had a clearer outline than in the iPhone scan and could potentially be reconstructed. In contrast, the rim and barrel areas showed such high deformation that they could not be properly evaluated. Overall, the wheel showed deviations of approximately ± 2.5 mm with a distribution close to normal, but it also contained many spikes with deviations greater than 5 mm, which were not included in the evaluated range.

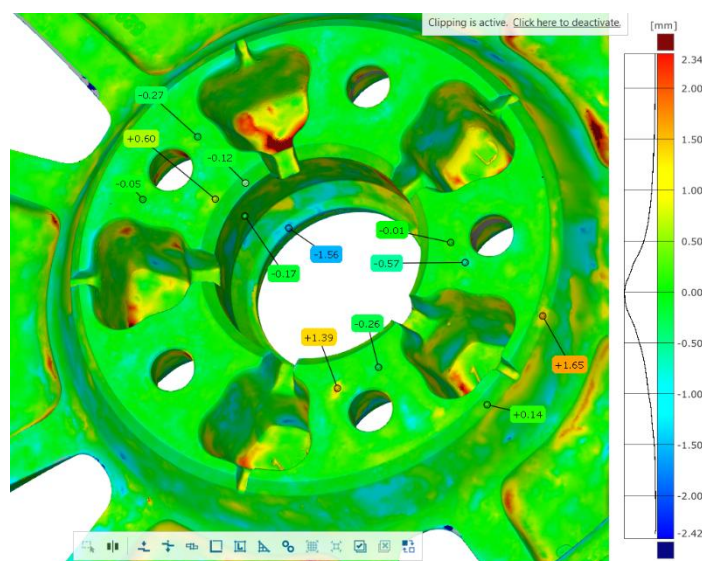


Fig. 40 Photogrammetry car wheel's hub surface deviations

14 USE OF OPTICAL 3D SCANNERS FOR AUTOMOTIVE GEARBOX APPLICATIONS

To evaluate the practical applicability of the compared scanning methods a 1-speed transmission unit 0MH (rear axle) of the Audi Q4 e-tron (*Fig. 42*), was selected as a case study. This gearbox without a shifting mechanism represents a simplified but dimensionally demanding design, making it appropriate for generalization to broader gearbox families.



Fig. 42 Components of the 1-speed transmission unit 0MH (Audi Q4 e-tron)

For the purposes of this analysis, gearbox components are grouped into following functional categories:

- Housing and casing of the transmission, typically an aluminum alloy or cast-iron with complex geometry. It includes flanges, coolant passages and bearing seats. The outer surfaces are geometrically variate, but mostly accessible, while internal bearing bores and oil channel geometry presents significant occlusion limitations for optical scanning methods.
- Helical and spur gears have gear teeth with complex shapes and highly precise profiles. Tolerances being in the range of a few micrometers to tens of micrometers, depending on the quality grade. The tooth may be superfinished, resulting in surfaces with very low roughness and high specular reflectivity.
- Shafts and rotating elements with keyways, threaded features and bearing seats. These components have high dimensional precision, rotational symmetry, and highly reflective surface finishes.
- Bearing assemblies, seals, and fasteners are standardized components identifiable by catalogue designation rather than geometric scanning and are not typically subject to reverse engineering by optical methods.

Gearbox housing is suitable for reverse engineering for laser and SLS scanning methods. iPhone LiDAR and photogrammetry are capable of capturing only general dimensions and shape, requiring proper scaling, but with deviations insufficient for reverse engineering. Handheld laser and structured-light scanners compared in this thesis are well suited for capturing both external and internal features. Also having access to the site is an advantage against structured-

light stationary ATOS Q and, which would require more re-positioning to capture holes. For the most accurate reconstruction of the sharp edges and fillets ZEISS ATOS Q remains the only choice.

Gear elements are the most challenging components for all optical scanning methods. None of the evaluated scanners can be considered adequate for reverse engineering of gears. Complex tooth geometry is difficult to access optically. The flank area of the tooth, especially the dedendum region, cannot be reliably scanned, because it is not visible to the scanner. In addition, reflections tend to occur in these regions, further reducing reconstruction quality. The necessary coating adds micrometer level surface deviations, which in case of high precision gears is relevant. Tight tolerances are only reproducible by ZEISS ATOS Q, which might be able to scan the base circle and the number of teeth with sufficient accuracy.

Shafts present challenges analogous to those described for gear elements. High surface reflectivity, keyways and spline teeth with tight dimensional tolerances. The cylindrical form itself is in principle well-handled by structured-light scanning, although out of compared scanners only ZEISS ATOS Q being a viable option. The T-SCAN hawk 2 can acquire the cylindrical shape of the shaft but will exhibit significant deviations on chamfers and fillets, especially for bearing seats. The resulting data might be used for the documentation of shaft layout, step diameters, and relative positioning of functional features.

15 DISCUSSION

Accuracy of the chosen scanning methods

All deviation scales were unified to the same range of ± 1.00 mm for both the car wheel (Fig. 43) and the steering knuckle (Fig. 44). The corresponding histograms show the point distribution for each scanner. All scanners exhibited narrower deviation fields and smaller deviations on the steering knuckle than on the car wheel. The laser scanners produced more uniform and accurate results than the other 3D scanning methods, excluding ZEISS ATOS Q, which served as the reference scanner and was therefore more accurate than all compared devices. The consumer-grade methods exceeded the selected comparison scale and therefore could not be directly compared with the semi-professional and professional alternatives. For detailed surface deviation results for each scanner, see the corresponding results sections.

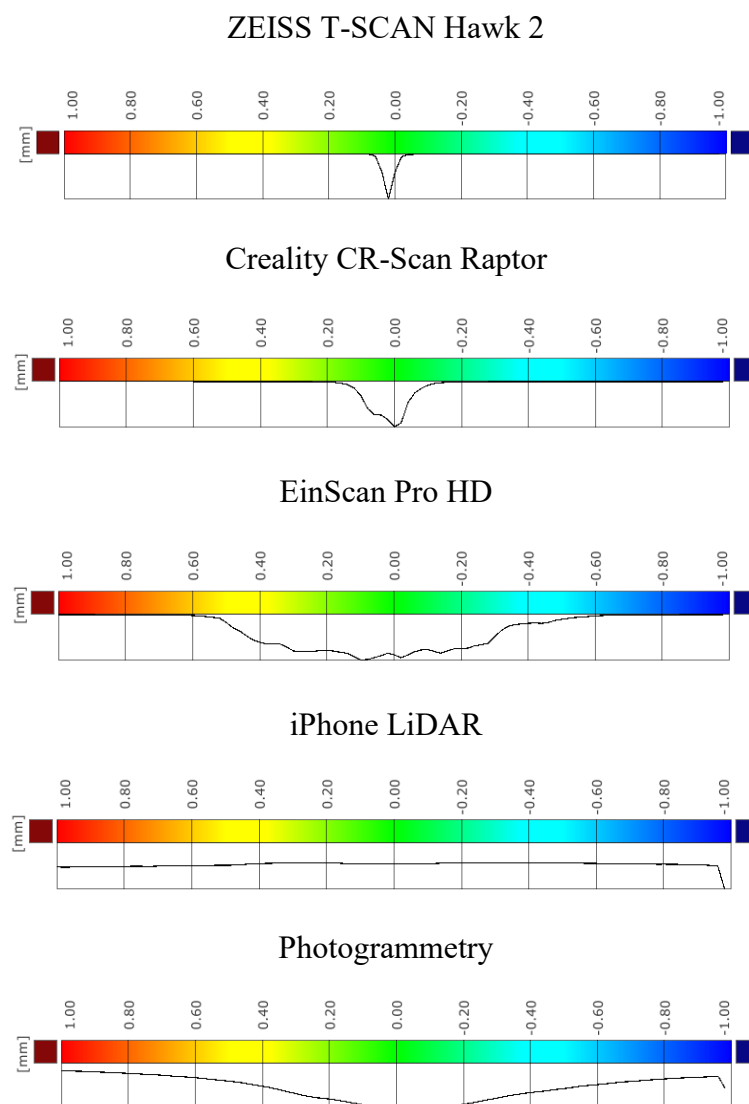


Fig. 43 Car wheel surface deviations across all scanners

As shown by the histograms, where the distributions are shifted to the left from zero, the scanners tended to capture points slightly closer to the scanner than the reference surface. Only ZEISS T-SCAN Hawk 2 showed a similar distribution for both the car wheel and the steering knuckle

knuckle. The semi-professional scanners exhibited various errors that resulted in different distribution shapes for each part. EinScan HD histograms for the car wheel also show that the structured-light scanner introduced more errors in handheld mode (*Fig. 43*) than in stationary mode (*Fig. 44*). Both LiDAR and photogrammetry showed higher deviations on the lower part of the steering knuckle, mainly due to occlusion.

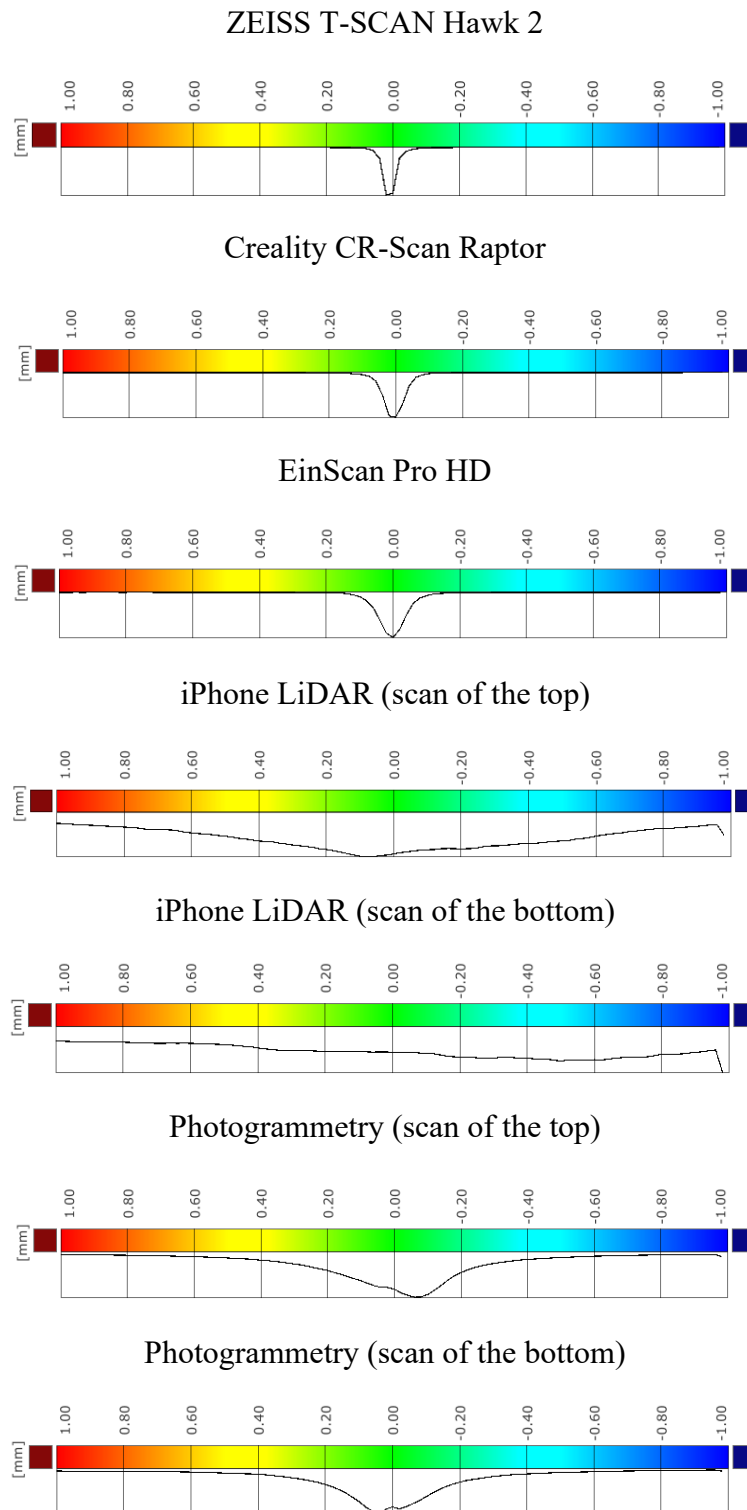


Fig. 44 Steering knuckle surface deviations across all scanners

Compared with ZEISS ATOS Q, the most accurate scanner was ZEISS T-SCAN Hawk 2, with surface deviations of approximately ± 0.05 mm on both scanned parts and the highest surface coverage (see Chapter 6), reaching up to 99.60% (*Tab. 8*). The second most accurate scanner was Creality CR-Scan Raptor, with deviations of ± 0.10 mm for the steering knuckle and ± 0.18 mm for the car wheel (*Tab. 8*). EinScan Pro HD was ranked third, with deviations of ± 0.12 mm on the steering knuckle and ± 0.60 mm on the car wheel, however, achieving slightly higher surface coverage for both parts than the Creality Raptor scanner (*Tab. 8*).

The iPhone LiDAR achieved an approximate accuracy of ± 3 mm for the steering knuckle and ± 11 mm for the car wheel. Photogrammetry showed smaller deviations of approximately ± 1 mm and ± 2.5 mm, respectively. For the asymmetrical steering knuckle, photogrammetry captured the overall shape more closely to the reference model, but the resulting mesh contained a significant amount of noise and distortion. Although the photogrammetry for the car wheel showed smaller numerical deviations, the reconstructed mesh of the wheel barrel contained substantial mesh distortions and failed to represent even the general shape of the part. In contrast, the iPhone LiDAR results at least preserved the overall form of the wheel barrel and rims. Both consumer-grade methods failed to capture the top and bottom of the steering knuckle within a single measurement series or merge them into one point cloud. Therefore, the part had to be divided into two separate models. Nevertheless, these methods still achieved approximately 70–80% surface coverage.

Tab. 8 Comparison of the accuracy of chosen 3D scanning methods

Parameter	ZEISS ATOS Q	ZEISS T-SCAN Hawk 2	iPhone 16 LiDAR	Creality CR-Scan Raptor	EinScan Pro HD	Photogrammetry
Scanner type	Blue Structured-light	Blue Laser	LiDAR	Blue Laser	White Structured-light	Photogrammetry with Android camera
Surface-to-surface deviation [mm]	0 (Reference)	Knuckle: ± 0.05 Wheel: ± 0.05	Knuckle top: ± 2.5 Knuckle bottom: ± 3 Wheel: ± 11	Knuckle: ± 0.10 Wheel: ± 0.18	Knuckle: ± 0.12 Wheel: ± 0.60	Knuckle top: ± 1 Knuckle bottom: ± 1 Wheel: ± 2.5
Surface coverage completeness [%]	100% (Reference)	Knuckle: 97.52% Wheel: 99.60%	Knuckle top: 80.61% Knuckle bottom: 78.74% Wheel: 88.32%	Knuckle: 87.30% Wheel: 93.62%	Knuckle: 91.46% Wheel: 97.63%	Knuckle top: 91.52% Knuckle bottom: 83.05% Wheel: 97.25%
Number of points	Knuckle: 8 960 731 Wheel: 61 623 793	Knuckle: 935 324 Wheel: 3 401 762	Knuckle top: 65 936 Knuckle bottom: 41 309 Wheel: 54 278	Knuckle: 3 004 413 Wheel: 10 686 038	Knuckle: 2 920 910 Wheel: 16 157 336	Knuckle top: 25 142 Knuckle bottom: 65 899 Wheel: 81 797
The presence of mesh defects	Small gaps	Small gaps	Substantial shape distortions, moderate depth spikes, small to big gaps	Small to moderate gaps, minor depth spikes, minor ripples	Small to moderate gaps, minor depth spikes, minor ripples	Substantial shape distortions and depth spikes, small to big gaps

Complexity of the chosen scanning methods

Complexity of the scanning methods was evaluated based on the time required to complete the full scanning procedure, including post-processing. The fastest method was iPhone LiDAR, as it only required opening the scanning application and positioning the part (*Tab. 9*). However, its post-processing stage took substantially more time, making the total time consumption comparable to that of ZEISS T-SCAN Hawk 2. The most time-consuming methods were ZEISS ATOS Q, due to its multi-step calibration procedure, and photogrammetry, due to the nuanced acquisition process (*Tab. 9*).

Tab. 9 Comparison of the complexity of chosen 3D scanning methods

Parameter	ZEISS ATOS Q	ZEISS T-SCAN Hawk 2	iPhone 16 LiDAR	Creality CR-Scan Raptor	Einscan Pro HD	Photogrammetry
Scanner type	Blue Structured-light	Blue Laser	LiDAR	Blue Laser	White Structured-light	Photogrammetry with Android camera
Time to set up a scanner [hour]	1	0.5	~5 min	0.5	0.5	1-2
Time of scanning [hour]	Knuckle: ~0.5-1 Wheel: ~2-3	Knuckle: ~0.5 Wheel: ~0.5	Knuckle: ~15-30 min Wheel: ~15-30 min	Knuckle: ~1 Wheel: ~2-3	Knuckle (stationary): ~1 Wheel (handheld): ~20 min	Knuckle: 0.5-3 (depends on operator) Wheel: 0.5-3 (depends on operator)
Time of post processing [hour]	~2	~2	~3-4	Knuckle: ~1 Wheel: ~3-4	Knuckle: ~0.5 Wheel: ~3	~2-10 (depends on software and experience)
Complexity	Moderate with software guidelines	Easy with software guidelines	Easy with and without guidelines	Easy to follow guidelines, but high experience factor in scanning	Easy to follow guidelines, but moderate experience factor in scanning	High, no explicit guidelines and software
Software for scanning	ZEISS INSPECT	ZEISS INSPECT	Scaniverse	CrealityScan	ExScan Pro	None for acquisition, RealityCapture for mesh generation
Mesh format	STL	STL	STL, OBJ	STL	STL, OBJ	OBJ (has to be converted to STL)
Portability	Stationary	Handheld, 10 m cable	Handheld, wireless (smartphone)	Handheld, ~2 m cable	Hybrid, ~3 m cable	Handheld, wireless (smartphone)

The easiest method to use was iPhone LiDAR, followed by ZEISS T-SCAN Hawk 2 and the EinScan Pro HD. The Creality CR-Scan Raptor required a more experienced operator, particularly with regard to sufficient marker placement and proper scanning technique. Without adequate preparation, the scanning process required multiple attempts and readjustments, even for the smaller steering knuckle.

The iPhone LiDAR software, Scaniverse, did not provide detailed guidelines, however it was simple and intuitive enough for the scanning process. ZEISS software required familiarization with its workflow and guidelines, but it was well structured and provided the best overall scanning experience. It clearly indicated whether the part was overexposed or underexposed, whether the part was moving during acquisition, the quality of each scan, and the real-time position of the scanner relative to the reference-point field. The Creality and EinScan software packages were more user-friendly than ZEISS software and provided a simpler workflow.

However, they were less stable and offered fewer options for parameter adjustment. In particular, the Crealty software occasionally froze during scanning, which interrupted the workflow. These software packages also did not visualize the scanning process during acquisition as effectively as ZEISS software, which made the scanning process less fluent. Nevertheless, both software packages were sufficient for the intended comparison.

Photogrammetry required the use of third-party software and was the most complex method in terms of both image acquisition and mesh generation. The photographs had to be captured under specific lighting conditions and from appropriate angles to ensure sufficient image overlap and reconstruction quality. Two free third-party software packages were used for mesh generation. Meshroom was utilized for that purpose first, but it proved to be very time-consuming and inefficient for this application. RealityCapture was then used as a more practical, faster, and more user-friendly alternative, which also produced higher quality meshes.

Conclusion

This thesis compares accuracy and complexity of several optical 3D scanning methods for reverse engineering application, ranging from industrial metrology systems to consumer-grade devices. The obtained results confirmed that scanner performance strongly depends not only on the measurement principle itself, but also on the relationship between scanner resolution, measuring volume, accessibility of the geometry, and optical properties of the scanned surface.

The theoretical prediction that industrial metrology scanners would outperform semi-professional and consumer-grade systems in dimensional accuracy and reconstruction quality was confirmed. However, the results also showed that nominal scanner accuracy alone is not sufficient to guarantee successful reconstruction of all geometric features and should therefore not be used as the only selection criterion. The scanner's ability to reliably reconstruct fine geometric details, such as chamfers, radii, fillets, or machined edges, depends on several factors, particularly the type of projection source, point density, and measuring volume.. Therefore, scanner selection should be based on the required feature resolution, particularly when small details must be accurately reconstructed. All evaluated methods showed a systematic tendency to round sharp external edges and lose small-radius fillets. As a practical consequence, only ZEISS ATOS Q produced meshes from which the chamfered spindle profile could be reconstructed with engineering fidelity. Wheel hub chamfers longer than 4 mm were captured well by all scanners except iPhone LiDAR and photogrammetry, confirming the presence of a minimum resolvable feature threshold.

The measuring volume in relation to the size of the part was identified as a critical factor, particularly for consumer-grade and semi-professional scanners. Due to its smaller field of view, the CreaLity CR-Scan Raptor required a substantial number of additional reference markers and repeated scanning passes on the wheel. Although still resulting in incomplete rim coverage and uncaptured central bore. Ultimately it demonstrated that it is better suited to parts comparable in scale to the steering knuckle, where its performance was competitive with EinScan Pro HD.

EinScan Pro HD, despite easier acquisition, introduced a different failure, the white LED structured-light source proved more susceptible to the slightly reflective wheel barrel than the blue LED of ATOS Q or the blue laser of T-SCAN Hawk. The EinScan in handheld mode produced car wheel mesh with bigger gaps on the rims than the CreaLity Raptor scanner. A wider point-deviation distribution was observed on the wheel barrel, which may be associated with scan drift in handheld mode. A wider point-deviation distribution was observed on the wheel barrel, which may be associated with scan drift during handheld operation. Based on these results, it can be assumed that the evaluated structured-light scanner performed less effectively in handheld mode than in stationary mode. The results may also indicate greater sensitivity to lighting conditions and surface reflections, possibly due to the use of white structured light rather than blue structured light.

The most accessible methods evaluated in this comparison did not meet the dimensional accuracy requirements for reverse engineering of mechanical components. The iPhone 16 LiDAR produced deviations of approximately ± 2.5 mm on the steering knuckle and ± 11 mm on the wheel. The resulting meshes showed significant shape distortions, particularly on rotationally symmetric surfaces, which made them unsuitable for CAD reconstruction. The unexpected finding was that Photogrammetry showed an advantage on geometrically complex surfaces of the steering knuckle, where its ± 1 mm accuracy was better than ± 2.5 mm of the

iPhone LiDAR, and its ability to resolve the chamfer outlines of the wheel's hub. Photogrammetry did not consistently outperform iPhone LiDAR on the wheel barrel and spindle, specular reflection caused complete reconstruction failure, while the iPhone LiDAR produced at least a partial mesh in those regions. However, based on the results obtained in this thesis, it must be stated that neither of these methods appears suitable for any quantitative technical application beyond rough shape acquisition followed by correct scaling during post-processing.

For gearbox applications the results demonstrate that scanner selection must be based primarily on the intended engineering task. For example, for scanning a gearbox housing, ZEISS T-SCAN Hawk 2, EinScan Pro HD and Crealty CR-Scan Raptor appear to be suitable for external and partially internal surfaces, whereas ZEISS ATOS Q is required wherever dimensional traceability is needed. None of the optical scanning methods compared in this study is sufficient for detailed reverse engineering or inspection of gear tooth profiles, although the ATOS Q could potentially capture the basic tooth profile and number of teeth. For shafts, ZEISS metrological scanners could potentially capture their overall layout, stepped diameters, and the relative position of functional features.

Several limitations of the presented methodology should also be acknowledged. The comparison was based on only two representative automotive components and used ZEISS ATOS Q as the reference geometry instead of original CAD models. The wheel barrel was left uncoated, but this decision introduced an additional variable into the scanner comparison. Furthermore, only a single scanning session per method was performed, meaning operator skill variability and scan-to-scan repeatability could not be quantified. Future work should include repeated measurements under identical conditions to determine the statistical reliability of the reported deviation values. Future work could include additional experiments involving components with a variety of industrially relevant surface conditions (e.g. corroded, painted or anodized surfaces) alongside varied lighting conditions would provide a more comprehensive understanding of the practical limitations of optical 3D scanning in mechanical engineering application.

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LIST OF USED ABBREVIATIONS AND SYMBOLS

2D	Two-Dimensional
3D	Three-Dimensional
CAD	Computer-Aided Design
DOE	Diffraction Optical Element
EM	Electromagnetic
FDM	Fused Deposition Modeling
FOV	Field of View
GD&T	Geometric Dimensioning and Tolerancing
HD	High Definition
IMU	Inertial Measurement Unit
IR	Infrared
ISO	International Organization for Standardization
LASER	Light Amplification by Stimulated Emission of Radiation
LED	Light-Emitting Diode
LiDAR	Light Detection and Ranging
MV	Measuring Volume
NA	Numerical Aperture
RGB	Red, Green, Blue
SLAM	Simultaneous Localization and Mapping
SLA	Stereolithography
SLS	Structured-Light Scanners
SPAD	Single-Photon Avalanche Diode
ToF	Time-of-Flight
VCSEL	Vertical-Cavity Surface-Emitting Laser

VDE		Verband der Elektrotechnik, Elektronik und Informationstechnik (Association for Electrical, Electronic & Information Technologies)
VDI		Verein Deutscher Ingenieure (Association of German Engineers)
VIO		Visual-Inertial Odometry

b	[m]	baseline distance
c	[m·s ⁻¹]	speed of light
d	[px]	disparity
f	[px]	focal length
NA	[–]	numerical aperture
n_{1res}	[min ⁻¹]	resonance speed of the first mode shape
n_{2res}	[min ⁻¹]	resonance speed of the second mode shape
t	[s]	measured time of flight of the emitted ray
v_0	[m·s ⁻¹]	flow velocity of an incompressible liquid
Z	[m]	depth
Δp	[Pa]	pressure difference
κ	[–]	harmonic order
λ	[m]	wavelength
ρ	[kg·m ⁻³]	density

LIST OF APPENDICES

Appendix 1 I

Appendix 2 II

Appendix 3 III

Appendix 4 IV

Appendix 5 V

APPENDIX 1

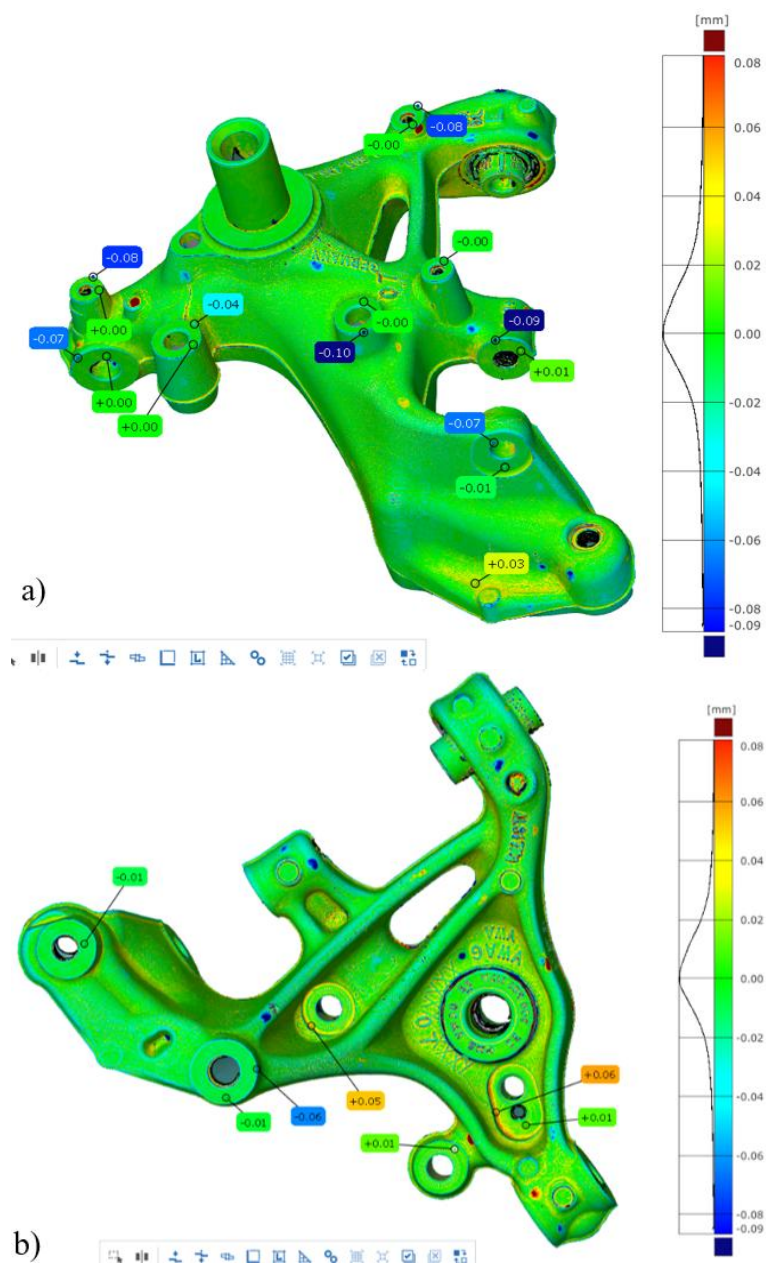


Fig. 45 T-SCAN Hawk 2 steering knuckle surface deviations:
(a) top; (b) bottom

APPENDIX 2

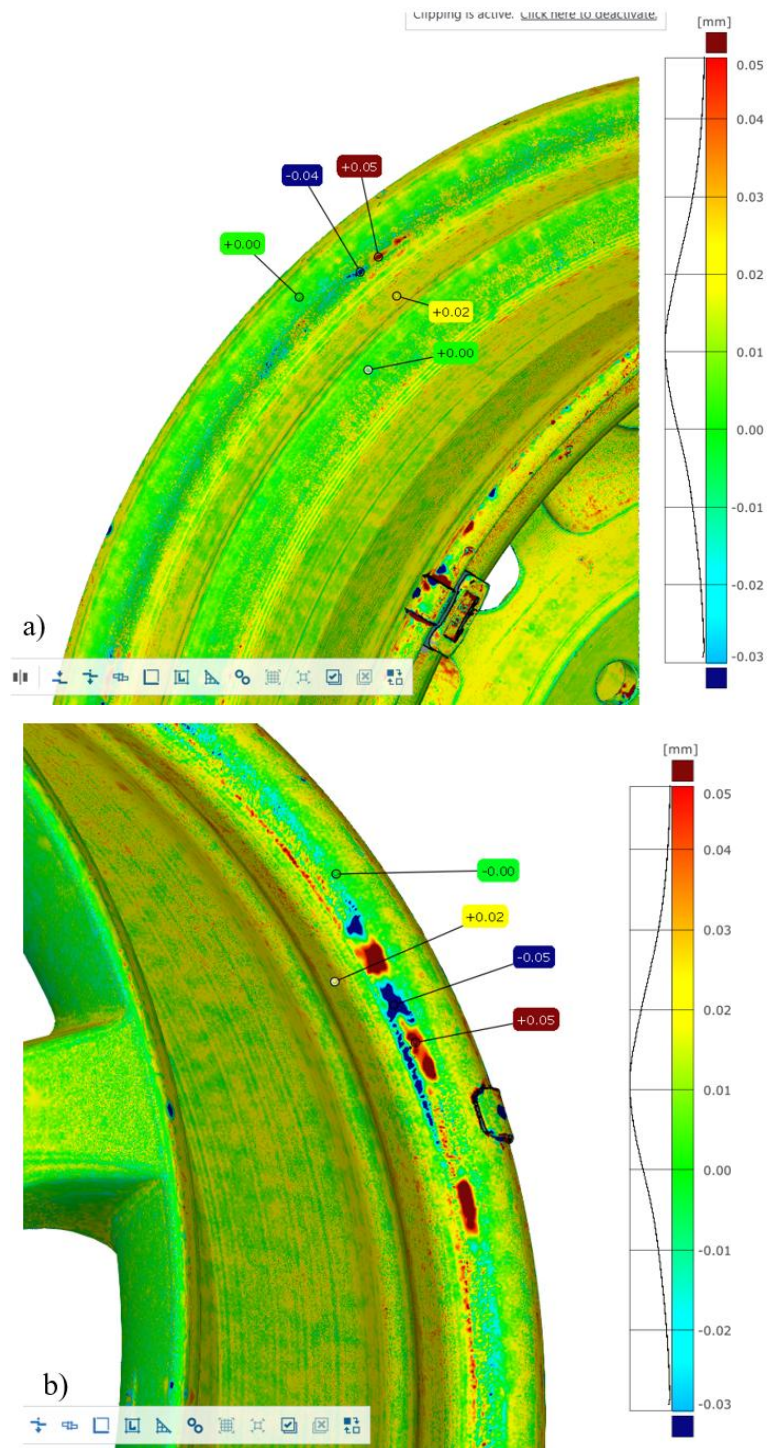


Fig. 46 T-SCAN Hawk 2 rim surface deviations: (a) outer rim;
(b) inner rim

APPENDIX 3

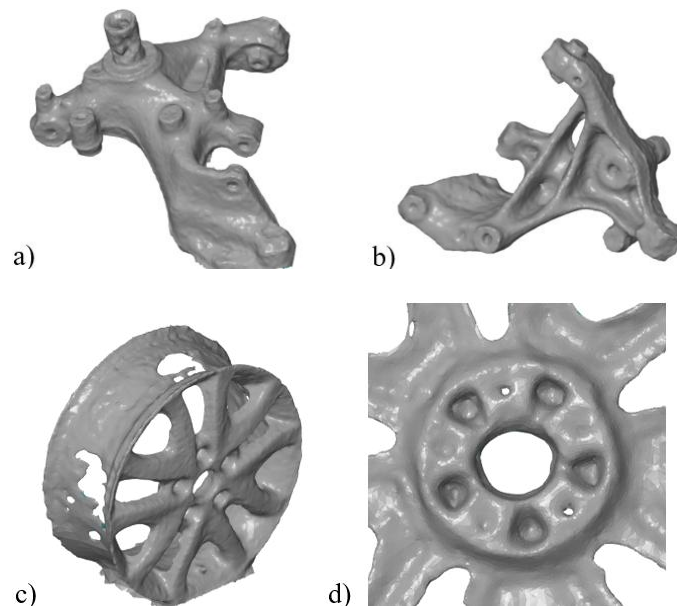


Fig. 47 iPhone LiDAR mesh: (a) steering knuckle top; (b) steering knuckle bottom; (c) car wheel outside; (d) car wheel' hub

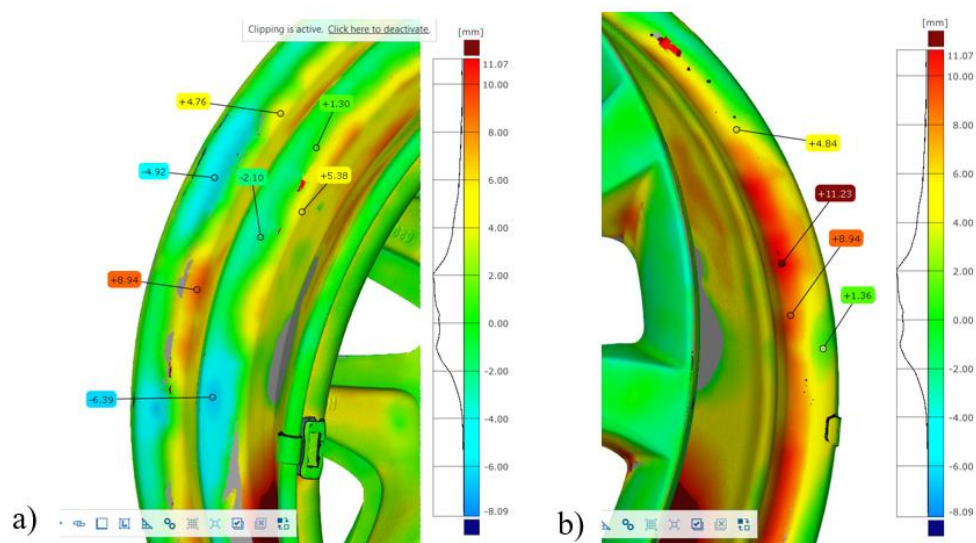


Fig. 48 iPhone LiDAR car wheel's rim surface deviations: (a) outer rim; (b) inner rim

APPENDIX 4

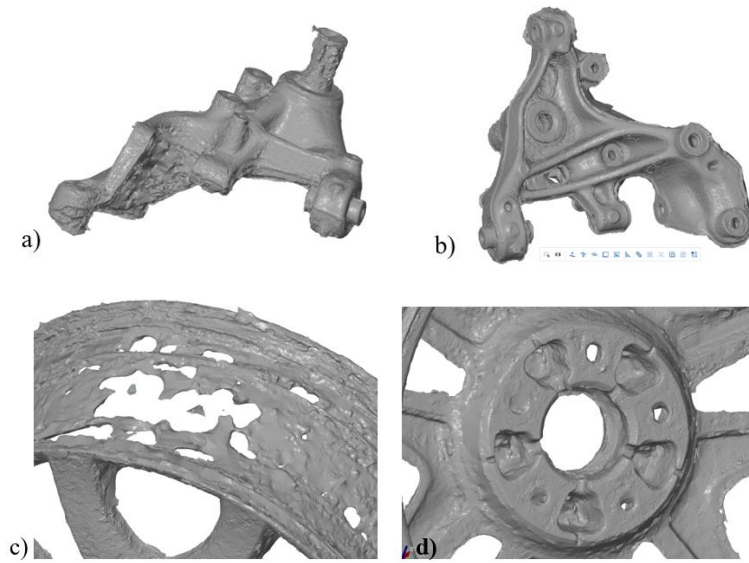


Fig. 49 Photogrammetry mesh: (a) steering knuckle top; (b) steering knuckle bottom; (c) car wheel barrel; (d) car wheel hub

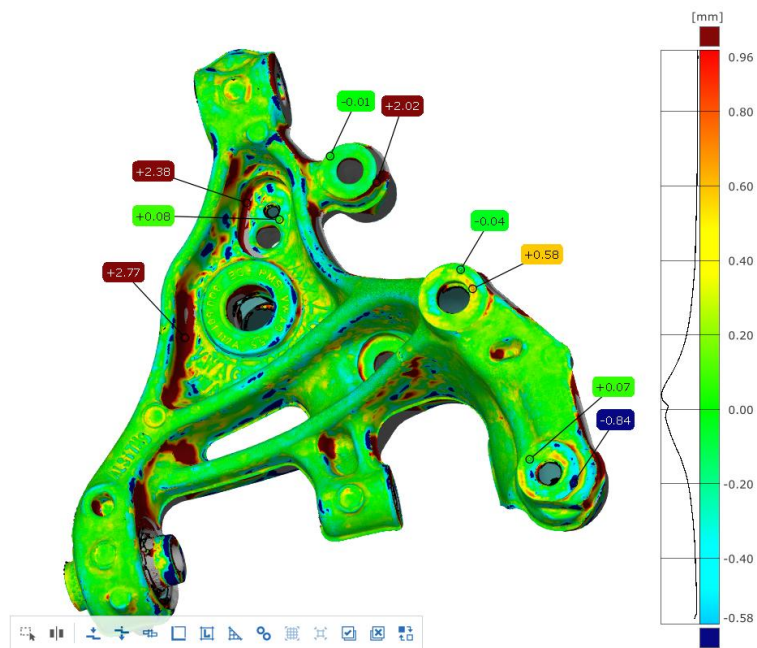


Fig. 50 Photogrammetry steering knuckle bottom surface deviations

APPENDIX 5

I critically verified the outputs of generative AI checking factual claims in primary sources and based on my own judgement. Below is an overview of the individual uses of generative AI.

Language proofreading and stylistic reformulation of my text:

- Period: 2026-03-01–2026-05-17
- Tool: Claude (Anthropic); model/version: Opus 4.6; URL: <https://claude.ai/>
- How the output was used: for inspiration/support only
- Where in the thesis: Thesis text (paragraphs in chapters)
- Extent: Medium
- Prompt/input: “Check for grammatical and stylistic mistakes and suggest corrections”
- Prompt/input: “Suggest a different formulation, do not change the meaning”

Translation of English and Czech:

- Period: 2026-03-01–2026-05-17
- Tool: Claude (Anthropic); model/version: Opus 4.6; URL: <https://claude.ai/>
- How the output was used: for inspiration/support only
- Where in the thesis: Thesis text (paragraphs in chapters)
- Extent: Limited
- Prompt/input: “Translate to English”
- Prompt/input: “Translate to Czech”