# Remote sensing of 4D point cloud (4DPC) for digital twin construction: A time-dynamic, occlusion-minimized data source exploiting low-cost LiDAR sensors

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**Abstract:** In the era of smart construction, many sensing technology systems, such as the Internet of Things, AI cameras, and terrestrial laser scanning, have been applied to collect data on multi-objective and highly time-dynamic construction activities on site. However, these systems are handicapped in computing for civil engineering by various issues, such as cost, data coverage, accuracy, and battery life. This paper presents a novel time-dynamic 4D ($x$, $y$, $z$ and *time*) point cloud (4DPC) data streaming system for highly time-dynamic construction activities. The 4DPC sensing device in this paper integrates an edge computer and self-driving car's low-cost LiDAR sensor at

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less than US$1,000. The 4DPC platform employs a cloud server collecting 4DPC data streams from multiple devices offline or via Wi-Fi or 5G, and visualizes the data streams on a GIS platform. In contrast with the existing technologies, the presented platform offers a novel, low-cost, time-dynamic, and occlusion-minimized 4DPC data source that opens a new avenue to various digital twin construction applications.

**Keywords:** 4D point cloud (4DPC); digital twin construction; time-dynamic LiDAR data source; sensor fusion; cloud-edge system

# 1 Introduction

Smart construction aims to adopt and develop information technology to improve productivity, reduce costs, and monitor risks at construction sites. Digital twin construction (DTC), which promises understanding and reasoning, gained increasing attention in recent years (Zhao et al. 2023). To facilitate the development of smart construction, researchers and experts focused on how to use novel sensors such as the Internet of Things (IoT), Artificial Intelligence (AI) cameras, and terrestrial laser scanning to replace a portion of management or survey work in the construction industry (Štefanič & Stankovski 2018). However, IoT sensors and AI cameras have several limitations (Liang & Xue 2022). IoT technology is vulnerable to poor networks and high costs (Al-Sharekh & Al-Shqeerat 2019), and AI cameras lack depth (Chen et al. 2017).

With the rapid development of sensing technologies, LiDAR sensing evolves swiftly for smart city applications, such as robotics and self-driving cars. There are a variety of Light Detection And Ranging (LiDAR) data, of which the time-dynamic 4D (*xyz* and *time*) point clouds (4DPC) can simultaneously collect both spatial and temporal information (Liang & Xue 2022). The LiDAR sensors also became affordable due to the scale effect. However, the volume of the 4DPC data can be huge, thereby leading to high bandwidth during transmission or local storage. Furthermore, there can be strong occlusion, or obstruction of laser 'eyesight', leading to large 'shadow' areas in the site area. Also, the common 4DPC LiDAR sensors are designed for moving objects, such as robots and cars. In summary, there is a gap in the literature on how to integrate 4DPC remote sensing into the scenarios of digital twin construction.

This paper presents a 4DPC data streaming platform to address the three limitations above for monitoring highly time-dynamic construction activities for DTC. This platform includes multiple 4DPC sensing edge devices and one cloud service. First, 4DPC data is captured by an edge computer with a self-driving car's low-cost LiDAR sensor. Then, multiple 4DPC edge devices are planned to minimize occlusion before the construction activities. Finally, a cloud server collects the 4DPC data streams offline or via WiFI or 5G with data compression options enabled. The platform's feasibility was validated with a couple of real-world pilot projects. As far as we are concerned, the multi-sensor fusion architecture of the presented 4DPC platform is the first of this kind of research, which contributes to the body of knowledge of real-time site monitoring and data source of DTC.

# 2 Related Works

There exist schools of smart technologies at construction sites, especially for large civil engineering projects. The management and coordination of construction projects using an IoT cloud-based platform were validated by real-world data under realistic conditions (Bucchiarone et al. 2019). In addition, real-time video surveillance captured by AI cameras was applied to avoid the arisen of construction accidents (Luo et al. 2020). An edge-based solution for video surveillance in the smart construction site assisted by a graph neural network was presented to address the limitations of video surveillance (Ming et al. 2022). However, the high-resolution camera has an inevitable limitation in that it cannot work at night because of the need for illumination (Vargas et al. 2021). Point clouds generated from photogrammetry and laser scanning were compared and utilized for smart heavy equipment planning (Moon et al. 2019). Besides, the benefits of the use of 5G technology in the construction industry were analyzed and a global framework for the application of 5G technology was also presented (Mendoza et al. 2021).

Compared with traditional 3D point clouds collected by fixed-point laser scanning (Tang et al. 2022; Zhang & Arditi 2020), 4DPC collected by compact and portable LiDAR sensors can simultaneously capture the spatial and temporal information of highly time-dynamic activities. Some sensor models, such as DJI Livox Mid-70, have detection range at 260 m, angular resolution at 0.1°, and 10~20 frames per second. Therefore, 4DPC gained increasing attention in various industries. The construction site monitoring typically needs in-person inspections, thereby resulting in high labor costs. To overcome this limitation, 4DPC can be used for automatic monitoring (Cheng et al. 2022). 4DPC data can also be used to conduct semantic registration for monitoring crane-related activities on the construction site (Liang et al. 2023). However, the previous research mainly focused on the usage and postprocessing of 4DPC, and the capture of 4DPC data is still on-site. It should be noted that 5G technologies can be employed to improve the data transmission speed, thereby facilitating data collection remotely. Therefore, remote sensing technologies of 4DPC data in the construction industry can be further explored and researched.

# 3 The proposed 4D point cloud (4DPC) sensing platform for DTC

## 3.1 The general framework

Figure **1** shows the architecture of the proposed 4D point cloud (4DPC) sensing platform. In general, the architecture of the platform has three layers, as shown in Figure **1**. The following subsections describe the details.

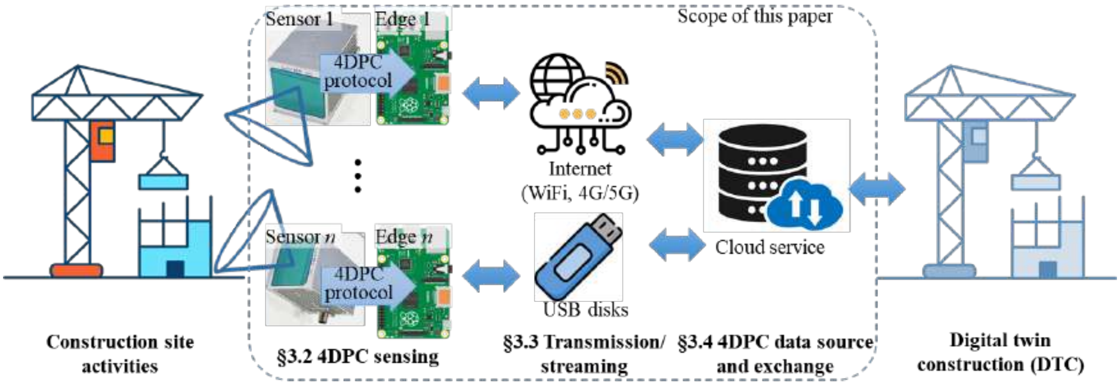


**Figure 1. Architecture of the proposed 4D point cloud (4DPC) sensing platform.**

## 3.2 4DPC sensing device

Each 4DPC sensing device has one sensor and one edge device. There are multiple choices in the market for collecting 4DPC. We selected a low-cost LiDAR sensor model, the DJI Livox Mid-70. The sensor has an appropriate view angle (about 70° cone field of view) and depth (up to 260m). It emits an infrared laser for range detection, so it works well for nighttime construction work. The edge device was a Raspberry Pi 4. A set of device cost about USD 993 (Liang et al. 2024). The edge device runs a lightweight Linux OS and is good for programable extensions. The 4DPC data protocol was the Livox SDK (https://github.com/Livox-SDK/Livox-SDK) over HTTP protocol. The CPU load and temperature are also collected and reported in addition to 4DPC data.

Multiple edge devices can be installed at different sensor locations ($x_i$, $y_i$, $z_i$) and heading directions to. 4DPC data from different edge devices can be merged into the universal *xyz-time* coordinate, according to the sensor pose and synchronized time. An optimized multi-sensor fusion plan can minimize occlusion. Indoor-outdoor fusion is also enabled by a multi-sensor fusion plan.

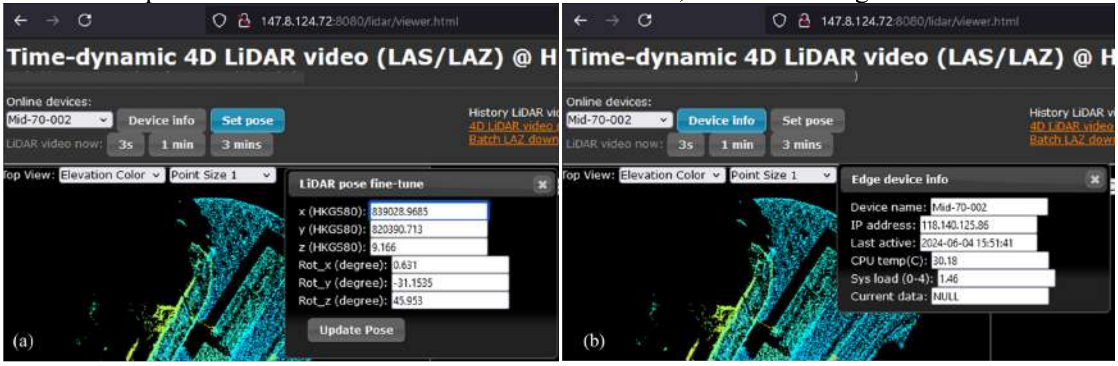
## 3.3 4DPC data transmission and streaming

The collected 4DPC data can be streamed to a cloud server via WiFi or 5G. If Internet is not available at the site, the data can also be transmitted offline via a USB drive. Whether online streaming or offline transmission, the data volume is enormous, leading to possibly expensive 5G data plans.

The platform implements two value functions to handle the costs of uploading massive volume of 4DPC data. The first function is a Zip/7-Zip-based 4DPC file-level compression. The file-level compression does not change the bytes of Livox SDK's format, but does reduce the file size and bandwidth considerably. The other function is a streaming-on-demand function that streams live data only for user-demanded (short) periods of time, such as five-minute crane hoisting events or 1-minute daily progress checking (in the early morning every day).

### 3.4 Integrated 4DPC source and exchange

A cloud server integrates and exchanges the 4DPC data with DTC and end users. First, it receives 4DPC from edge devices with the sensor poses. The sensor poses are presumed to be fixed locations, as demonstrated in Figure 2a. A user can set up the sensor pose according standard coordinate system, e.g., the Hong Kong 1980 Grid System (EPSG:2326) shown in Figure 2a. The edge device's CPU load and temperature are also readable from the cloud server, as shown in Figure 2b.



(a) LiDAR pose fine-tune

x (HKGS80): 839028.9685
y (HKGS80): 820390.713
z (HKGS80): 9.166
Rot_x (degree): 0.631
Rot_y (degree): -31.1535
Rot_z (degree): 45.953

(b) Edge device info

Device name: Mid-70-002
IP address: 118.140.125.86
Last active: 2024-06-04 15:51:41
CPU temp(C): 30.18
Sys load (0-4): 1.46
Current data: NULL

**Figure 2. Integration of multiple 4DPC edge devices**

Then, the cloud server employs a technological pipeline, as shown in Figure 3, to convert the 4DPC data format. The conversion starts from the .7z archive format and unzips the Livox native files (.lvx). Then, the 4dPC data is registered to standard coordinates concerning the sensor pose, as shown in Figure 2a, to be converted to a common LiDAR format .las for exchange. A part of this conversion was reported in Liang et al. (2023). In addition, the 4DPC data is geo-referenced and converted to the .pnts format for live visualization on the Cesium platform. The visualization effects were reported in Liang et al. (2024).

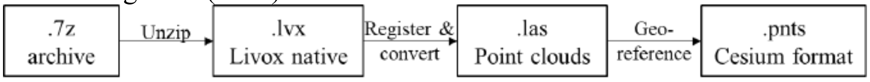


**Figure 3. 4DPC data format conversion pipeline on the platform**

## 4 Pilot Tests

### 4.1 Cases description

Two cases studies were conducted in Hong Kong. The first case was a footbridge construction project at midnight on June 28, 2022. The aims of first case test were edge device planning for occlusion minimization, offline transmission, and visualization. The other case was an excavation project in November 2023, where the aims of test included unattended 4DPC streaming and remote edge device control.

### 4.2 Results of occlusion minimization, transmission and visualization in pilot 1

We planned two edge devices to cover the target site area, as shown in Figure 4. The site was small, so that the sensor detection range achieved far beyond the site. More details can be found in Liang et al. (2023; 2024).

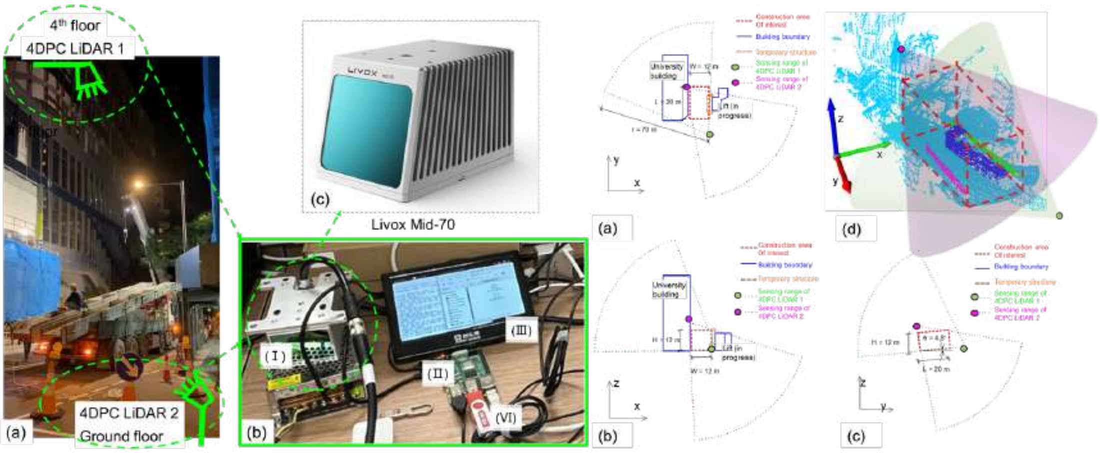
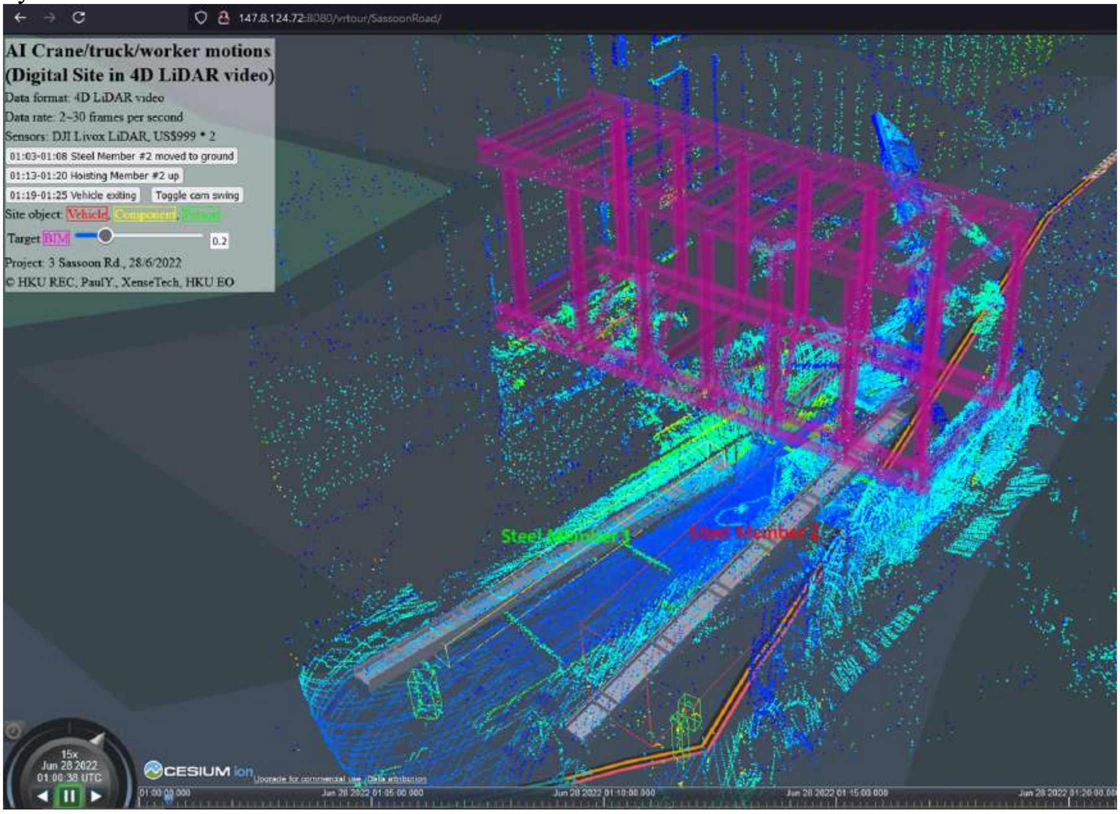


**Figure 4. 4DPC edge device planning for occlusion minimization** *(Liang et al. 2023; 2024)*

Each edge device recorded about 1.4 MB of 4DPC data per second. However, we found one device did not work stably. The No. 1 edge device attached to the fourth floor's 220V power supply recorded the whole period of 6.5 hours of construction activities. In contrast, the same edge device (No. 2) attached to the site's 220V power rebooted from time to time. The main reason could be the voltage surges caused by heavy construction equipment.

Figure 5 shows the visualization of 4DPC on the Cesium. The offline transmitted 4DPC data was integrated to Hong Kong's local grid system. The 4DPC files were successfully converted to .las formats and .pnts formats for exchange and visualization. In addition, 3D building information models and Geographical Information System objects were programable compatible with the time-dynamic 4DPC data.



**AI Crane/truck/worker motions (Digital Site in 4D LiDAR video)**

Data format: 4D LiDAR video
Data rate: 2~30 frames per second
Sensors: DJI Livox LiDAR, US$999 * 2

Site object: Vehicle, Component, Worker
Target BIM 0.2
Project: 3 Sassoon Rd., 28/6/2022
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**Figure 5. Visualization of 4DPC of pilot case #1 on Cesium**

## 4.3 Results of unattended 4DPC streaming and remote device control in pilot 2

Table 1 lists the comparison of online 4DPC data streaming methods. The original Livox file format (.lvx) was about 1.4 megabytes (MB) per second, or 11.4 megabits per second (Mbps) bandwidth. In contrast, the Zip files achieved a 1:0.334 compression ratio, without any data loss. The best results were from 7-Zip and XZ Utils. Both achieved a 1:0.235 compression ratio, which indicated a 76.5%

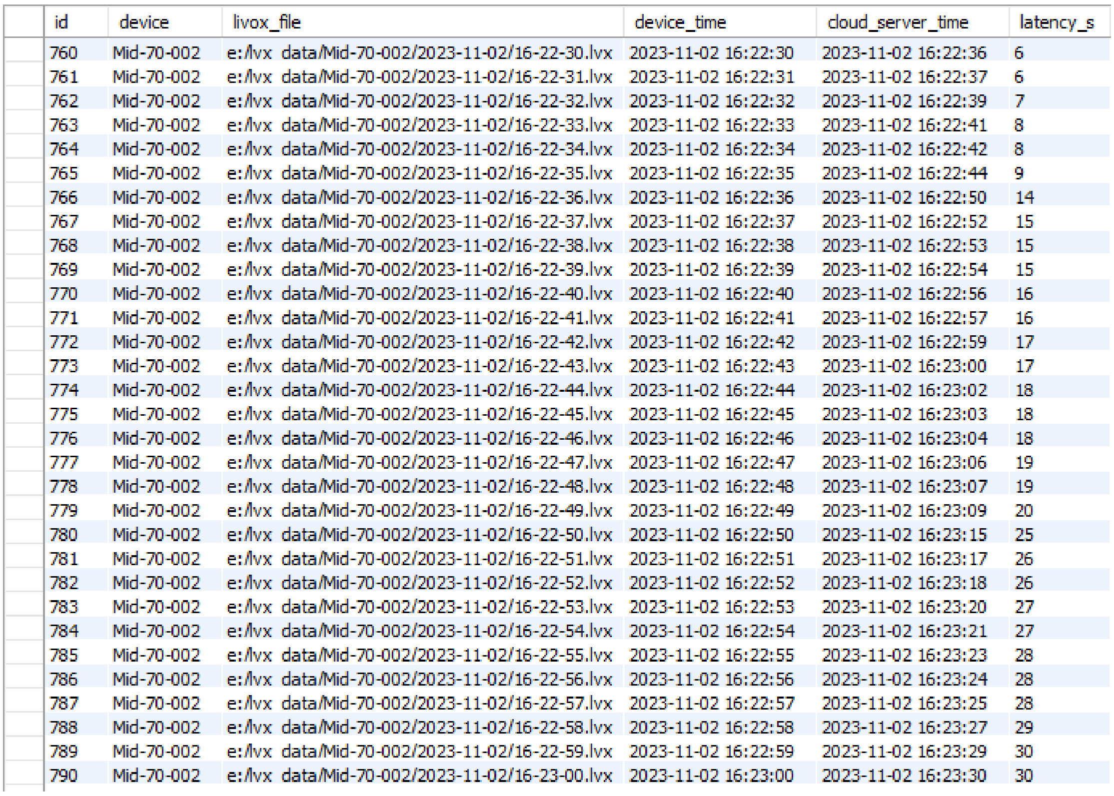
saving in terms of 5D data plan.

**Table 1. Comparison of online data streaming with file compression methods**

| Group | Method | File size (KB) | Compression ratio |
|---|---|---|---|
| Original .lvx | – | 1388 | 1:1 |
| Zip | Gzip | 558 | 1:0.402 |
|  | bzip2 | 463 | 1:0.334 |
| Advanced zip | XZ Utils | **326** | **1:0.235** |
|  | 7-Zip | **326** | **1:0.235** |

The remote sensing device control functions in Figure 2 worked well as designed. An edge device can be set up the sensor pose and checked for the latest system loads. A user could request all sensors to stream 4DPC data for a period of time, e.g., 3 seconds, 1 minute, or 3 minutes, by clicking the buttons on the platform UI.

However, we encountered one issue of accumulated latency of on-demand 4DPC streaming, as shown in Figure 6. The 30-second 4DPC data started streaming with a latency at 6 seconds, and ended with a latency increased to 30 seconds. The latency showed a continuous increase in the test. Possible reasons included the complex electromagnetic environment at the construciton site and unable 4G/5G connection.



| id | device | livox_file | device_time | cloud_server_time | latency_s |
|---|---|---|---|---|---|
| 760 | Mid-70-002 | e:/lvx data/Mid-70-002/2023-11-02/16-22-30.lvx | 2023-11-02 16:22:30 | 2023-11-02 16:22:36 | 6 |
| 761 | Mid-70-002 | e:/lvx data/Mid-70-002/2023-11-02/16-22-31.lvx | 2023-11-02 16:22:31 | 2023-11-02 16:22:37 | 6 |
| 762 | Mid-70-002 | e:/lvx data/Mid-70-002/2023-11-02/16-22-32.lvx | 2023-11-02 16:22:32 | 2023-11-02 16:22:39 | 7 |
| 763 | Mid-70-002 | e:/lvx data/Mid-70-002/2023-11-02/16-22-33.lvx | 2023-11-02 16:22:33 | 2023-11-02 16:22:41 | 8 |
| 764 | Mid-70-002 | e:/lvx data/Mid-70-002/2023-11-02/16-22-34.lvx | 2023-11-02 16:22:34 | 2023-11-02 16:22:42 | 8 |
| 765 | Mid-70-002 | e:/lvx data/Mid-70-002/2023-11-02/16-22-35.lvx | 2023-11-02 16:22:35 | 2023-11-02 16:22:44 | 9 |
| 766 | Mid-70-002 | e:/lvx data/Mid-70-002/2023-11-02/16-22-36.lvx | 2023-11-02 16:22:36 | 2023-11-02 16:22:50 | 14 |
| 767 | Mid-70-002 | e:/lvx data/Mid-70-002/2023-11-02/16-22-37.lvx | 2023-11-02 16:22:37 | 2023-11-02 16:22:52 | 15 |
| 768 | Mid-70-002 | e:/lvx data/Mid-70-002/2023-11-02/16-22-38.lvx | 2023-11-02 16:22:38 | 2023-11-02 16:22:53 | 15 |
| 769 | Mid-70-002 | e:/lvx data/Mid-70-002/2023-11-02/16-22-39.lvx | 2023-11-02 16:22:39 | 2023-11-02 16:22:54 | 15 |
| 770 | Mid-70-002 | e:/lvx data/Mid-70-002/2023-11-02/16-22-40.lvx | 2023-11-02 16:22:40 | 2023-11-02 16:22:56 | 16 |
| 771 | Mid-70-002 | e:/lvx data/Mid-70-002/2023-11-02/16-22-41.lvx | 2023-11-02 16:22:41 | 2023-11-02 16:22:57 | 16 |
| 772 | Mid-70-002 | e:/lvx data/Mid-70-002/2023-11-02/16-22-42.lvx | 2023-11-02 16:22:42 | 2023-11-02 16:22:59 | 17 |
| 773 | Mid-70-002 | e:/lvx data/Mid-70-002/2023-11-02/16-22-43.lvx | 2023-11-02 16:22:43 | 2023-11-02 16:23:00 | 17 |
| 774 | Mid-70-002 | e:/lvx data/Mid-70-002/2023-11-02/16-22-44.lvx | 2023-11-02 16:22:44 | 2023-11-02 16:23:02 | 18 |
| 775 | Mid-70-002 | e:/lvx data/Mid-70-002/2023-11-02/16-22-45.lvx | 2023-11-02 16:22:45 | 2023-11-02 16:23:03 | 18 |
| 776 | Mid-70-002 | e:/lvx data/Mid-70-002/2023-11-02/16-22-46.lvx | 2023-11-02 16:22:46 | 2023-11-02 16:23:04 | 18 |
| 777 | Mid-70-002 | e:/lvx data/Mid-70-002/2023-11-02/16-22-47.lvx | 2023-11-02 16:22:47 | 2023-11-02 16:23:06 | 19 |
| 778 | Mid-70-002 | e:/lvx data/Mid-70-002/2023-11-02/16-22-48.lvx | 2023-11-02 16:22:48 | 2023-11-02 16:23:07 | 19 |
| 779 | Mid-70-002 | e:/lvx data/Mid-70-002/2023-11-02/16-22-49.lvx | 2023-11-02 16:22:49 | 2023-11-02 16:23:09 | 20 |
| 780 | Mid-70-002 | e:/lvx data/Mid-70-002/2023-11-02/16-22-50.lvx | 2023-11-02 16:22:50 | 2023-11-02 16:23:15 | 25 |
| 781 | Mid-70-002 | e:/lvx data/Mid-70-002/2023-11-02/16-22-51.lvx | 2023-11-02 16:22:51 | 2023-11-02 16:23:17 | 26 |
| 782 | Mid-70-002 | e:/lvx data/Mid-70-002/2023-11-02/16-22-52.lvx | 2023-11-02 16:22:52 | 2023-11-02 16:23:18 | 26 |
| 783 | Mid-70-002 | e:/lvx data/Mid-70-002/2023-11-02/16-22-53.lvx | 2023-11-02 16:22:53 | 2023-11-02 16:23:20 | 27 |
| 784 | Mid-70-002 | e:/lvx data/Mid-70-002/2023-11-02/16-22-54.lvx | 2023-11-02 16:22:54 | 2023-11-02 16:23:21 | 27 |
| 785 | Mid-70-002 | e:/lvx data/Mid-70-002/2023-11-02/16-22-55.lvx | 2023-11-02 16:22:55 | 2023-11-02 16:23:23 | 28 |
| 786 | Mid-70-002 | e:/lvx data/Mid-70-002/2023-11-02/16-22-56.lvx | 2023-11-02 16:22:56 | 2023-11-02 16:23:24 | 28 |
| 787 | Mid-70-002 | e:/lvx data/Mid-70-002/2023-11-02/16-22-57.lvx | 2023-11-02 16:22:57 | 2023-11-02 16:23:25 | 28 |
| 788 | Mid-70-002 | e:/lvx data/Mid-70-002/2023-11-02/16-22-58.lvx | 2023-11-02 16:22:58 | 2023-11-02 16:23:27 | 29 |
| 789 | Mid-70-002 | e:/lvx data/Mid-70-002/2023-11-02/16-22-59.lvx | 2023-11-02 16:22:59 | 2023-11-02 16:23:29 | 30 |
| 790 | Mid-70-002 | e:/lvx data/Mid-70-002/2023-11-02/16-23-00.lvx | 2023-11-02 16:23:00 | 2023-11-02 16:23:30 | 30 |

**Figure 6. Accumulated latency in seconds using 4G/5G network (screenshot of cloud database)**

## 4.4 Discussions

The two tests validated the feasibility of the proposed 4DPC sensing platform. In summary, the first pilot test showed that the proposed 4DPC platform employs edge sensing devices for time-dynamic 4DPC data, integrates multiple devices for occlusion minimization, and converts 4DPC data into various formats for exchange and visualization. The second test confirmed the 4DPC streaming with a latency issue and remote edge device control.

In comparison to traditional AI camera surveillance solutions, the 4DPC platform has several advantages. First, the 4DPC data offers accurate depth and 3D information. Also, the 4DPC sensors work perfectly without good lighting at midnight. The fusion of 4DPC data streams from multiple sensors is natural and precise, thanks to standard geospatial coordinate systems.

Disadvantages of the 4DPC platform, nevertheless, were also found. The first was the vast data volume of 4DPC, which led to large disk size and live streaming latency. Although the 7-Zip was proven useful in saving 76.5% of the size, the compressed data volume streaming was still unsatisfactory and accumulated over time. Thus, stronger and domain-specific 4DPC compression is a promising future research direction. Another one was the low-level point density outside the center of the cone field of view of LiDAR sensors. The fast-evolving LiDAR hardware may resolve this problem in the future. The third drawback is the lack of colors in the 4DPC in this paper. Industry practitioners can supplement a camera to the 4DPC edge device in this paper.

Several challenges have also been identified in downstream DTC applications. First is the difficulty in object detection and activity monitoring using the 4DPC data source. One recent work can be referred to (Liang et al. 2024). Another one is the complexity of DTC, barring proactive risk identification and smart responses.

# 5 Conclusion

The time-dynamic 4DPC stream is a promising data source for DTC. This paper presents a cloud-edge system architecture for construction sites' 4DPC sensing that exploits self-driving cars' low-cost LiDAR sensors. The platform employs three layers: (i)_4DPC sensing edge devices, (ii) data transmission and streaming, and (iii) 4DPC integration and exchange. Two pilot tests confirmed that the platform collects occlusion-minimized 4DPC data and works unintendedly for 4DPC streaming.

The proposed 4DPC streaming platform is the first of its kind in the literature, as far as we are concerned. In contrast with the existing technologies, the presented platform offers a novel, low-cost, time-dynamic, and free-of-occlusion 4DPC data source that opens a new avenue to various digital twin construction applications. Future work includes testing advanced 4DPC sensors, advanced 4DPC data compression methods, integration with RGB camera, semantic object detection and pose estimation for construction activities in 4DPC, and proactive risk identification and smart responses.

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