Research on Frontier Applications of 3D Printing in Autonomous Vehicles

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Abstract: 3D printing has become increasingly popular in the automobile industry. It contributes to rapid integrated manufacturing of complex components and lightweight components. It is widely used in producing prototypes because of the practical functionality of the prototype produced in this way, which can be modified quickly based on computer-aided design (CAD). Currently, 3D printing has been widely used in vehicle designing for producing prototypes. Some companies apply 3D printing to produce whole car for most of its components in small batch production. This article analyzes and prospects the current and future applications of 3D printing in the industry based on literature review and relevant examples. In this paper, 3D printing technology of the automobile industry is systematically summarized. The application status of various routes of 3D printing technology in automobile design and manufacture is analyzed. The advantages and limitations of various 3D printing technologies in the design and manufacture of specific automobile parts are discussed. Further, the possible ways of applying 3D printing technologies to autonomous vehicles in the future are explored. This study provides a systematic reference for the exploration of related fields.

Keywords: 3D printing; Autonomous driving; Automotive engineering

1 Introduction

Autonomous driving has received growing interest for the convenience to the public in relevant markets. In response, producers in the industry compete to take the lead in improving the degree of autonomous driving and designing of body and components of autonomous vehicles. 3D printing plays an important role in prototype production for testing. Seven categories of 3D printing technology were defined in the ISO/ASTM 52900:2021 additive manufacturing by the international organization for standardization (ISO) and the American society for testing and materials (ASTM) [1]. Powder bed fusion, binder jetting, and material extrusion are suitable for vehicle manufacturing. Powder bed fusion is the most widely used one, which fulfills the high requirements of some components for mechanical performance such as ductility and yield strength [2].

3D printing can eliminate the intrinsic delay for vehicle designing caused by Handcrafted clay models and mold development, possibly months. Using a

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combination of 3D printing and component placement robots can produce prototypes with the function as same as the final mass-produced products despite some predictable differences in appearance [3]. Moreover, several benefits can be provided by 3D printing in vehicle manufacturing. Components with complex shapes can be produced as an entire body rather than an assembly of multiple small parts with reduced costs and time consumption [4]. 3D printing can be used to produce lightweight components helping to reach higher speed and lower fuel consumption. It is also superior to traditional manufacturing processes Testing instruments and specialized workpieces without the high average fixed cost of mold in small batch production. However, it cannot replace the whole manufacturing process but rather optimize several aspects of the process, because of its high cost in mass production, especially for some key components (e.g., electrical machinery).

Most of the vehicles in international markets are between L2 (partial driving automation) and L3 (conditional driving automation) in the autonomous driving standards developed by the Society of Automotive Engineers [5]. The broad development prospects of autonomous vehicles can indicate its trend of updates and replacements. The competition in the market encourages the producers to launch new generation products at a faster speed.3D printing is also used for manufacturing sensors needed in autonomous vehicles [6]. Therefore, the benefits of applying 3D printing technology to vehicle designing and manufacturing, including accelerating development efficiency and reducing costs for trial production can be amplified.

The current application of 3D printing in the automobile industry is limited to manufacturing prototypes and small-batch production of a few components. Its high cost and time consumption make it difficult to effectively combine with Computer numerical control machine tools (CNC) widely used in the industry. The review aims to introduce the concepts and advantages of 3D printing technology and analyses its application in autonomous vehicle designing and manufacturing with examples. The review provides feasible application ideas for vehicle designing and manufacturing based on examples.

2 3D Printing Technology and its Advantages

2.1 The Concepts and Principles of 3D printing

3D printing, or additive manufacturing, is a technique of constructing objects through layer-by-layer printing using adhesive materials (e.g., powdered metal or plastic).3D printing creates physical objects from computer graphic data of CAD. Its concepts grow rapidly with more kinds of raw materials available, more diverse techniques, and broader application scenarios, which means that its defects and limitations keep shrinking [4]. It is gradually replacing milling, casting, or turning in increasing parts in the vehicle casting process, from functional prototypes to small batch production, and then to aftermarket and spare parts [4].

ISO and ASTM defined 3D printing in seven categories: vat photopolymerization (photocurable polymers), material jetting (metals, ceramics and photocurable polymers), material extrusion (generally thermoplastics), binder jetting (generally metals or ceramics), powder bed fusion (metals and polymers), directed energy deposition (metals and ceramics), sheet lamination (paper, plastic, metal, composites) [7]. They have different features in materials, costs, and time consumption.

The top three famous industries in current for 3D printing are aerospace and defense, medical and dental, automotive and electronics, while mechanical and plant engineering is predicted to have great potential [8]. Its most famous applications are prototyping, proof of concept, and production [8]. Plastics, resins, and metals are the most common materials used in 3D printing [8].

The biggest difference from traditional manufacturing of vehicles is that 3D printed cars first print out a single, integrated body, and then fill in other components, rather than assembling the various parts of the body together.

2.2 The features and advantages of 3D printing

3D printing impacts the world by enabling to manufacture of complex products, improving industrial efficiency and quality, protecting the environment, and boosting the economy. The characterizations of its products include a relationship between the structure, properties, performance, and manufacturing process. There are many ways to find the characterizations in different factors: Powder and material characterization.

Predicts the compaction of the powder and affects the density of the part and the possibility of defects from the size distribution of the powder used. Defect and inner inspection detect the quality of the build influenced by the quality of powder including voids and impurities to determine process parameters influence. Surface and dimensional quality inspections ensure proper assembly and functionality of the part by scanning the surface of the product. Dimensional accuracy is critical to ensure the functionality of the product with a comparison of the product to the CAD models.

The main advantages of 3D printing in the manufacturing process can be summarized by increasing efficiency in minor manufacturing, decreasing costs, and printing complex-shaped components and lightweight components. Customized manufacturing and prototype production are suitable for 3D printing because there is no expensive fixed cost for 3D printing and the products can be rapidly produced and modified through CAD models. Many large products (e.g., bridges) and complex structural components] can be produced as a whole body by 3D printing to reach better performance. Moreover,3D printing can decrease the mass of the product by choosing proper materials (e.g., aluminum and titanium alloys), which is helpful to decrease the usage expenditure (fuel costs for vehicles) of the products.

The drawbacks of 3D printing are indicated in mass production. It cannot replace CNC in mass production due to its high average costs and low speed, rather is used to optimize some parts of CNC. Sometimes its limited kinds of materials cannot be accepted by manufacturers. Moreover, even though the complexity of parts that 3D printing can manufacture is much higher than CNC, the machining accuracy of CNC is greatly higher than that of 3D printing.

3 Application of 3D Printing in Autonomous Vehicle

3.1 3D Printing in Autonomous Vehicle Designing

3D printing can accurately convert CAD models into physical objects in hours or days. Compared to the conventional plastocene model, the prototype made by 3D printing is more precise and can run like the final product. More choices of materials are available for 3D printing to get different mechanical performances for precise functional prototypes. The designers can find the deficiencies in their models and verify improvement ideas quickly.

Most of the vehicles in the markets are between L2 and L3 in the autonomous driving standards developed by the Society of Automotive Engineers shown in Table 1 [5].

Table 1. The autonomous driving standards developed by the Society of Automotive Engineers [5]

Level	Name	Narrative definition	Dynamic driving task (DDT)		DDT fallback	Operational design domain (ODD)
			Sustained lateral and longitudinal vehicle motion control	Object and event detection and response (OEDR)		
Driver performs part or all the DDT						
0	No Driving Automation	The driver is responsible for the entire DDT, including the presence of active safety systems.	Driver	Driver	Driver	N/A
1	Driver Assistance	The driving automation system is only responsible for the continuous and ODD specific execution of one of the lateral or longitudinal vehicle motion control subtasks for DDTs, and the remaining part of the DDT is executed by the driver.	Driver and System	Driver	Driver	Limited
2	Partial Driving Automation	The continuous and ODD specific execution of the horizontal and vertical vehicle motion control subtasks for DDTs in the driving automation system requires drivers to complete the OEDR-subtasks for	System	Driver	Driver	Limited

		targets and events and supervise the driving automation system.				
ADS ("System") performs the entire DDT (while engaged)						
3	Conditional Driving Automation	ADS is responsible for the continuous and ODD specific performance of the entire DDT, and it is expected that DDT fallback-ready users must accept intervention requests issued by ADS, handle and respond to system failures related to DDT performance in other vehicle systems.	System	System	Fallback-ready user (becomes the driver during fallback)	Limited
4	High Driving Automation	ADS can independently execute the continuous and ODD specific performance of the entire DDT and DDT fallback without expecting users to respond to any intervention requests.	System	System	System	Limited
5	Full Driving Automation	The sustained and unconditional (l.e., not ODD-specific) performance by an ADS of the entire DDT and DDT fallback without any response from users.	System	System	System	Unlimited

3.2 3D Printing in Autonomous Vehicle Manufacturing

3D printing has advantages in small batch production, complex-shaped component production, and lightweight production. In the field of automobile manufacturing, the earliest to adopt 3D printing technology was the racing teams of manufacturers, which meets the three descriptions mentioned.

The three categories of 3D printing suitable for metals in vehicles are powder bed fusion, binder jetting, and material extrusion.

Powder bed fusion selectively melts or sinter powder materials to construct 3D-printed structures [8]. It can quickly and accurately prepare metal components. Its characteristics include integration, high precision, and complex manufacturing. As an example, Porsche 3D printed the 911 GT2 RS piston integrating a closed cooling pipe inside the piston head to enhance the heat resistance. Powder bed fusion requires a high-power heating source and building room without reactive gas [9]. Its relatively low yield and high cost both for the equipment and its usage limit its few applications in high-end brands.

Binder jetting uses an ink-jet print head to spray adhesive into the powder, thereby bonding a layer of powder in the selected area, layer by layer, to create a three-dimensional structure of the component. Binder jetting has several advantages. It works at room temperature and can deal with any powder material with varying particle sizes [9]. Composite structures with multilaterals can be manufactured [9]. For example, different levels of porosity can be achieved by purging out sacrificial powders [9]. Binder jetting is also suitable for prototype production, and desktop binder jetting based on extrusion has a convenient design for office work, eliminating the risk of dust and laser exposure, and providing a more user-friendly end-to-end solution [10].

Material extrusion distributes materials from the pressurized injector on the gantry system. It moves the construction platform or index print head downwards before the next layer is added [10]. Its most prominent features are fast printing speed (tens or even hundreds of times of powder bed fusion) and low cost for the equipment and the traditional powder used as same as the one used in metal Powder Injection Molding Technology [11]. Therefore, it has the potential to achieve mass production of metal 3D printing. One widely used kind of material extrusion is Fused Filament Fabrication (FFF), which does not provide excellent resolution and surface finish [8]. It can deal with the printing of metal-loaded filaments and sometimes several high-temperature thermoplastic plastics [8].

Autonomous vehicles include many different types of sensors and processing computers linked with blockchain [8]. 3D printing has become a key participant in manufacturing sensors [6]. Aerosol jet printing (AJP) technology, a kind of material jetting has many advantages compared to traditional inkjet and screen printing used. AJP can print on 3D surfaces due to its 5-axis platform with higher printing resolution [6].

3.3 Analysis Based on Typical Examples of Application of 3D Printing on Autonomous Vehicles

LM3D Swim. LM3D Swim is the first 3D printed electric vehicle around the world developed by Local Motors.75% of the vehicle's components are 3D printed, including all chassis and body parts. The materials used include 80% Acrylonitrile Butadiene Styrene (ABS) mixed with 20% carbon fiber. ABS is a thermoplastic polymer material with high strength, good toughness, high-temperature resistance, and easy processing. It is often used to manufacture plastic shells.

Big Area Additive Manufacturing (BAAM) is a kind of material extrusion using large-sized granular materials. The facility used by the company has a size of approximately 4.0 x 2.0 x 0.9m. The entire car is shaped by a nozzle spraying molten resin with a thickness of about 8mm (20 times the nozzle width used in FFF). The movement distance of the nozzle per second is 76mm. The coarse body parts still need to be additionally machined by 5 Axis Machining (a mode of CNC Machine

Tool Processing) to enhance the shape precision of the assembly parts and show a smooth appearance.

Olli. Olli is a self-driving vehicle produced in collaboration with manufacturers of International Business Machines Corporation and Local Motors. The former provides the computer system Watson, and the latter is mentioned as the company that manufactured the first 3D-printed electric vehicle. It has provided commuting services for people in some regions of the United States and Germany with a load capacity of 12 people and a top speed of 25km/h. It has the function of converting between speech and text. It has a 3D-printed shell with a chassis. Its manufacturers also designed, 3D printed, and integrated some additional windshield wiper upgrades to meet policy in European projects.

Tesla Model Y. Tesla is the leader in the current international market of electric and autonomous vehicles. Autopilot, its autonomous driving system has already managed autonomous driving assistance with advanced safety and convenience features. Meanwhile, the new Tesla vehicles are equipped with the hardware necessary to achieve fully autonomous driving in many future situations. Its vehicles have eight cameras and powerful visual processing capabilities to achieve a 360-degree field of view, with a monitoring distance of up to 250 meters for the surrounding environment shown in Fig. 1.

Tesla introduced the Unboxed Assembly Process which is the latest application of integrated body die-casting technology that redesign and die-casts multiple independent parts into complete components. The technology can simplify vehicle structure, reduce weight, improve production efficiency, shorten the production cycle, and enhance vehicle reliability and performance. Its actual impact includes reducing the production cost and factory space. Such techniques are very suitable for substitution by 3D printing which can produce complex shaped components rapidly. In fact, a 3D printed part is found in the disassembly video of Tesla vehicles, possibly to solve a defect of the original mold and avoid delaying the launch, thus utilizing the advantages of flexible and fast iteration of 3D printing technology.

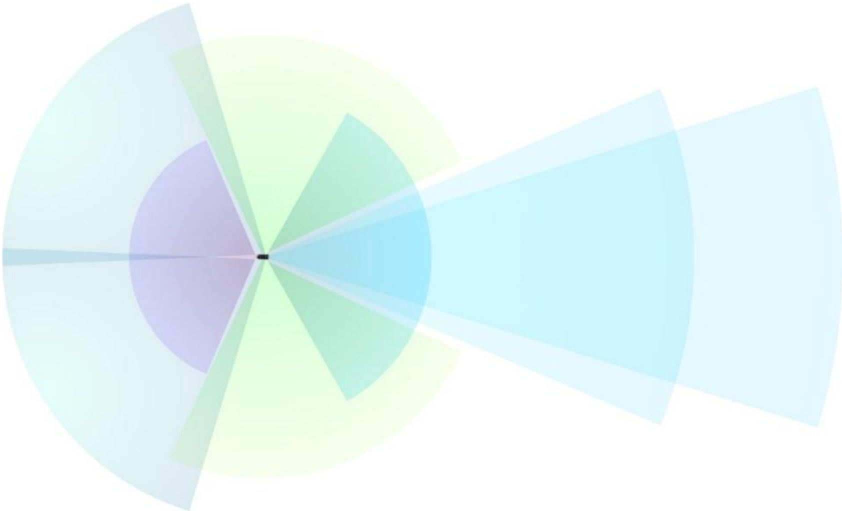

Fig. 1. Detection range of cameras in Tesla vehicles (with a monitoring distance of up to 250m [12].

4 The Prospect of 3D Printing Applied to Autonomous Vehicle

Many car companies are following up on integrated die-casting technology. It suggests the wide prospect of 3D printing in vehicle manufacturing as a substitution with its advantages for producing complex shaped components rapidly and its flexibility helpful in prototype and component producing. The position of 3D printing in vehicle design is still rising. When relatively cheap techniques of 3D printing such as BAAM are used, additive machining of CNC can provide a good combination of traditional manufacturing way with high efficiency and low cost suitable for medium batch production, meeting the one of greatest advantages of integrated die-casting technology in low cost.

5 Conclusion

The article reviews the established 3D Printing used in automobile industry and its combination with CNC is widely used in current vehicle manufacturing and provides specific insights into the features and application direction of different categories of 3D printing technology.

The three categories of 3D printing suitable for use in vehicles are powder bed fusion, binder jetting, and material extrusion. Powder bed fusion is consuming in cost and time, thereby it is commonly used in producing prototypes for vehicle designing, especially in small batch, high-value applications. Binder jetting is also suitable for prototype production, and it can work at room temperature, so it has a convenient office design without the risk of dust and laser exposure, providing a more user-

friendly end-to-end solution. Material extrusion has a low cost for the equipment and powder which is also used in traditional metal powder injection molding technology. Therefore, it has the potential to achieve mass production of metal 3D printing. A combination of making a coarse body with BAAM and then additionally machined by 5-axis machining has been applied in the first 3D-printed electric vehicle mentioned. With the trend of integrated die-casting technology, 3D printing has broad prospects in this way meeting the significance of integrated die-casting at a low cost.
The article introduces basic concepts and features of 3D printing and analyzes the application of three principles of 3D printing suitable for the automobile industry with different advantages and application directions, thereby providing possible ways for 3D printing to be applied in the automobile industry in the future to compose more efficient and inexpensive mass production. The article concentrates on the way of applying 3D printing in the designing and manufacturing of autonomous vehicles but does not provide a practical automobile manufacturing plan in detail because of the limitation of experimental equipment. The author hopes that future research provides feasible plans of replacing a part of conventional manufacturing with 3D printing with computable budgets.

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