Applications of 4D Point Clouds (4DPC) in Digital Twin Construction: A SWOT Analysis

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Abstract: Digital twin construction (DTC), the virtual replica of physical construction, is an essential enabler for the promised Construction 4.0. Thanks to its real-time virtual-physical synchronicity, many uncertainty-tolerant functions, and applications, such as system integration, testing, monitoring, and maintenance, could be dynamically simulated and optimized through the DTC. The data foundation for creating or updating a DTC is real-time reality capture on construction sites. Despite a lot of efforts such as the Internet of Things (IoT) and AI cameras, so far, it is very challenging to capture the spatial-temporal information of the whole construction site. Time-dynamic 4D point cloud (4DPC) is an emerging sensing technology consisting of three-dimensional point cloud scans at a frequency, e.g., two frames per second. 4DPC has been successfully used in several industries, such as autonomous driving and motion analysis in sports science, due to its ability to capture dynamic objects and environments. This paper presents a strengths, weaknesses, opportunities, and threats (SWOT) analysis of the possible applications of 4DPC in DTC. In summary, 4DPC can effectively capture the dynamic feature of construction progress, with strengths in real-time information updating, covering more precise geometry dynamics, and providing localization and mapping information, etc., which are in line with the development of DTC. Meanwhile, the disadvantages include errors or noise in recognizing lign-permeable materials and water, enormous data volume, challenges in modeling spatial-temporal structure, and computation load in processing. The 4DPC receives several opportunities, such as establishing a dynamic data foundation for construction automation and modeling of workspace and integrating with 4D BIM for creating DTC; However, threats such as LiDAR-hostile weather and emerging competitors are also identified. Overall, 4DPC is a promising research direction that may interest DTC researchers and practitioners for various application situations in the construction industry.

Keywords: 4D point cloud; Construction; Digital twin; Digitalization and automation; SWOT analysis.

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1 Introduction

Digital twin, representing a physical system or process by a real-time virtual system to enable simulations, analyses, and optimization, has been adopted by several industries, such as the aircraft and manufacturing industry. The digital twin has been introduced into construction to ensure more automatic, faster, and more collaborative processes in recent years[1]. The purpose of the construction digital twin (DTC) is to improve existing construction processes and enrich current building-related models (i.e., building information modeling (BIM))[2]. Within the context of cyber-physical synchronicity, the digital twin models should have the ability to reflect the construction of physical assets in real-time. However, most current DTC models, such as BIM models, are static and cannot be updated in real-time, which cannot meet the demand of the modern construction projects with the increasing complexity and increasing number of involved parties. One of the main reasons is that current measures in construction site sensing for reality capturing are restricted to routine laser scanning, manual management updates. Some advanced digital modeling and simulation technologies could not be fully utilized if the dynamic feature of construction progress could not be effectively captured. Therefore, a real-time DTC modeling approach that is fast, inexpensive, reliable, and automated is required. The technique should be able to rapidly create and update accurate, comprehensive, semantically rich models in a master format that can be used to any engineering situation and is broadly applicable to all building projects.

Sensors for spatial data have developed over the last several decades from basic range sensors based on sonar or IR, which provided a few bytes of information about the environment, to ubiquitous cameras and laser scanners[3]. Recent advances in LiDAR technology have made it possible for these sensors to produce high-quality 3D reconstructions of the world: point clouds[4]. Point clouds, a three-dimensional collection of data points or coordinates, provide more information than two-dimensional pictures and are insensitive to light[5]. Compared to other geometric representations like grids, point clouds do not experience quantization mistakes as much[6]. In most cases, point clouds always refer to 3D point clouds, the phase that comes before creating an accurate 3D model of the actual environment. 3D point clouds have already been widely used in many research and industrial domains, such as surveying, electricity, construction, and industry, due to their excellent ability to represent our three-dimensional world. In the construction industry, the 3D point cloud is currently used for various aims such as as-built building reconstruction and geometry quality inspection[7-9]. It should be noted that the application of 3D point clouds is limited in capturing some static objects due to only spatial information contained in the data.

The advent of the 4D point cloud, consisting of three dimensions and time information, has expanded the application of the point cloud into a dynamic world[10]. The most significant improvement of a 4D point cloud compared with a 3D point cloud is that temporal structure is added to data. The 4D point cloud, a window into the dynamics of the 3D world we live in, is a rich source of visual data that demonstrates how objects move against backdrops and what occurs when we take action[11]. There are some reasons why the 4D point cloud has gained popularity since it appeared. First of all, the ability to comprehend a changing 3D world is essential for robotic agents and a variety of other applications. In addition, various identification tasks, such as calculating a moving object's acceleration or identifying human activities, benefit from temporal data sequences longer than two frames[12]. The current popular 4D point cloud research and application fields include but are not limited to autonomous driving, robot vision, human-robotics interaction, simultaneous localization and mapping (SLAM), and motion analysis in sports science. For instance, autonomous agents need to use 4D point clouds to understand the dynamic 3D environment in many applications, such as robotic manipulation[13].

As an effective sensing technology for dynamic environments, the 4D point cloud (4DPC) has the potential to promote the development of the digital twin of the construction industry. The 4DPC could help achieve the 4D modeling, making it possible to represent, examine, and evaluate all processes associated with construction, such as graphical models, management, resources, and safety concerns, from a temporal viewpoint. The dynamic digital twin model may provide a new way to view some applications such as lean construction, site monitoring, safety or environmental aspects.

Given its great potential for application in construction, as briefly illustrated in Figure 1, this paper analyzes strengths, weaknesses, opportunities, and threats of 4DPC in construction application sceneries.

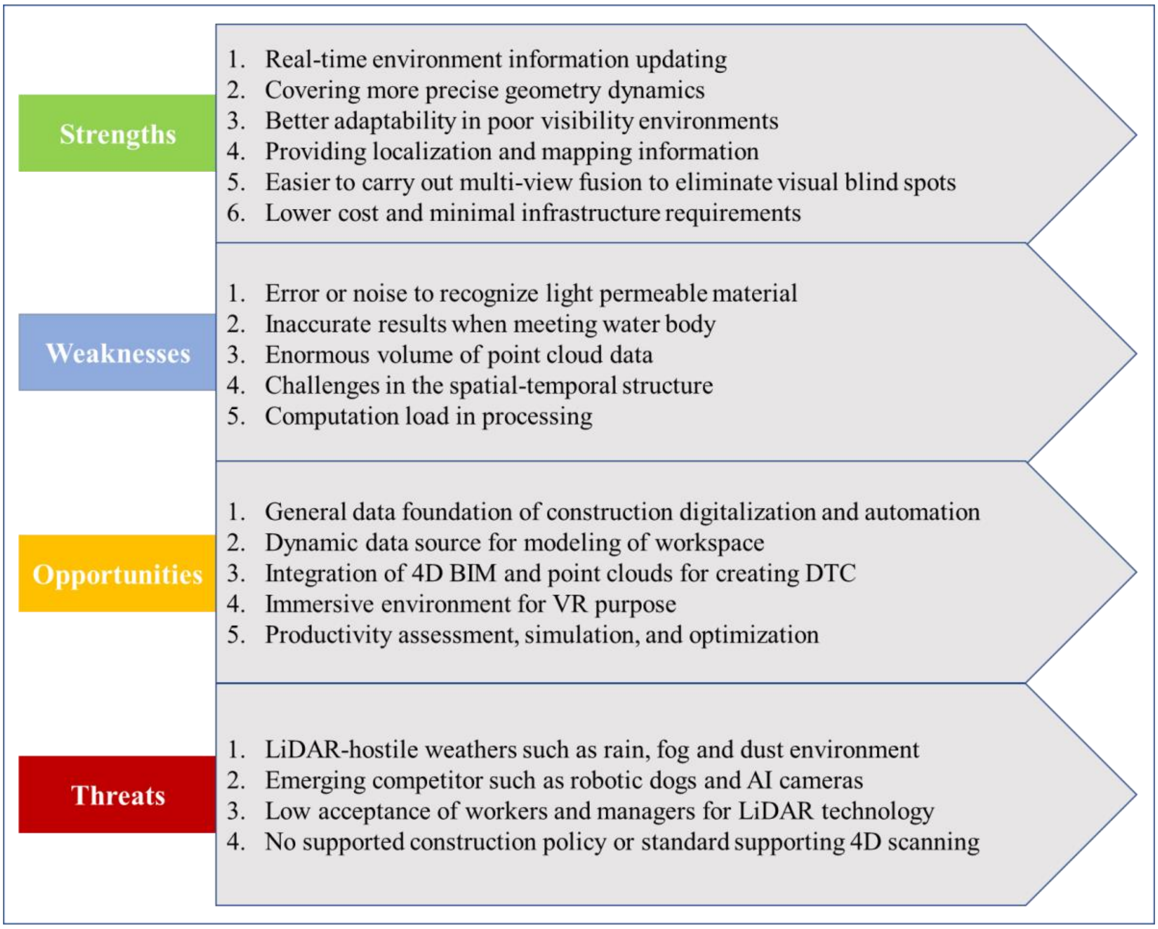

Figure 1 Summary of key findings from SWOT analysis

3 Strength

As 4DPC data records the additional time dimension compared with the 3D point cloud, it can help update real-time environment information[12], which is essential for continuous and disorderly changing construction scene. To facilitate machine automation and digitalization management in construction site, it is crucial to understand dynamic 3D environments for robotics agents and many other applications. 4DPC could offer an effective measure to construct and update the dynamic environment modeling, which could serve for the automation application.

Compared with conventional videos that are widely used in monitoring and detection work, the 4DPC shows its advantages in covering more precise geometry dynamics[11]. The reason behind that is point clouds do not suffer as much from quantization errors compared to other geometric representations such as grids. Therefore, point cloud video is more suitable for some applications requiring dynamic detail detection, and typical instances include calculating the acceleration of a moving object or identifying human activities. For human action recognition, one typical application of 4DPC video is to analyze the technical action of the professional athlete, and another one is to help robotics understand human-to-robot gesture instructions in human-computer interaction.

Another advantage of point cloud video compared with conventional video is good adaptability in poor visibility environments[11]. Point cloud video exhibits its advantage over conventional image-based video for some applications, including low-light work environments at night, such as autonomous driving and construction site monitoring. The strength is that point cloud Lidar is an active system generating light, while conventional video requires an external light source.

In addition, the 4DPC could provide localization and mapping information due to its principle of signal acquisition and the coordinate information contained[14]. Specifically, it could serve for simultaneous localization and mapping (SLAM), an algorithmic effort to solve the issue of mapping an unknown area while navigating that environment using the map.

It is easier and more efficient to acquire the full-view spatial-temporal data of the whole environment using a set of 4DPC LiDAR. On the construction site, mechanical equipment, material accumulation, and as-built buildings can cause visual blind spots if a single sensing device such as a camera or LiDAR is used. Therefore, multiple LiDARs must be combined to eliminate the visible bind spots. Compared with other video resources, such as image-based video, the alignment complexity for multi-source point cloud data is lower.

Finally, compared with other sensing devices such as 360° virtual reality cameras, Internet of Things (IoT), and Real-time kinematic positioning (RTK), the cost of common 4D LiDAR Sensors such as Livox is low. For example, the price of a high-performance LiDAR designer for L3/L4 autonomous driving is about 1299 USD, while the price of the basic version of the virtual reality camera (Insta360 Pro 2) is around 5280 USD. Therefore, the low cost and minimal infrastructure requirements could be a strength of the 4DPC to be used in the construction sector.

3 Weaknesses

For some building materials, such as glass, LiDAR waves may pass wholly or partially transmit through the material. The possible result is no reflected wave is collected or a large number of virtual points are collected, which depends on the light transmittance of the material[15]. If no point is generated, point cloud data cannot cover the object composed with a light-permeable material. If mobile robotics relying on LiDAR for navigation cannot recognize them as obstacles, some unexpected collision can happen. In addition, virtual points' reflection noise may negatively impact 3D reconstruction and other related techniques.

In addition, LiDAR waves may experience refraction when meeting water bodies; thus, the acquired point cloud is not accurate in those locations[16]. The problem is first discussed in autonomous driving since the road's puddle is always considered an infinite black hole. Because there is often stagnant water after rain on the pavement or component surface in the construction site, the use of 4DPC also needs to be concerned about such issues. Otherwise, some unexpected errors may be caused without awareness.

Enormous data volume is a critical issue in the 4DPC[17]. For LiDAR with higher scanning density and scanning frequency, the amount of data acquired per unit time is also more significant. Although much research on point cloud video systems focuses on data compression of the point cloud, the large size of 4DPC still puts higher requirements for storage systems and transmission systems.

The processing of stationary 3D point clouds may be done using a variety of methods. However, 4DPCs have unique characteristics that cannot be handled by these conventional methods[18]. Modeling the Spatial-temporal structure, such as 3D action recognition or 4D semantic segmentation, in a 4DPC is highly challenging because random and unordered coordinate sets inconstant point cloud density of individual regions over time and inconsistent points emerging across different sets/frames.

Meanwhile, achieving real-time processing of 4DPC is compute-intensive due to large data volumes and complex modeling processes[19]. For a disordered environment such as a construction site, even some basic processing procedures such as point cloud segmentation can be challenging to achieve real-time or near-real-time completion.

4 Opportunities

Digital 3D environments are already crucial components of construction and are on the critical route to complete end-to-end site autonomy, but existing solutions lack real-time functionality[20]. Using 4DPC, the digitalization construction environment could be real-time established and updated. Therefore, the 4DPC provides a chance to create a digital twin of the construction site. First, It may serve as a platform for the digitization and automation of the construction industry, which is necessary to encourage the use of automation and autonomy in the sector.

Second, a series of 4DPC LiDAR could help establish dynamic workspace modeling of the construction site. The real-time updating modeling is crucial for giving operators of heavy equipment, such as cranes, real-time support, including danger identification, collision avoidance, and 3D visualization[21]. The real-time environment updating enables operators to quickly detect their surroundings and perform manipulation activities safely and effectively. In addition, a site safety alert system could be established using dynamic modeling based on a 4DPC, and it has the potential to help reduce the construction fatalities such as being struck by a moving vehicle.

Third, the 4DPC could help create the 4D building information modeling (BIM), which enable users represent, evaluate, and analyze all aspects of the BIM process (graphical models, management, costs, resources, safety issues, etc.) from a temporal perspective[2]. The 4D BIM could help achieve dynamic management assignments such as progress monitoring and checking of construction projects. In recent years, although BIM models have been widely adopted in construction projects and have become necessary in the design stage in many countries and regions, they are not effectively used in the construction stage. One important reason is that there is no effective method to bridge the dynamic construction site with the BIM models. The use of 4D BIM will improve the current situation.

In addition, by integrating with Unity3D, a versatile 3D engine to enable the user to view and interact with the environment, the 4DPC could provide a virtual reality (VR) platform for remote managers to have an immerse experience in the construction site. Such experience could help increase the collaboration efficiency of different parties and help them make optimal decisions according to the site's real-time situation.

Finally, 4DPC records could be used for productivity assessment and optimization. Benefiting from full-view monitoring of construction sites, the movement path of workers and machine facilities could be extracted and analyzed. The productivity of different roles could be assessed, and optimization work could be conducted for a similar construction project in the future.

5 Threats

Point cloud Lidar is mainly used to detect environmental information in different scenarios in unmanned applications. However, point cloud lidar would have a poor performance in rain, fog, and dust environments due to its inherent characteristics of Lidar[22]. It will recognize rain, fog, and dust as physical things such as obstacles. The root cause of this problem is that there will be reflections when the beams of several Lidars hit rain, fog and dust, LiDAR observation would become noisy owing to the reflection and attenuation of raindrops, or even LiDAR will judge that the rain, fog, and dust are obstacles, resulting in misidentification. Misidentification caused by rain, fog, and dust has become problematic in Lidar applications. The above are the common problems of point clouds, which also occur in 4DPCs. On construction site, dust and rain may be the main threat that needs to be considered for 4DPC applications. In some special scenarios, such as the earth excavation stage or rainy day, 4DPCs should be used with caution, or other sensors need to be supplemented.

Some other emerging technologies, such as AR cameras, maybe a potential competitor of 4DPC LiDAR for reality capturing. AR camera has already been used in many areas, such as navigation and education applications[23], and also has the potential to model the real-time digital twin of the construction site.

In addition, there is no construction standard or policy for establishing a dynamic digital twin platform-based 4DPC in Hong Kong and mainland of China. The dynamic 4DPC-based digital twin will revolute the traditional schedule-based construction management strategy. The benefit and necessity of the application of the 4DPC in the construction industry need to be further explored and discussed from economic and social aspects.

Acceptance of workers and managers is also one of the factors that should be considered. In the process of 5G technology promotion, there have been civilian boycotts in many parts of the world. The main reason is that people worry about their health being affected by the signal radiation from the 5G infrastructure. A similar situation may also happen in the application of a 4DPC on the construction site since LiDAR would emit light waves toward workers.

6 Summary

In summary, the 4DPC appears to be a promising applied technology to promote the development of digital twins for the construction sector. Due to its spatial-temporal data structure, the 4DPC could update the environmental information in real time and provide more precise geometry dynamics. In addition, the unique perception mechanism of LiDAR provides a 4DPC with good adaptability in a poor visibility environment and localization and mapping functions. Meanwhile, low cost and minimal infrastructure requirements are potential advantages for application in the construction industry. However, practitioners and researchers should also be aware of the limitations, including the inaccurate result when meeting water and light permeable construction materials, large data volume, and the challenging and compute-intensive modeling process of the 4DPC. After fully understanding its advantages and disadvantages, potential opportunities are proposed from five aspects, i.e., for facilitating construction digitalization and automation, workspace assistance, 4D BIM-based construction management, virtual environment interaction, and productivity assessment and optimization. The final analyzes the possible threats of the 4DPC in construction scenarios in terms of the adaptability of the construction site, competitors' acceptance of workers and managers, and related policies.

On the one hand, as stated by Düking[24], the SWOT analysis process is inherently subjective and has several inherent limitations. On the other hand, it is anticipated that the results of this work will aid researchers and practitioners in determining the suitability and feasibility of the 4DPC for various application situations in the construction industry.

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