Photogrammetry for Game Environments 2014-2019: What Happened Since *The Vanishing of Ethan Carter*

Nataska Statham
Uppsala University, University of Porto
621 67 Visby, Sweden
Rua Dr. Roberto Frias, 4200-465, Porto, Portugal
nataska.statham@speldesign.uu.se

João Jacob
University of Porto
Rua Dr. Roberto Frias, 4200-465, Porto, Portugal
joao.jacob@fe.up.pt

Mikael Fridenfalk
Uppsala University
621 67 Visby, Sweden
mikael.fridenfalk@speldesign.uu.se

ABSTRACT
This review examines how the use of photogrammetry in game environment art has changed since *The Vanishing of Ethan Carter*. It identifies 26 games released between 2014–2019 featuring photoscanned environment assets, including the well-established AAA franchises *Battlefront, Far Cry*, *Forza,* and *Resident Evil*. In popular media, photogrammetry went from an unknown technique to become entrenched with high-quality realistic game graphics, and gamers have come to expect that productions of high caliber should utilize photogrammetry. So far, developers have focused on photoscanned natural assets and small props, while photogrammetry for architecture and modular assets remains underdeveloped, still battling with technical challenges both in terms of capturing the data as well as processing it. Legal and ethical ramifications of digitally representing real-world locations in games remain for the most part unaddressed, as do the visual identities of franchises that rely on photoscanned game environments.

Keywords
game environments, modular assets, natural assets, photogrammetry, photoscanned environments.

INTRODUCTION
In 2014, *The Vanishing of Ethan Carter* (The Astronauts 2014) caused a stir among developers: a small indie game featured environments comparable, if not superior in quality, to those of AAA productions. Its secret was quickly attributed to its innovative use of photogrammetry, a technology that recreates 3D meshes from multiple photos and that until then had mostly been reserved for characters' faces (Poznanski 2014). The following year, EA announced its flagship game *Star Wars Battlefront* (EA DICE

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2015) would also rely on photogrammetry to reproduce the franchise's iconic environments (Brown and Hamilton 2016).

Quickly, photogrammetry went from relatively unknown to becoming associated with high-quality game graphics. It has since featured in AAA games, technical demos, and is a recurring topic in panels discussing the future of game graphics (Maximov 2017). Today, photoscanned textures are simple to create and Quixel Megascans' vast library of photoscanned textures has recently become free for Unreal developers (Epic Games 2019). Photogrammetry for characters has expanded to include clothes and prosthetics make-up (Kurosu and Endo 2016). But when it comes to developing meshes for game environment assets, what has been the extent of the integration of photogrammetry in this five year period? This review seeks to provide an overview of the games market to answer this question.

The first part of the paper identifies games featuring photoscanned environment assets and, based on secondary sources in the form of interviews and technical panels with developers, seeks to understand how such assets benefit production. The second part examines public reception through articles in popular media, and how it has changed between 2014 and 2019. The third part examines to what extent photoscanned environment assets are used in the identified games, highlighting subcategories in which photogrammetry is more prevalent and others in which widespread integration remains challenging and why. It concludes with a summary discussion of the key benefits, misconceptions, and ongoing challenges that must still be overcome.

MARKET SHARE OF PHOTOSCANNED GAME ENVIRONMENT ASSETS

The first step was to identify games featuring photoscanned environment assets since 2014. For the purpose of this study, photoscanned environment assets refers to ingame meshes and textures or meshes only derived from photogrammetry that are used to assemble a game's environment. Measuring the market share of any game technique is no easy task: over 25,000 games were published between 2014 and 2018 for PC on Steam alone (Gough 2019), excluding consoles and other platforms such as Ubisoft's Uplay and EA's Origin. Manually inspecting each game would therefore be highly time-consuming, making inspection of primary sources (games) an unproductive approach.

Therefore the authors turned to secondary sources, querying the keywords "photogrammetry" and "photoscan" in industry-specific conferences, trade magazines, and popular game news publications. The authors complemented this process with online searches using Google, Google Scholar and Yahoo with the keywords: photogrammetry + game, photoscan + game, photogrammetry + "game environment" and photoscan + "game environment". This led to relevant articles in other sources, such as coverage of racing games in popular automobile magazines. Amateur reviews and public discussions in game forums, Reddit, Discord and similar were discarded as being overly speculative. The relevant sources are summarized below, and issues consulted range from January 2014 to November 2019.

- Conferences: ACM Siggraph, CEDEC, GDC, Unite, Unreal Fest.
- Developer blogs: Activision, Autodesk, Capcom, Digital Foundry, EA DICE, EA Frostbite, Kickstarter, The Astronauts, The End of the Sun, Ubisoft, Unity, Unreal.
- Trade Magazines: 80 Level, CG Society, CG World, Gamasutra, Gnomon School of VFX.

- Popular Magazines: Archeogaming, Car Throttle, DSOG Dark Side of Gaming, Dualshockers, Eurogamer, Full Throttle Media, GTP Planet, IGN, PC Gamer, PC Games Hardware, PC Games N, Reboot Magazine, Red Bull, Rock Paper Shotgun, Rocket Chainsaw, Techradar, Techspot, US Gamer, Venture Beat, Windows Central.

Results were filtered, including games featuring photoscanned environment assets, but discarding photogrammetry for textures or characters only. Projects that use game engines but fall outside the scope of games, such as virtual tours without gameplay elements, were also discarded. Results were further filtered to encompass published games or in development, excluding those that were discontinued. Where possible, secondary sources were corroborated by two or more publications, where interviews with the developers were considered of higher factual value than reviews by journalists only. Data about Japanese games were harder to corroborate with multiple sources due to the language barrier.

When a game was positively identified by secondary sources as featuring photoscanned environment assets, the authors visually confirmed it through direct observation of the primary source in the form of gameplay footage. Photoscanned assets were identified based on the level and quality of surface detail, weathering, wear patterns, and overall "imperfections", characteristics that are common in photoscanned meshes but hard to achieve via traditional methods. There were no instances where a claim inter-corroborated by secondary sources could not be verified by observation of the primary source. Table 1 presents a summary of all games identified through this process, totaling twenty-six published games, plus seven still in development.

Game	Publication Date	Platform	Developer/ Publisher	Team Size
In Development				
Elder Scrolls 6	TBA	TBA	Bethesda	800+
Serious Sam 4: Planet Badass	TBA	PC, OS, Linux	Croteam/ Devolver Digital	40+
Dreadful Bond	TBA	TBA	Clod Studio	N/A
The Beast Inside	TBA	PC	Illusion Ray Studio/ PlayWay, Movie Games	N/A
Witchfire	2020	PC	The Astronauts	N/A
The End of the Sun	2020	PC	The End of the Sun Team	3
Beautiful Desolation	2020	PC	The Brotherhood	3
Published				
Death Stranding	08 Nov 2019	PS4	Kojima Productions/ Sony	100-300
Call of Duty: Modern Warfare (2019)	25 Oct 2019	PC, PS4, Xbox One	Infinity Ward/ Activision	550+
Chernobylite	16 Oct 2019	PC, PS4, Xbox One	The Farm 51	100+
Anthem	22 Feb 2019	PC, PS4, Xbox One	Bioware/EA	800+

Game	Publication Date	Platform	Developer/ Publisher	Team Size
Tom Clancy's The Division 2	15 Mar 2019	PC, PS4, Xbox One Standia	Ubisoft	1000+
A Plague Tale	14 Mar 2019	PC, PS4, Xbox One	Asobo Studio/Focus Home Interactive	140
Resident Evil 2 (2019)	25 Jan 2019	PC, PS4, Xbox One	Capcom	1000+
Battlefield V	9 Nov 2018	PC, PS4, Xbox One	DICE/EA	800
Forza Horizon 4	2 Oct 2018	PC, Xbox One	Playground Games/ Microsoft	200+
The Bard's Tale IV	18 Sep 2018	PC, OS, Linux, PS4, Xbox One	inXile Entertainment	70
Ride 3	30 Nov 2018	PC, PS4, Xbox One	Milestone	150
Onrush	5 Jun 2018	PC, PS4, Xbox One	Codemasters Evo/ DeepSilver	400+
Far Cry 5	7 Mar 2018	PC, PS4, Xbox One	Ubisoft	1000+
Star Wars Battlefront II	17 Nov 2017	PC, PS4, Xbox One	DICE/EA	800
Middle-earth: Shadow of War	27 Sep 2017	PC, PS4, Xbox One	Monolith Productions/ Warner Bros	150+
Forza Motorsport 7	3 Oct 2017	PC, Xbox One	Turn 10/ Microsoft	200+
Project Cars 2	21 Sep 2017	PC, PS4, Xbox One	Slightly Mad Studios/ Bandai Namco	150+
Get Even	23 Jun 2017	PC, PS4, Xbox One	Farm 51/ Bandai Namco	100
Resident Evil 7: Biohazard	24 Jan 2017	PC, PS4, Xbox One	Capcom	1000+
Final Fantasy XV	29 Nov 2016	PC, PS4, Xbox One	Square Enix	1000+
Battlefield 1	21 Oct 2016	PC, PS4, Xbox One	DICE/EA	650
Forza Horizon 3	27 Sep 2016	PC, Xbox One	Playground Games/ Microsoft	200+
Star Wars Battlefront	17 Nov 2015	PC, PS4, Xbox One	DICE/EA	650
Fishing Planet	11 Aug 2015	PC, Xbox Live	Fishing Planet LLC	50
The Talos Principle	11 Dec 2014	PC	Croteam/ Devolver Digital	40
The Vanishing of Ethan Carter	25 Sep 2014	PC, PS4, Xbox One	The Astronauts/ Microsoft	N/A

Table 1: List of games featuring photoscanned environment assets. Team sizes are based on number of employees unless specific information was available; N/A refers to data not available.

Based on Table 1, the next step sought to identify trends and patterns in the adoption of photoscanned environment assets for games. A relational conceptual analysis was applied to the developers' interviews and technical panels identified among the secondary sources listed above. It sought to understand what benefits photoscanned environment assets bring to a game production, and if independent (indie) and larger AAA developers were drawn to it for similar or different reasons. Findings are presented next, illustrated with direct quotes from developers where appropriate.

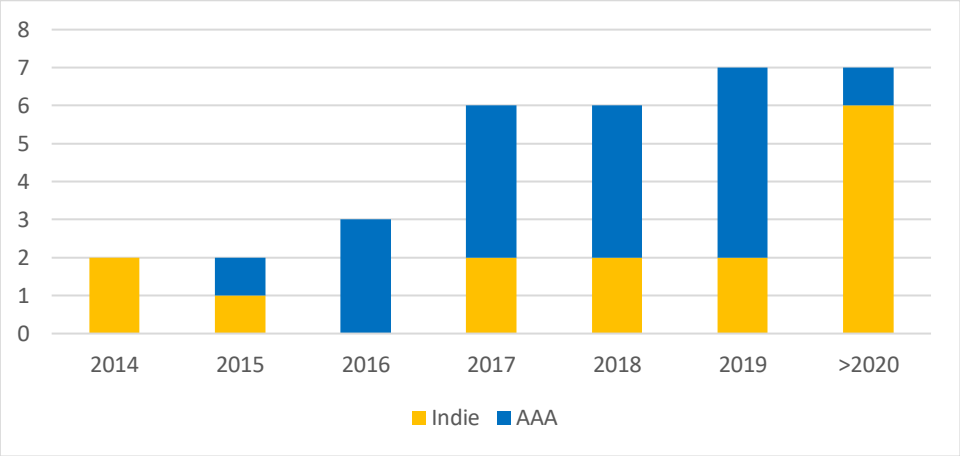

Figure 1: Published games per year featuring photoscanned environment assets.

Figure 1 shows a growing number of adopters each year, where the majority of games have been published since 2017. This is a natural timeline for developers that first became interested in the technique following the 2014 *The Vanishing of Ethan Carter* and the 2015 *Star Wars Battlefront*, displaying a traditional technological hype cycle (van Lente, Spitters, and Peine 2013).

All of the games were developed for PC and console, without examples of mobile or VR (virtual reality) games. Figure 2 shows a predominance of four broad genres: FPS (First Person Shooter), action, racing, and horror. First-person (61%) is favored over third-person (30%), and only three games offer both options. Whether this is because these genres and viewpoints lend themselves well to photogrammetry or because the developers were early adopters is too early for determination.

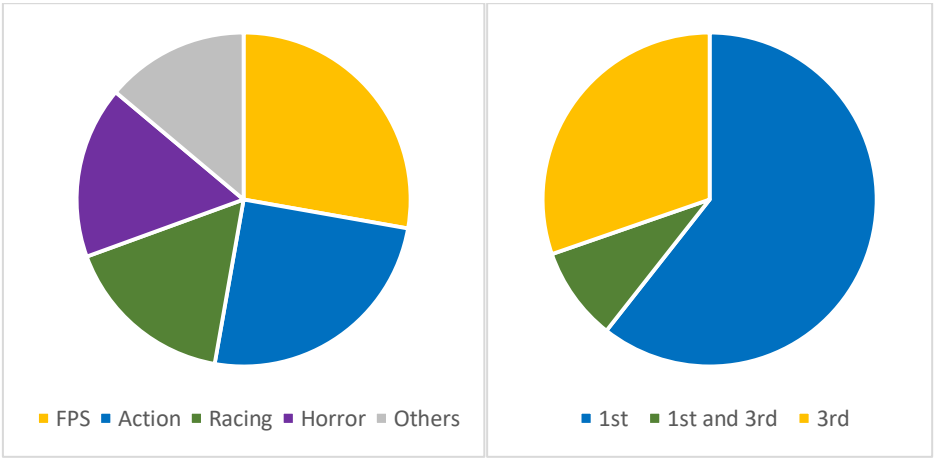

Figure 2: Predominant genres (left) and viewpoints (right) of games featuring photoscanned environment assets.

Recurring use accounts for half of the identified games (Figure 3) and suggests that the experience with photoscanned environment assets is overall positive, as once adopted, developers continue to rely on it for future projects.

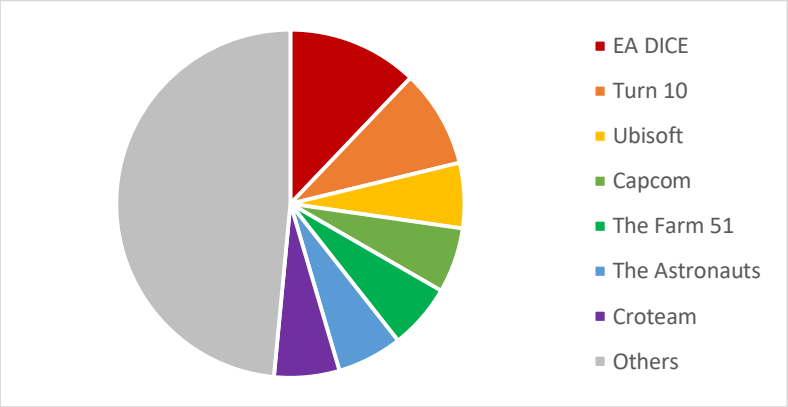

Figure 3: Distribution of games featuring photogrammetry-based environment assets between recurring developers and those with only one listed game, grouped under Others.

Distribution is even between smaller independent (indie) and larger AAA developers (16 vs 17 games), as shown in Figure 1. Indie developers express appreciation for photogrammetry's high level of detail and realism that may otherwise not be achievable within their limited budget and team size (between 3 and 100–200 developers). *The Vanishing of Ethan Carter's* Lead Artist Andrzej Poznanski explains:

> *Photogrammetry is incredible… So much detail, so many intricacies, but most importantly, all of them just make deep sense. Cracks, stains, erosion – Mother Nature has worked a billion years on some of these assets, it's almost unfair to expect comparable quality from artists who spend no more than few days on similar assets* (Poznanski 2014).

Reduction in production time is routinely reported by developers adopting photogrammetry, varying from 70% (EA DICE) to an extreme example by The Farm 51 where a photoscanned exterior took three days to process, while to achieve the same level of quality manually it required three months (Brown and Hamilton 2016; Pazdur 2018). However, these reports focus on post-processing time only, starting with a pre-existing photoscan and ending with a game-ready asset. While optimistic, without including the time and costs for photoscanning as well as post-processing, they are ultimately incomplete.

Another point highlighted by developers is photogrammetry's ability to provide a unique selling point. In *Ride 3* (Milestone 2018), Italian developer Milestone wanted to provide players with the experience of riding one of Italy's most iconic roads, the Strada della Forra:

> *Reproducing the amazing sensation of riding these curves has been a real challenge. And this time we really stepped our game up. Through aerial photogrammetry and drone-scanning, we gathered the data needed for a perfect recreation of all the "hot spots" from this amazing road* (Loiudice 2018).

Similarly, inXile Entertainment caters to players' craving for authenticity by featuring historical objects scanned in Scotland in *The Bard's Tale IV* (inXile Entertainment 2015). Clod Studio promises to feature objects from abandoned buildings from the 60s

and 70s to craft a cinematic horror experience in *Dreadful Bond* (Clod Studio 2019). For *Beautiful Desolation*, the three brothers behind the development team The Brotherhood elected to scan miniatures to achieve a unique artistic style (Bishop 2017), an approach that is reminiscent of analogue special effects for movies. The Farm 51 intentionally chose to photoscan Chernobyl, a location of high sociocultural value and limited accessibility:

> *Chernobyl… is a place where most of us won't ever dare to go, be it because of the war in Ukraine or out of fear of radiation… a truly forbidden zone… We decided to visit the place to document it for future generations* (The Farm 51 2016, 1'30").

Photogrammetry is not limited to developers that can invest in extensive field trips. Third-party libraries are increasingly adding photoscanned assets, as explained by Asobo Studio's Lead Artist, Oliver Cannonne, regarding *A Plague Tale: Innocence*: "We used Megascans assets for all the organic details (trunks, rocks, vegetation). Photogrammetry of Megascans rocks, for instance, are so realistic that we did not need to do it by hand" (Umar-Khitab 2019).

Photogrammetry also attracts AAA developers, where integrating a new technology within extensive teams and large-scale projects presents unique challenges. At GDC 2016, EA DICE presented a technical panel about photogrammetry for *Star Wars Battlefront*; one of their key challenges was quality-matching photoscanned and traditionally modeled assets:

> *With the old asset creation, you get to a certain level of quality with a certain amount of effort and tech. Suddenly with photogrammetry your increase in quality is significant because of the tech and the techniques, not necessarily because of the effort. So when you're unable to use that technique for an asset that doesn't lend itself to photoscanning, how do you bridge that gap?* (Brown and Hamilton 2016, 24')

This sentiment is echoed by Capcom's 2016 CEDEC panel on *Resident Evil 7: Biohazard* (Capcom 2017), as shown on Figure 4 (Kurosu and Endo 2016).

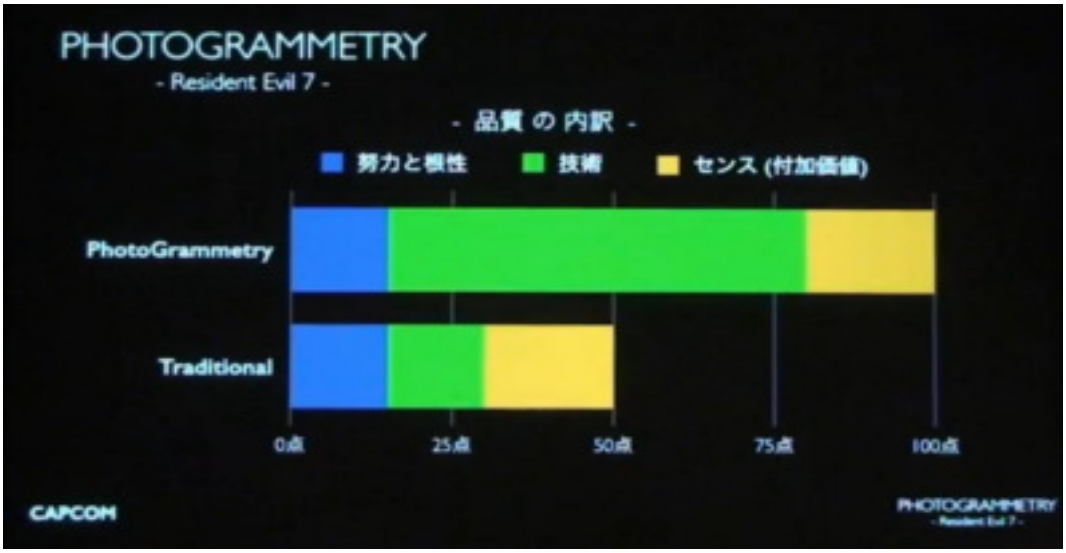

Figure 4: Comparison of quality of game assets using photogrammetry vs. traditional methods. Translation of legend: - Breakdown of quality – [blue] Effort and guts/ Manual labor, [green] Technology, [yellow] Sense (additional value).

To bridge the quality gap, EA DICE adopted Physically Based Rendering (PBR), added detail maps and terrain tessellation throughout the game. It required training hundreds of artists over separate continents, as well as developing new production tools. Photoscanning locations was another new challenge, involving multiple field trips and 100,000 photos that had to be individually pre-processed and quality-checked. Post-processing each scan was also laborious and, unsurprisingly, one of the key takeaways of the panelists was to invest in automation and improving the workflow (Brown and Hamilton 2016).

In 2019, EA DICE held a new panel discussing the game environments for *Battlefield V* (EA DICE 2018). In the three years between games, the developer refined its approach: whereas for *Battlefront* each game location was assigned to an autonomous team responsible for that location from start to finish, including photogrammetry, in *Battlefield V* a single team of three artists was tasked with all the photogrammetry onsite. This shift was reflected in the equipment: *Battlefront*'s teams traveled light, relying on a single DSLR camera. *Battlefield V* included an UAV (Unmanned Aerial Vehicle) as well as an indoor rig for small items. Attention to planning also increased, adding a proof-of-concept for *Battlefield V* to fine-tune the list of assets and location-scouting prior to the field trip. Standardization was achieved by the use of a Macbeth color chart, and the photos were organized into pre-established folders (Brown and Hamilton 2016; Rambelli et al. 2019).

Overall, in 2015 EA DICE was still experimenting with photogrammetry in a learning by doing approach, whereas in 2018 the developer displays greater maturity and familiarity with the process, with a focus on quality over quantity. For *Battlefield V*, 3D artist Guilherme Rambelli states specifically seeking characterful, rundown buildings as: "It's a lot easier to remove things from a scan and make it look more pristine than to add things and make it look realistic" (Rambelli et al. 2019, 24'). While there are still challenges to overcome, as will be discussed ahead, EA DICE's mastery of photogrammetry in a short amount of time indicates that the technology has the potential of becoming an integral part of the pipeline of realistic games.

POPULAR MEDIA RECEPTION OF PHOTOSCANNED GAME ENVIRONMENTS

Popular media's relationship with photogrammetry has also changed significantly. Articles from 2014 report an unfamiliar technology: photogrammetry must be explained to the public, sometimes incorrectly, and occasionally used between quotation marks – "photogrammetry" – further signaling its unfamiliarity. This is exemplified by the following statements from Eurogamer and Rock Paper Shotgun:

> *The Vanishing of Ethan Carter will use a revolutionary visual technique in which the artists take a boatload of photos then use the magic of technology to recreate digital 3D representations of said pics. It's called photogrammetry and it's mighty impressive looking. Using something called Lowe's Scale Invariant Feature Transform (SIFT) algorithm, the art team can transfer photos into game assets like magic* (Matulef 2014).

> *The gang are showing off their mastery of the arcane science of photogrammetry, or smooshing loads of photos together to make a 3D model* (O'Connor 2014).

Photogrammetry is described as a "revolutionary visual technique" and compared to "magic" and an "arcane science", despite being commonly used in games by 2014 for characters' faces (EA Sports FIFA 2011). Unfamiliarity with photogrammetry

followed by garbled explanations persists throughout the 2015 publication of *Star Wars Battlefront,* as in this example by Polygon:

> *Behind it is a technology many are unfamiliar with, known as photogrammetry… So what is photogrammetry? In short, it's taking hundreds, perhaps thousands, of still images of a single object and feeding them into a piece of software, hitting a button, and having a 3D digital asset pop out. It's certainly not new technology, but it was never applied to gaming at scale until last year's The Vanishing of Ethan Carter* (Hall 2015).

It perpetuates an over-simplification of the pipeline where one "hits a button" and a 3D asset "pops out". It implies an unrealistic level of automation while at the same time undervaluing the manual and artistic labor involved. As with the example above, many articles from 2015 refer to *The Vanishing of Ethan Carter* as a short-hand explanation, bestowing by association the same level of graphic quality to other games featuring photogrammetry.

As more games continued to adopt photogrammetry between 2016 and 2018, its association with high-quality realistic graphics was solidified. Photogrammetry is often portrayed as a fail-proof solution, regardless of the type of game, budget, size or experience of the development team. Popular media often implies that by using photogrammetry developers will be able to produce reality simulators, as in this GT Planet article about *Forza Motorsport 7* (Turn 10 Studios 2017):

> *In terms of accuracy, one of the focal points is giving the player the same feeling as a race driver when visiting any one of the track locales. For that to happen, there needs to be a near-identical recreation of the track; a 1:1 likeness in other words.... Photogrammetry brings everything full circle. By taking photos of real world objects, the team can recreate 3D meshes. It goes without saying it's an interesting topic* (Leary 2018).

As in this example, recent articles display a growing familiarity with photogrammetry: it no longer needs to be explained, and can now be used as a stand-alone description. Nothing illustrates this change better than this quote from PC Gamer about *Dreadful Bond*: "I do love me some photogrammetry. I like saying it, too. It's a fun word!" (F. Brown 2019). In an interview with TechRadar, an unnamed representative from Capcom's *Resident Evil 2* (Capcom 2019) remarked that: "Photogrammetry will eventually cease to be special, and in some ways it's already reaching that point" (O'Keefe 2019).

If anything, it is the lack of photogrammetry that starts to be questioned, as this review about the racing game *WRC 8* (Kylotonn 2019) illustrates: "I was a little shocked that they didn't utilize Codemasters or Milestone's technique of using drones to laserscan the track and then rely on photogrammetry to map out the base topographical mesh" (Usher 2019).

Popular confidence in photogrammetry has transformed it into a powerful marketing tool. Of the games identified in this study, five involved a Kickstarter campaign where photogrammetry was a selling point featured in the written description as well as promotional videos. The marketing campaign of *Call of Duty: Modern Warfare* (Infinity Ward 2019) heavily emphasized its use of photogrammetry, even in articles unrelated to the game graphics; the following paragraph, part of a press release from the 30th of May 2019, returned 58,400 results on a Google search a month prior to the game's release:

The new technology utilizes the latest advancements in visual engineering, including a physically-based material system allowing for state of the art photogrammetry, a new hybrid tile based streaming system, new PBR decal rendering system, world volumetric lighting, 4K HDR, DirectX Raytracing (PC) and more as well as a new GPU geometry pipeline.

Listing photogrammetry alongside other techniques to provide a game with a technical pedigree is an increasingly common marketing practice. Moreover, the listed techniques are often not new or ground-breaking, but the way they are described makes them seem so. As well as over-selling the potential of photogrammetry, popular media tends to imply, sometimes erroneously, that photoscanned assets were used throughout the whole game. As will be discussed next, this is not always the case.

EXTENT OF THE INTEGRATION OF PHOTOGRAMMETRY

Among the games identified in this study (Table 1), there are different levels of integration: some are heavily reliant on photoscanned environment assets, whereas others use them sparingly. To better understand the level of integration, a more detailed inspection of the primary sources is necessary. Rather than simply ascertaining its presence, this section queries which specific areas of the game environment are based upon photogrammetry, and to what extent.

Game development traditionally distinguishes between environment assets and props, where the former are used to build the overall architectural structures and landscapes and the latter are used as set dressing. Props also include small interactive objects such as weapons, levers, and pieces of puzzles. This distinction between environment assets and props is commonly reflected in how games organize their contents (Epic Games 2018) and in staffing, with environment artists and prop artists often being distinct job positions. Environment assets can be further divided between modular and non-modular. Modular environments rely on multiple tileable meshes to form a visually continuous structure, whereas non-modular environments usually rely on unique hero meshes that are modeled as a single mesh per structure (Burgess and Purkeypile 2016).

Due to the observed propensity of photogrammetry for natural subjects in games, the author added the further distinction of natural or man-made. Thus, the types of game environment assets are classified in this study according to five subcategories: (1) natural props, (2) man-made props, (3) natural environment assets, (4) man-made environment assets, and (5) modular environment assets.

	Natural Props	Man-made Props	Nat. Env. Assets	Man-made Env. Assets	Modular Env. Assets
Scale	Small to Medium	Small to Medium	Medium to Large	Medium to Very Large	Varied
Origin	Natural	Man-made	Natural	Man-made	Both, generally man-made
Potential Reusability[1]	High	High	Medium	Low-Medium	High
Stand-alone	Yes	Yes	Yes	Yes	No
Clustered	Yes	Yes	Generally yes	Generally not	Generally not
Modular	No	No	No	No	Yes

Table 2: Subcategories of environment assets and description of morphology and intended use.

This classification is based upon the morphology and intended use of the asset, differentiating in terms of dimension, origin (natural or man-made), whether it is meant to be reused extensively or not, if it is stand-alone or not, and if it is designed to be clustered or in modularity with other assets or not, as summarized in Table 2.

Natural props refer to assets of small to medium dimension of a natural or organic origin. As props, these assets are intended to be used as set dressing, repeated several times throughout the game to dress up the environment. Common natural props include low-ground vegetation, rocks, tree stumps, mushroom clusters, crystalline formations, bird nests, animal burrows, etc.

Man-made props, similar to natural props, refer to assets of small to medium dimension intended to be used as set dressing, except in this case they are man-made. This includes crates, barrels, chests, road barriers, debris, garbage, furniture, decorative furnishings, statues, etc. Man-made is a generic description that encompasses several levels of industrialization and historical periods, from handmade to mass-produced. Nor does "man"-made have to refer to objects of a human origin alone, for example, in a sci-fi game objects manufactured by an alien species would also fall within this category.

Natural environment assets refer to medium to large assets of a natural or organic origin. These are the building blocks of the natural game environment and may be intended as stand-alone (such as a large fallen tree) or clustered (such as a boulder made up of multiple large rock assets). Examples include boulders, large rock formations, trees, fallen trees, caves, etc.

Man-made environment assets refer primarily to stand-alone and hero buildings or ruins, where the building is produced as a single asset or broken down into a handful of parts. When broken down into parts, these are not meant to be modular, only to facilitate implementation in engine – for example, when the total polycount exceeds the maximum per asset allowed by the game engine and the mesh must be split into multiple parts. This usually applies to small stand-alone architecture such as shacks, sheds, trading stands, or to key building exteriors, such as a castle, church, temple or similar.

Modular environment assets are designed to be combined with each other in a modular fashion, similar to real-world LEGO pieces, modular furniture or modular architecture. Unlike clusters, where a handful of assets can be either stand-alone or randomly grouped, modular assets are generally not stand-alone and depend upon being assembled with other modular assets to form an integral visual unit. Although generally applied to architecture, modular assets can also include natural environments such as caves and grottos.

The games identified in Table 1 were visually inspected for the use of photogrammetry in the subcategories described above. Ideally one would prefer to rely on a precise percentage of assets provided by the developers; however, this type of data is not publicly available nor are developers willing to disclose it. Instead, the authors relied on inspection of the games themselves. This process involved primary observation as well as secondary sources. First, secondary sources where representatives of the development team confirmed the use of photogrammetry in specific subcategories were consulted. Next, primary observation confirmed information gathered from secondary sources through a visual inspection of the game itself either through video footage of gameplay or by playing the actual game. Only ingame content was reviewed, as trailers and other promotional material are often not an accurate reflection of the published game.

A notation of "O" stands for Observed, confirming the presence of photogrammetry in the subcategory through direct observation. "LE" indicates Limited Extent, meaning that while confirmed, it is limited to a few key or experimental assets. "NO" stands for Not Observed, indicating that the authors could not detect the use of photogrammetry for that subcategory. "NA" stands for not applicable, where based on primary observation the authors could not detect the presence of assets in that particular subcategory in the game. "U" stands for unavailable, where the game is still in development and no ingame footage has been released. The findings are summarized in Figure 5.

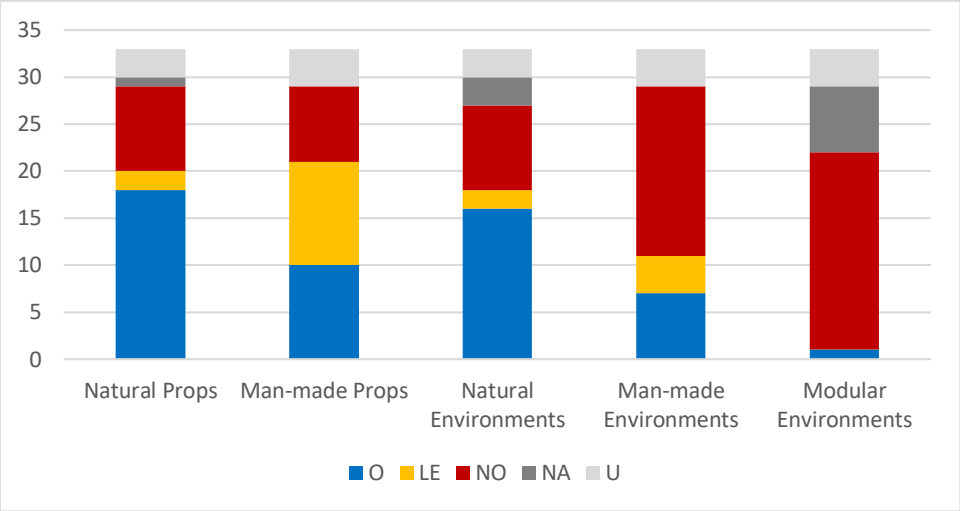

Figure 5: Use of photogrammetry per subcategory of game environment assets.

This inspection reveals that photogrammetry is not equally integrated in all subcategories: props and natural environment assets feature higher overall use of photogrammetry, whereas it is less common for man-made environments and only a single game incorporates photoscanned modular assets. Furthermore, photoscanned natural props and natural environment assets are more widespread throughout each game, where man-made props are often featured to a limited extent. The authors noted that when a game adopts photogrammetry for natural environments, it tends to adopt it for both props and larger environment assets.

The high presence of photoscanned props is not surprising as smaller objects are easier to scan and can usually be transported to and photographed at an indoor location with controlled lighting. Nor is there inconvenience with passersby and traffic, as there is when photographing at a public location. For game assets, controlled lighting translates into better textures, as strong shadows and highlights can be minimized (Lachambre, Lagarde, and Jover 2017). Controlled lighting also enables photometric stereo, where the same subject is photographed under different light conditions to capture highly detailed normal and tessellation maps (Rambelli et al. 2019).

Availability is an advantage when photoscanning natural assets, and game artists routinely report experimenting with locally available subjects (Lundevall and Tokarev 2016). Only games with extensive budgets can afford to fly staff to remote locations, and even then it is usually a handful of artists who take upon themselves the task of documenting the location for the rest of the team (Brown and Hamilton 2016; Williams 2017). This is true whether photogrammetry is used or not.

As well as being easily accessible, natural assets benefit from the realistic weathering captured via photogrammetry, including immersive details that might ordinarily be overlooked. As described by *Far Cry 5* (Ubisoft 2018) developers:

> *"When Richard, our lead on biomes, came back and scanned a birch, and there was actually a heart shape with initials and names, and we're like 'this is awesome!'" says Associate Producer Philippe Fournier. "This is the level of detail you can find in some of the assets. We can tweak it and make it story-based, but getting that sort of detail is definitely a first for us"* (Ubisoft 2017).

Natural subjects also feature largely in photoscanned textures, where only the texture information is extracted and it can be applied to meshes created by traditional methods (Lundevall and Tokarev 2016). Speedtree, a vegetation middleware widely used in games and movies, has of 2019 announced support for photogrammetry. While still early to observe its impact in games, promotional material (Figure 6) shows the potential for highly realistic and customizable vegetation, blending photoscans with procedurally generated meshes within the same tree asset (Scruggers 2019).

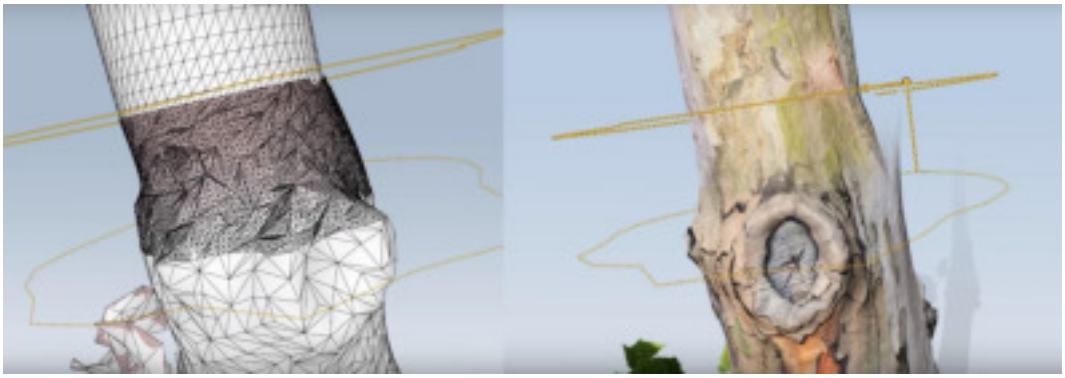

Figure 6: Left, Speedtree wireframe of a tree combining photoscan (bottom half) and procedurally generated mesh (top half). Right, the same tree shaded with textures.

To capture famous roads and tracks, racing games use a combination of aerial photogrammetry, ground photogrammetry, and in the high budget franchise *Forza*, laser scans and 360 video. This wide arsenal of information provides artists with highly-accurate 3D references, where man-made structures tend to be traditionally modeled using the scans as guidelines only, and natural landmarks are derived from photoscans (Gosnnel 2018; Loiudice 2018).

The lower integration of photoscanned man-made environments is widespread, with developers generally opting to combine traditionally modeled buildings with photoscanned and procedurally generated textures instead (Bosset 2018).With the exception of The Farm 51, games that extensively feature photoscanned architecture are rare. When photoscanned architecture is present, it is usually limited to key locations only such as the Naboo palace for *Star Wars Battlefront 2* (Tokarev and Zakrisson 2019), or smaller structures such as the outhouses and cottages in *The Vanishing of Ethan Carter* (Poznanski 2014).

This can be partially explained by the difficulty in photographing buildings with sufficiently high quality to derive ingame meshes (Rambelli et al. 2019). When scanning extensive outdoor locations, other fields such as architecture, heritage and city planning tend to rely on aerial photogrammetry performed by UAV at a mid to high

altitude. An experienced drone operator can record a building exterior in under an hour, acquiring thousands of photos from hard-to-reach angles (Ruiz Sabina et al. 2015). However, while sufficient as references, these scans tend to lack the level of detail needed to be converted into game assets, and aerial scans must in general be complemented by traditional ground photogrammetry or low-altitude close-up aerial photogrammetry (Lachambre et al. 2017). The latter is hard to perform in populated areas due to obstruction with power-lines and other structures (Rambelli et al. 2019) and may require special permits to fly a UAV at low altitude.

Of all the games identified in this study, *Chernobylite* (The Farm 51 2019) is the only one to feature photoscanned modular assets. However, the developers struggled to achieve true modularity, especially for architectural interiors (Pazdur 2018). Modular game environments traditionally rely on small flat individual assets, what in architecture are referred to as non-volumetric components or sub-assemblies, such as flat walls, floors, ceilings and similar (Smith 2010). These individual assets are then assembled into large and visually unified volumetric structures (Figure 7) either by directly snapping individual assets together in the level, or through an intermediate step of prefab modules. Here the process also resembles real-world architecture, finishing with the prefab modules of interiors and exteriors being assembled in the level into a visually continuous structure (Burgess and Purkeypile 2016).

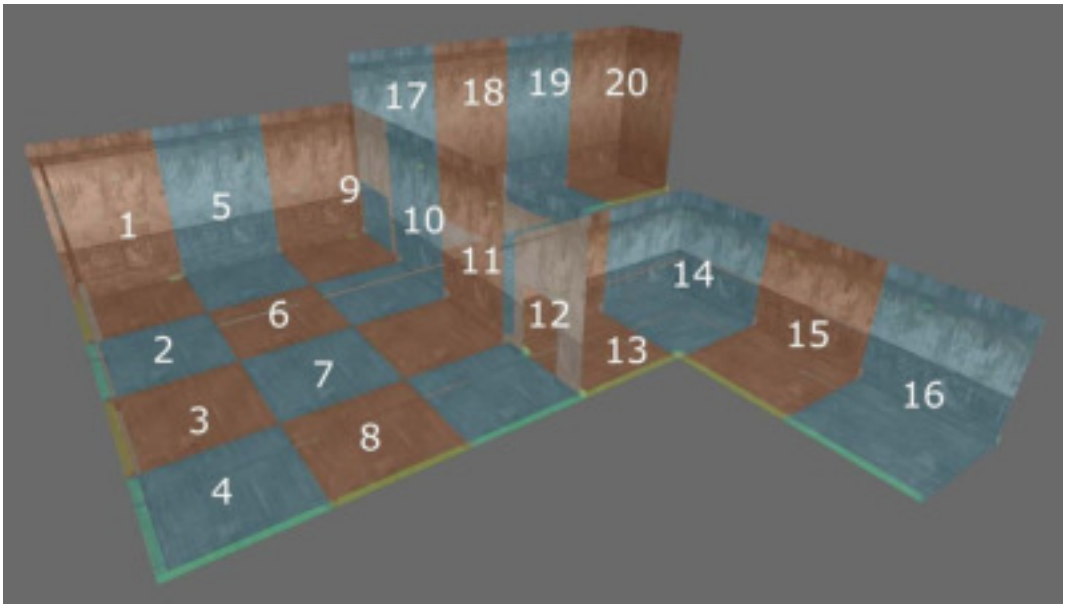

Figure 7: Modular game environments are a assemble of multiple smaller assets (Burgess and Purkeypile 2016).

When creating modular assets from photoscans, the developers of *Chernobylite* concluded that breaking the scans into non-volumetric components was not a feasible approach. Instead, the team decided to adopt volumetric modularity, the equivalent of using prefabs with traditional methods. Each room was treated as a modular block, and rooms could be repeated within and between buildings as needed. The corridors connecting the modules were traditionally modeled, as artists struggled to reconcile the dimensions of real-world passageways with optimal game requirements. Games favor doorways, corridors, and stairs that are wider than their real-world counterparts, as well as higher ceilings. This helps with character navigation within enclosed environments, minimizing unwanted collisions and clipping of character-environment meshes (Pazdur 2018).

Photoscanning architecture is further complicated by the lack of experience of the game industry securing permission for the ingame representation of real-world locations, a process aggravated by laws that are out of date with current technology. This is not limited to games: services such as Google Street Map also struggle to distinguish between what is public access and how far the rights of private property can be extended to digital representations (Judge and Brown 2018). Recently the residents of rue Crémieux in Paris petitioned the prohibition of filming and tourist photos after the mostly residential street became the target of over-tourism due to its popularity in Instagram (Le Foll 2018). It is reasonable to expect that as the use of photoscanned game environments expand, developers will have to become increasingly aware of securing legal permissions and copyright agreements. Here, racing game developers are ahead, already used to licensing the use of cars and racing teams. Regarding the portrayal of well-known racing tracks in *Project Cars 2* (Slightly Mad Studios 2017):

> *A fascinating element of starting this phase is the licensing process, because car companies have licensing departments, but tracks don't. So, Rod says it's tough getting in touch with circuits sometimes and receiving responses. So, the developers have to massage their motorsport contacts to find the right person to chat with. Once a dialogue has begun, the planning can start* (Leslie 2017).

Challenges aside, game representations of real-world locations tend to be positively received by gamers, who often embark on scavenger hunts in search of the locations that inspired the gameworld, as witnessed in the follow-up of *The Vanishing of Ethan Carter* (Mateusz 2014). When Notre Dame was damaged by fire in April 2019, Ubisoft made their game *Assassin's Creed Unity* (Ubisoft 2014), set in Paris, available for free so the public could connect with the famous landmark through its ingame representation (Ubisoft 2019). Games can also provide access to locations that players would otherwise be unable to experience, as in the example of *Chernobylite* described previously. At the same time, a meaningful discussion about the ingame portrayal of locations of high sociocultural value is lacking, including the ethical consequences of gamers interacting with these locations in ways that might be perceived as disrespectful by their cultural guardians (Statham 2019).

CONCLUSION

In 2014 photogrammetry was a relatively unknown technology in game development; five years later, it has become a desirable feature. While twenty-six games featuring photoscanned environment assets in a five year period is a small percentage of the game market, the caliber of these games tells a different story. In particular, among the AAA titles that have adopted photogrammetry are well-known and long-established franchises: *Battlefield*, *Call of Duty*, *Elder Scrolls*, *Far Cry*, *Final Fantasy*, *Forza* and *Resident Evil*. Combined, these franchises amass over 70 games (excluding expansions) spanning over two decades, and in the case of *Final Fantasy*, since 1987. That their developers have chosen to take a risk with a new and still relatively untested technology is a clear vote of confidence on photogrammetry.

Their publishers — EA, Activision-Blizzard, Bethesda, Ubisoft, Square Enix, Microsoft and Capcom — hold over a hundred development studios worldwide, employing tens of thousands of game developers, and it is common among these studios to share technologies between projects. This has already happened with photogrammetry at EA and Ubisoft. Nor is technology shared on a top-down basis only: the games industry has a high lateral movement, with individuals commonly switching between studios both locally and internationally, bringing with them a wealth of knowledge, including in this case the use of photoscanned environment assets.

As more games adopt photogrammetry, a question that must be asked is how to craft a unique visual identity using photoscanned assets. Certain genres are already derogatorily described as reality simulators, and as photogrammetry facilitates the quest for realism, it becomes ever harder to distinguish between games within the same genre, as exemplified in Figure 8.

Figure 8: Left, Battlefield V; right: Call of Duty: Modern Warfare (2019).

Here, indie developers are finding creative solutions. *Dreadful Bond* partners with a well-known horror cinematographer to add artistic value and carefully scouts locations that enhance the game's mood. *Beautiful Desolation* uses photogrammetry to scan miniatures for a distinctive visual style. *Chernobylite* is intentionally set in an inaccessible location of high sociocultural value.

How to add artistic value is not the only challenge. Whereas photoscanned props and natural environments are becoming viable production pipelines, photogrammetry for architecture remains underexplored. This is further complicated by the fact that real-world interior dimensions are not optimal for gameplay, and narrow passageways can promote visual and navigation bugs. Without modularity, photogrammetry for architecture remains limited to small structures and a handful of key locations, as observed in the games identified in this study. While modularity remains unresolved, one observes an increasing disparity between the visual quality of natural and architectural environments within individual games, as in this example in Figure 9 from *Call of Duty: Modern Warfare (2019)*.

Figure 9: The difference between photoscanned and traditionally modelled assets within the same game can be visually jarring, as observed in *Call of Duty: Modern Warfare.*

While developers focus on the technical aspects involved in integrating photogrammetry into game environments, broader legal and ethical questions remain unaddressed. At the moment, as the majority of photoscanned game environments focuses on natural subjects, it is easy to gloss over questions of legal and ethical ownership of photoscanned representations. However, these are questions that need to be addressed as photogrammetry expands to man-made props and structures. Game development is already riddled with backlashes against games that feature real-world locations without permission of their cultural guardians, varying from negative press-

coverage (Atkinson 2017) to imprisonment of members of the game development team (Gera 2013). The level of realism that photogrammetry brings to game environment assets and the intrusiveness of photo capturing existing locations naturally exacerbates these issues. Nor do laws appropriately cover the extent of private ownership and copyright protection when it comes to the digital representation of real-world property (Judge and Brown 2018), whether they are buildings and locations (such as the car tracks discussed earlier), or smaller items such as artwork and furnishings. Until laws are expanded to reflect the scope of digital technology today, games and other media developers are reduced to battling through red tape to obtain case by case permissions, or risk an "ask for forgiveness" approach. Both alternatives are costly and difficult for smaller developers.

The five years since *The Vanishing of Ethan Carter* indicate that photogrammetry for environment assets is already popular with the public and increasingly sought by developers. However, the fact that only twenty-six published games in a five-year period featured photoscanned environment assets also indicates that the technique is still at its infancy. There is a disparity between the popular perception of photogrammetry as an infallible and highly automated process with the reality of game development. Photoscans with high enough quality to produce game meshes are time consuming and expensive to capture and store. The post-processing workflow, while promising, is still labor-intensive and requires skilled game artists. And although over-inflated popular expectations pressures developers to meet unrealistic standards, studies have shown that inflated expectations can push the hype cycle of a technology towards a productive long-term outcome (van Lente, Spitters, and Peine 2013).

There are still technical and artistic obstacles to overcome, as would be expected for a technology that is still relatively new in game production. On the one hand, photogrammetry for common assets is facilitated by ever-increasing third-party libraries. On the other hand, photogrammetry for custom assets requires developers to consider aspects that are new to game: careful location scouting, selection of subjects based on mood and intention, and legal permission to reproduce real-world locations ingame. With the upcoming release of a new generation of consoles in 2020, it will be interesting to see what impact the extra hardware will have in enabling the high-quality graphics obtained via photogrammetry. It is safe to say that the next five years, as photoscanned assets are further developed and incorporated into game production, is likely to be a creative period for both developers and gamers.

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ENDNOTES

[1] Based on the most common use.