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无人机测量在景观设计科研与实践中的应用

UAV MEASUREMENT IN LANDSCAPE ARCHITECTURE RESEARCH AND PRACTICE

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摘要

传统景观测量自动化程度较低，时间与人力成本较高。本文介绍了无人机测量在景观设计领域相关场景的前沿研究与实践应用进展，详细阐释了无人机测量在建立景观场地数字模型、分析与三维可视化的应用，展望了无人机在其他领域的应用可能对景观设计带来的启发。本文认为，相较于传统卫星测量和地面工程测量，配合传感器的无人机测量方式可快速获得相对高精确度、高分辨率和高时效的二维及三维数据，并为景观规划设计的分析提供多源数据支持，有效提升工作效率，与当前科研及实践流程高度融合。通过对多源数据进行融合与建模，可快速构建目标场地的基础景观数字模型，辅助研究与规划设计，为景观设计领域的数字化发展提供基础。

关键词

无人机；测量；景观设计；数字三维模型；点云

ABSTRACT

Traditional landscape measurement methods often lack automation and cost lots of time and manpower, resulting in a low level of digitization in the field of Landscape Architecture. This paper introduces new research and application of UAV measurement in Landscape Architecture and related fields for generating terrain and three-dimensional scenes and landscape correlation analyses. It also forecasts the application of UAVs in other fields that may inspire the practice of Landscape Architecture. The paper suggests that, compared with the traditional satellite measurement and ground engineering surveying, UAVs can quickly obtain two- and three-dimensional data by using airborne sensors with relatively high accuracy, high resolution, and short timeframes, capturing diverse data that supports the research and practice of landscape planning and design and improves the working efficiency. Therefore, this method is highly compatible with the existing research and practice mode. Through fusion and modeling, these multi-source data can help construct basic digital models to assist the analysis, planning, and design of sites. Taken together, this improves the overall level of digitization of the profession of Landscape Architecture.

KEY WORDS

UAV; Measurement; Landscape Architecture; Digital 3D Model; Point Cloud

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1 引言

物联网（IoT）、地理信息系统（GIS）、建筑信息模型（BIM）及智慧城市建设相关技术等信息化感知、分析与表达技术的研究与应用，为建筑与城市规划学科提供了数字化平台，提高了工作效率，并引发了研究、设计及咨询业务工作流程的革新；相比之下，景观设计领域的信息化与数字化水平仍旧偏低。在景观设计领域，由于空间尺度变化大、场地类型及研究对象多样等原因，在获取地形地物等基础

空间数据时往往会遇到显著困难，进而影响了景观设计的数字化进程。

场地测量测绘是景观规划设计的重要前期工作。传统的景观测量大多使用全站仪、GPS设备、激光扫描仪等设备进行人工现场测量。测量及后续数据处理、建模工作繁重，耗时耗力，且不适用于规模较大、人无法靠近或存在安全隐患的场地[1]。使用可搭载多种传感器的无人机（Unmanned Aerial Vehicle，缩写为UAV）获取场地数据并用计算机对其进行自动化处理和分析，则可以大大节约时间与人力成本。同时，无人机也能提供多源数据融合接口，用于搭建基础景观数字模型，并进一步构建功能完善的景观数字信息平台，从而提高景观设计数字化程度。

2 无人机测量综述

2.1 无人机分类及适用场景

无人机（在英文中亦常被称为Drone）是通过无线电遥控或者机载计算机系统自动控制的不载驾驶员飞行器。与搭载驾驶员的飞行器相比，无人机更适合执行繁重的、机械性的或存在潜在危险的飞行任务[2]；由于无人机不需要搭载生命支持系统，机舱结构及控制系统均更为简化，因此体积更小、成本更低，更适于定向化应用。当前，无人机已经被广泛应用于航拍测绘[3]、精准农业[4][5]、应急救援[6][7]、影视拍摄、节庆表演[8]、考古[9][10]等领域，并正在向货物运输[11]、邮政通信[12]、卫生医疗[13]、城市管理[14]等领域普及。

较为常见的无人机构型是固定翼无人机及旋翼无人机（图1）。固定翼无人机通过机翼提供升力，旋翼无人机通过桨叶旋转提供动力。一般而言，相较于旋翼无人机，固定翼无人机的续航能力较强，但机


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1. 固定翼无人机（左）与四旋翼无人机（右）

1. A fixed-wing UAV (left) and a quad rotor UAV (right)

1 Introduction

The research and application of informational sensing, analysis, and expression technologies such as Internet of Things (IoT), Geographic Information System (GIS), Building Information Modeling (BIM), and the Smart City-related technologies, provide an information-based platform for Architecture and Urban Planning that updates the workflow of research, design, and consulting services with a higher efficiency. By contrast, the overall level of digitization of Landscape Architecture is still in its primary stage because the large variation of spatial scale and the diversity of site types and research objects make the collecting of basic landscape spatial data, such as terrain, quite difficult.

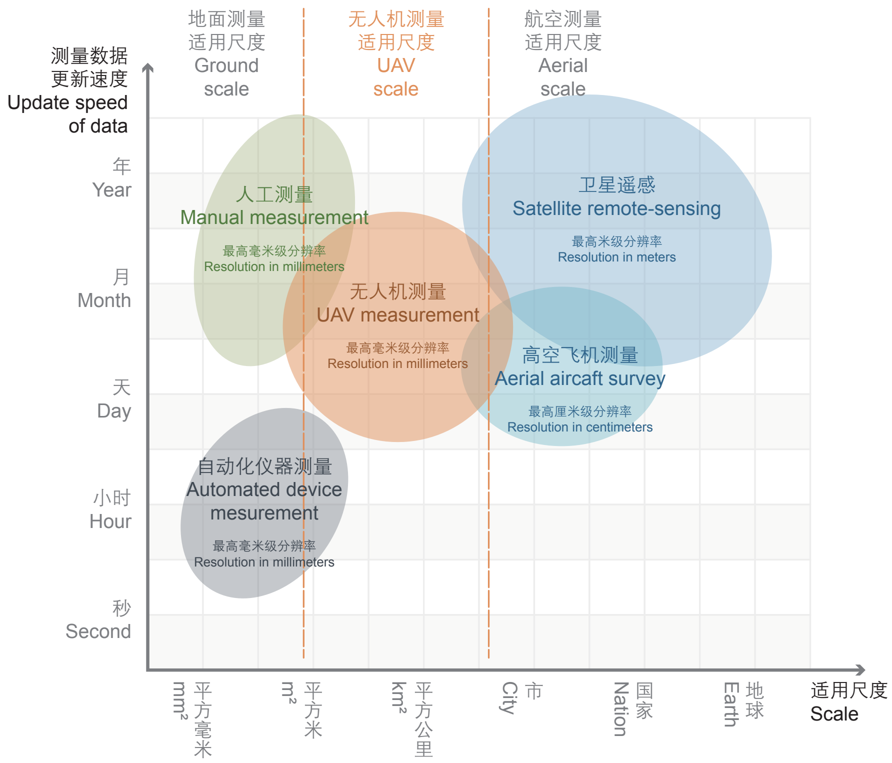
Site surveying and mapping is the groundwork of landscape planning and design. Traditional measurement methods are often carried out manually with total stations, GPS devices, and laser scanners and thus are unsuitable for dangerous or extremely large sites. Besides, data collecting, processing, and modeling usually take considerable time and manpower[1]. Unmanned aerial vehicles (UAV) use a variety of sensors and the data of a site can be best obtained, then processed and analyzed by computer automatically, saving time and cost. They can also work as a bridge for multi-source data fusion to build a basic digital landscape model which can be further improved into a well-functioning integrated interface that would enhance the overall level of digitization of Landscape Architecture.

2 A Review on UAV Measurement

2.1 UAV Types and Applicable Scenarios

Unmanned aerial vehicles (also called drones) are aircrafts that are controlled by radio or onboard computer systems without operators aboard. Compared with manned aircrafts, UAVs are more suitable for dull or potentially dangerous measuring missions[2]. They are better for targeted applications because of their smaller size and lower cost, thanks to their simple cabin structure and control systems without any life-supporting device. UAVs have been widely used in aerial mapping[3], precision agriculture[4][5], emergency rescue[6][7], film and television, festival performance[8], archaeology survey[9][10], and other civilian fields, also spreading to cargo transport[11], postal communication[12], health care[13], and urban management[14].

The two most common types of UAVs are fixed- and rotary-wing (Fig. 1). Fixed-wing UAVs provide lift through the



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2. 无人机测量可填补地面工程测量与传统航空测量之间的空白。

2. UAV measurement fills the gap between the ground engineering surveying and the traditional aerial photography.

动性较差，无法悬停、后退、单点旋转及垂直运动。固定翼无人机主要适用于城市尺度的任务，旋翼无人机适用于小尺度及定点任务。

无人机的适用环境条件较为宽泛。用于测量的无人机多为低空飞行，受云的影响相对较小，且对净空环境要求较低。此外，其所需起飞场地的面积较小，部分无人机还具有弹射起飞、手抛起飞或掌上直接起飞的能力。对于较大尺度或偏远的场地，可用车辆将无人机及其配套地面设备运送到作业区附近设站进行测量。一般情况下，无人机每天可以完成数十平方公里的测量任务，工作模式机动灵活。随着传感器尺寸的缩小、机载飞行控制系统的完善及电池密度的提升，无人机的尺寸将进一步缩小，未来有望支持在城市街巷、树林、室内等更为复杂的环境中飞行。

无人机测量具有高时效性，即拍摄与成果输出过程都相对迅速。使用无人机测量可以以单人单机的最小规模编组，快速完成中小尺度的外业测量任务并生成高分辨率影像数据，填补了测量领域从传统航空摄影测量（如卫星遥感、航空摄影）到地面工程测量之间的空白

wings, and rotary-wing UAVs are powered by blade rotation. Compared with rotary-wing UAVs, fixed-wing UAVs usually have a greater range ability, but they cannot hover, retreat, make single-point rotations, or move vertically. Currently, fixed-wing UAVs are mainly used for urban-scale missions and rotary-wing ones are more employed for small-scale and fixed-point missions.

UAVs adapts to various scenarios. In measurement missions, UAVs usually fly at a lower altitude, which are less affected by cloud cover and need only a small take-off space with lower clearance requirements. Some UAVs can also make a vertical take-off or by bouncing or hand throwing. For large-size or remote sites, UAVs can arrive quickly and measure tens of square kilometers each day with ground transporting and communicating devices. In the future, smaller sensors and improved airborne control systems and batteries with a higher energy density will make the UAVs even lighter and applicable to more complex missions, including urban street, forest, and indoor scenarios.

UAV measurement shows a high efficiency in image capturing. An UAV under one person's control can complete the measurement of small- or medium-size sites, and output high-resolution images quickly, bridging the gap between traditional

（图2）。无人机还可以搭载其他类型的传感器，为特定的设计或科研任务获取所需的数据。

此外，无人机测量具有较高的性价比优势：大部分无人机测量任务仅需使用消费级的无人机、手机与电脑就可以完成，无需配备额外的专业地面站设备。

2.2 数据获取和处理

无人机通过搭载传感器获取环境数据。目前的机载传感器以物理或化学传感器为主，如光谱类传感器、空气质量传感器、温湿度传感器等，可对环境中光线、压力、热辐射、位移、污染物浓度、温湿度等因子的变化进行感知与记录，以支持多个专业的研究应用[15]；在采集数据时还可引入三维空间坐标与时间信息，作为不同类型数据融合的媒介。

通过无人机获取的数据以二维或三维形式进行存储和加工，作为后续分析和可视化表达的基础。例如，通过摄像头、多光谱相机等光谱类传感器获得的数据以二维图像文件的形式存储，可以通过矫正和拼接加工为正射投影图，也可以通过三维重建技术形成三维点云，构建三维模型，并将数据映射到模型表面；通过激光雷达获得的数据以三维点云的形式进行存储，可通过三维连结的方式形成三维模型；空气污染物指数、温湿度等数据在进行空间定位后，可生成具有三维空间坐标的数据集。

二维数据是目前景观规划设计领域的主要工作媒介。通过无人机拍摄的图片及视频可直接传输至地面站，可用于现场人工判读，也可在进行加工后使用：如通过对图像进行矫正和拼接可获得正射投影图，用作设计平面底图；对旋翼无人机定点环绕拍摄的图像进行拼接及“补空”可生成高空720° 全景影像，用于屏幕浏览及虚拟现实（VR）体验。

由无人机捕获的图像可以使用运动结构算法（SFM）进行三维重建。该算法通过对一系列局部相互重叠的图像进行特征匹配，推演相机位置与角度，对物体控制点进行推算；再通过多次迭代的方式，对被拍摄物体的结构特征进行细化，从而获得物体完整的三维点云数据集（图3）[16][17]。SFM方法无需在测量过程中对镜头位置进行准确记录，即可获得毫米到厘米级分辨率的模型，且在各个尺度的测量任务

aerial photography and ground engineering surveying (Fig. 2). Equipped with other sensors, UAVs can also obtain diverse non-image data for specific design or research purposes.

In addition, UAV measurement sees an outstanding cost-performance. Today, in most cases without a dedicated ground station, UAV measurement missions can be implemented with consumer UAVs and mobile phones or computers.

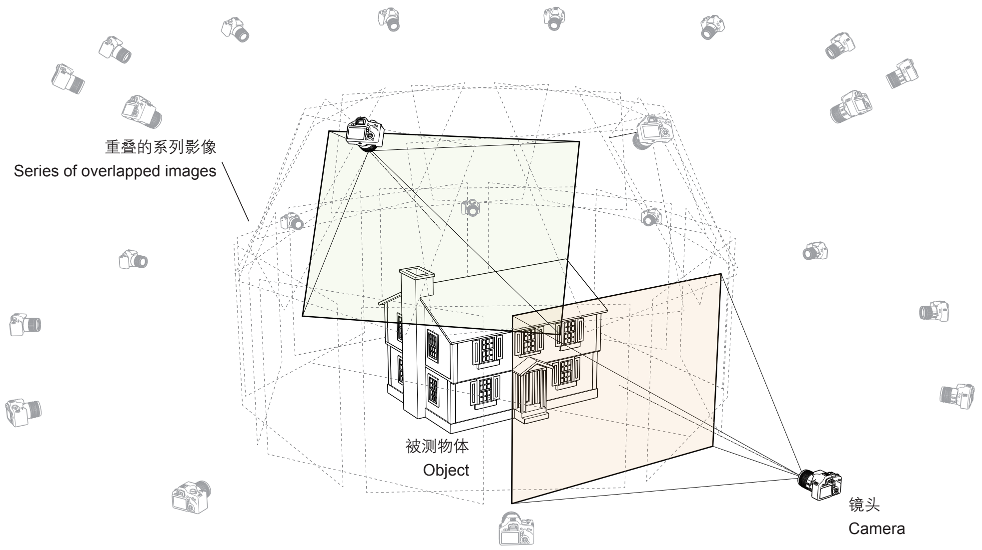
2.2 Data Acquiring and Processing

UAVs acquire environmental data by on-board sensors. These sensors collect physical and chemical data, recording variations in illumination, pressure, heat radiation, displacement, contaminant concentration, temperature, humidity, and other factors to support multiple professional research[15].The 3D space coordinates and time information of these data can also be collected by UAV measurement, working as the bridge for multi-source data fusion.

Data acquired by UAVs can be stored, processed, analyzed, and visualized in two- or three-dimensional formats. Specially, the data obtained by spectral sensors such as cameras and multi-spectral cameras are stored as two-dimensional (2D) image files, which can be processed into orthophotos through correction and splicing. It can also be processed into point clouds by 3D reconstruction, building a model for data mapping. The data obtained by Light Detection and Ranging (LiDAR) are stored as 3D point cloud files, which can generate visualized 3D models by point linking. By anchoring spatial coordinates, data such as air contamination indicators, temperature, and humidity can also form 3D datasets.

The 2D image file is the primary medium for landscape planning and design practice. The pictures and videos captured by UAVs can be directly transmitted to the ground station for on-site identification and interpretation or further processing and analysis. For example, the orthophotos can be used as base maps for design, and images acquired through rotating fixed-point photography can generate a 720° panoramic image after being jointed and completed for screen browsing and virtual reality (VR) experiences.

Using the Structure from Motion (SFM) method, a series of partly overlapping UAV images can be used to reconstruct a 3D model. By image feature matching, the camera's positions and angles can be derived to identify image control points before more and more details of the target's image can be recognized as a 3D point cloud dataset by multiple iterations (Fig. 3)[16][17]. The dataset has millimeter- and centimeter-level accuracy that does not require an accurate recording of the camera's position during measurement[18]~[20]; combined with



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3. SMF算法可以利用一系列局部互相重叠的影像数据集对被测物进行三维重建。

3. A series of partially overlapping images of the measured object can be reconstructed into a 3D model through SMF method.

中，误差均在可接受范围之内[18]–[20]；还可结合场地调研和地面测绘等数据，进一步提升三维重建成果的完整性和准确度。

利用三维数据进行分析和辅助设计是景观设计行业未来的发展趋势[21]。常见的三维数据类型包括三维点云、数字表面模型（DSM）、数字地面模型（DTM）、多面体模型等。三维点云以空间点的形式存储数据，可利用核密度分析等方法进行研究与可视化。以点云数据加工而成的DSM或DTM可用于GIS地形地物分析，DTM还可被进一步加工成各类地形图，例如等高线地形图、分层设色地形图及剖面图等。对点云数据进行联结和材质赋予可形成多面体模型文件，导入3DMax、CAD、SketchUp及其他设计软件中使用，也可以置入VR环境中进行浏览和设计，或通过3D打印机、数控机床等制作实体模型。

点云在无人机数据的三维计算、分析和表达阶段均有重要作用。点云的概念源于逆向工程，为空间中点数据的集合。通过激光雷达获取或三维重建得到的点云信息以表的形式进行存储，包括每个点的坐标信息和光学信息。在景观设计领域的尺度及精确度要求下，点云数据集往往十分庞大，需要使用PCL、PostgreSQL等点云数据库进行管理和运算。通过在点云数据库中增加新字段并赋值写入，可将多种来源的数据融合到同一点云数据集中，使点云模型能表达更丰富的信息。

additional site surveys, its integrity and accuracy can be further improved.

The use of 3D data for site analyses and design will be a common practice in landscape architecture[21], in forms of 3D point cloud, Digital Surface Model (DSM), Digital Terrain Model (DTM), polyhedron model, etc. Specially, the 3D point cloud stores data as spatial points. It can be analyzed and visualized through methods such as kernel density estimation or processed into DSMs or DTMs for GIS topographic analyses. DTM can also work as a basis for developing contour maps, layered topographic maps and sections, and other topographic maps. Through point linking and texture projection, the point cloud data can generate polyhedron models, which can be used in diverse design platforms like 3D Max, CAD, and SketchUp, or for the browsing and design in VR and physical model building with 3D printers or computer numerical control machines (CNCs).

Point cloud data is an important medium for 3D calculation, analysis, and representation of data acquired by UAVs. A form of reverse engineering, the spatial points are generated by LiDAR or 3D reconstruction and stored in table formats with coordinate and optical information. In landscape architecture projects, point cloud datasets often have large volumes and should be managed and edited in PCL, PostgreSQL or other point cloud databases. By adding new fields and assigning values, point cloud datasets can be more informative as an integration of multi-source data.

人工智能（AI）技术可以对无人机获取的海量数据进行辅助筛选和处理。基于对象识别的算法，可对无人机影像的内容进行识别和语义分割，提取植被、建筑等各种地物分类信息[22][23]。近年来，可训练的深度卷积神经网络技术（CNN）已被用于批量处理无人机获取的高分辨率图像信息，并获得更丰富的地物分类及更精确的边界信息[23]。二维图像的识别结果可以通过三维重建的方式将分类信息投影到点云数据集上，即以二维结构完成对三维点云的分类识别与标注[24]。基于三维结构的直接识别和分类算法仍在发展中，且在车载激光雷达传感器场景下的应用已有所突破[25]，未来有望延伸到航空测绘场景，实现更大尺度的点云分类和识别。

2.3 研究应用

在景观设计及相关领域，通过无人机获取数据，并对其进行处理和分析，可以支持包括场地遥感测绘、植被监测、灾害与应急监测、气候及空气污染物分布等方面的研究与应用（图4），以下介绍其中几个重点领域与相应的具体案例。

环境开发建设情况调查是无人机应用最广泛的场景之一。通过无人机实时传图、图像拼接与定位、三维重建等技术，可以在现场或内业完成对城市、村落、农田、矿坑、河流等多种环境的调查，如土地资源普查与分类，以及违章用地监测等[26]。

无人机可以快速便捷地获取不同分辨率的影像数据，支持农业、林业、生态学等领域的研究。在生态学研究中，使用无人机系统可实现景观尺度的高分辨率植被观测，填补了样地尺度地面调查与区域尺度卫星遥感测量之间的尺度差距[27]；同时，高分辨率影像数据能帮助识别单个或多个物种并得到其空间分布格局[28]。克里斯塔·L·茨威格等在湿地植物研究中利用无人机技术获取研究区的正射影像，进行植被物种鉴定和分类，进而得到研究区域的高精确度植被分布图[29]。

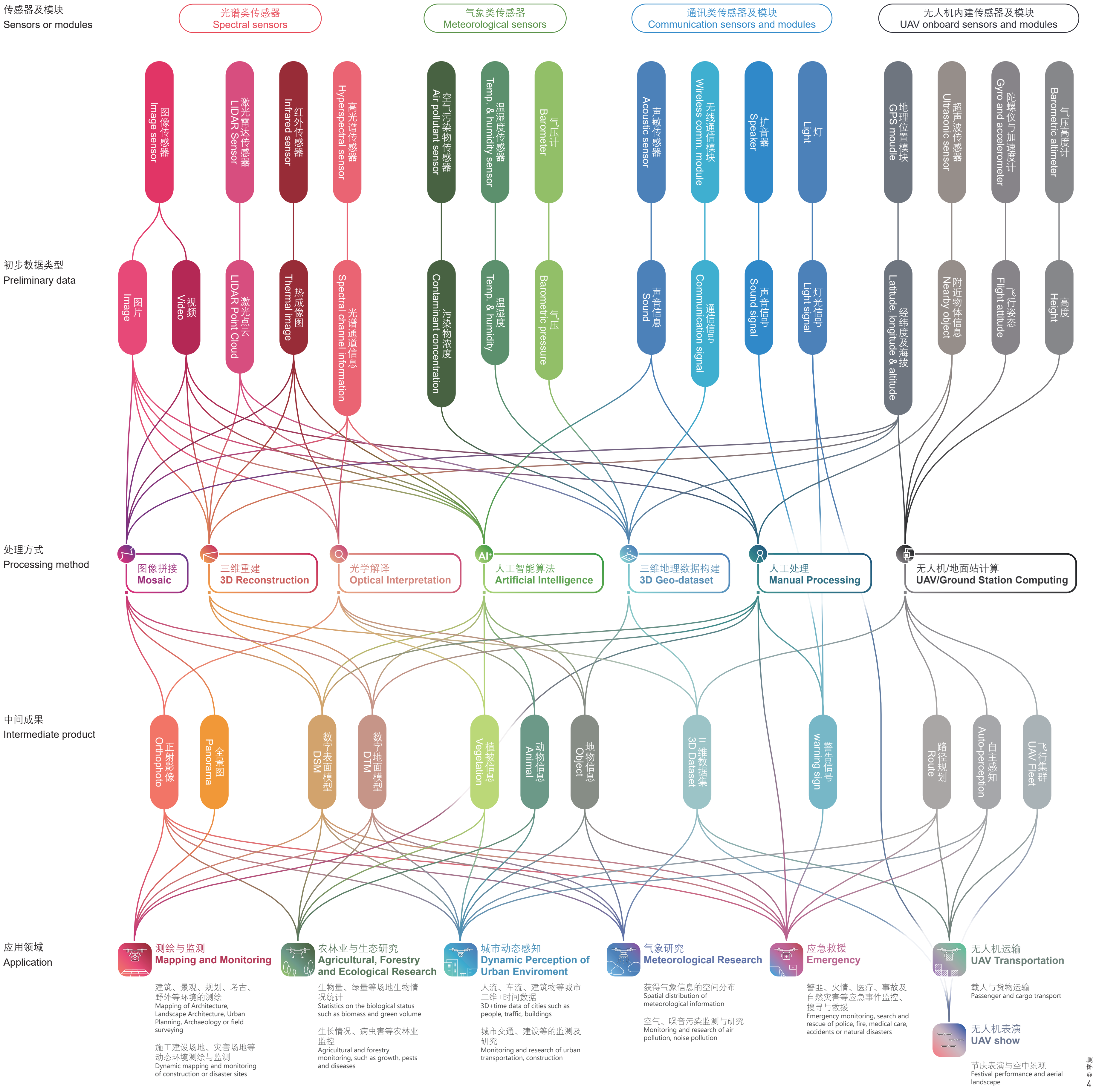
Artificial Intelligence (AI) can assist in screening and processing of massive data from UAVs. Object recognition algorithms can recognize and segment the features from the UAV images, extracting vegetation, buildings, and other objects[22][23]. The current technological advances of trainable deep Convolution Neural Networks (CNN) supports a mass processing of high-resolution UAV images to get accurate classification and boundary data[23]. The recognition results of the 2D images can be projected onto point cloud datasets through 3D reconstruction to annotate point cloud datasets[24]. Algorithms of direct recognition and classification of 3D data are still under development with a breakthrough in automobile LiDAR applications. It is expected to extend to aerial measuring and classification of larger-scale point clouds[25].

2.3 Application in Research and Practice

In Landscape Architecture and related fields, UAVs can acquire, process, and analyze data to support diverse research and application purposes, including remote-sensing and mapping, and monitoring on vegetation, disaster and emergency, climate, and air contaminant distributions (Fig. 4), in which a few of significant fields and the corresponding practice cases are listed below.

Development and construction investigations are one of the most common utilizations of UAVs. Through UAV real-time transmission, image mosaic and positioning, and 3D reconstruction, current UAV site measurement and investigation has been applicable in city, countryside, farmland, mining pit, and river to conduct land resource investigation and classification, and illegal land use monitoring[26].

UAVs can quickly acquire images at different resolutions, offering great support for research in Agriculture, Forestry, and Ecology. In Ecology research, UAVs can help high-resolution vegetation investigation at a landscape scale, filling the gap between sample plot surveys and satellite remote-sensing at regional scales[27]. The high-resolution images of UAVs can also be used for plant identification (individual species or communities) and related spatial distribution analyses[28]. Christa L. Zweig et al. used UAV technology to generate orthophotos of wetland plant habitats, identifying and classifying vegetation species in forms of high-accuracy distribution maps[29]. Stephan Getzin et al. used high-resolution images acquired by UAVs to assess the biodiversity of temperate forests by extracting forest gaps, calculating landscape patch indexes, and exploring the correlations between the results and the sampling data in plot and soil[30]. Jesper Rasmussen et al. calculated vegetation indexes by examining the farmland images acquired by UAVs



测绘与监测
Mapping and Monitoring

建筑、景观、规划、考古、野外等环境的测绘
Mapping of Architecture, Landscape Architecture, Urban Planning, Archaeology or field surveying

施工建设场地、灾害场地等动态环境测绘与监测
Dynamic mapping and monitoring of construction or disaster sites

农林业与生态研究
Agricultural, Forestry and Ecological Research

生物量、绿量等场地生物情况统计
Statistics on the biological status such as biomass and green volume

生长情况、病虫害等农林业监控
Agricultural and forestry monitoring, such as growth, pests and diseases

城市动态感知
Dynamic Perception of Urban Enviroment

人流、车流、建筑物等城市三维+时间数据
3D+time data of cities such as people, traffic, buildings

城市交通、建设等的监测及研究
Monitoring and research of urban transportation, construction

气象研究
Meteorological Research

获得气象信息的空间分布
Spatial distribution of meteorological information

空气、噪音污染监测与研究
Monitoring and research of air pollution, noise pollution

应急救援
Emergency

警匪、火情、医疗、事故及自然灾害等应急事件监控、搜寻与救援
Emergency monitoring, search and rescue of police, fire, medical care, accidents or natural disasters

无人机运输
UAV Transportation

载人与货物运输
Passenger and cargo transport

无人机表演
UAV show

节庆表演与空中景观
Festival performance and aerial landscape

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4. 无人机在景观设计学及其相关领域的数据采集、处理、分析与应用流程。

4. A workflow of data collecting, processing, analysis and application assisted by the UAV in landscape architecture.

斯特凡·盖特辛等利用无人机获取的高分辨率影像提取森林林窗，计算景观斑块指数，并分析其与实际植物样方数据、土壤数据的相关度，以估测温带森林的生物多样性[30]。杰斯珀·拉斯姆森等通过使用机载真彩色相机及彩色红外相机采集农田影像，完成了植被指数的测算[31]。韩东等在景观尺度下利用无人机监测平台和决策树算法实现了植被类型的自动划分和不同类型植被覆盖度的快速获取[32]。汪桂芳等采用分辨率为0.09m的无人机测量影像，并结合GIS空间分析法，对河南省漯河市土地利用景观格局的尺度效应进行了量化分析[33]。

在城市监测、立体分析与可视化领域，无人机也有巨大的应用前景。朴瑾炫与里德·尤因通过无人机低空拍摄，完成了城市公园内人群活动的监测与统计[34]。梁慧琳等使用无人机获得了城市公园的正射影像，完成了三维绿量的统计[35]。泰瑞克·莱卡和爱丽丝·戈罗德斯基使用机载红外传感器，对建筑的热辐射进行测量与立体可视化[36]。

无人机的高机动性使其十分适合灾害、紧急事件的动态监测与应急处理。托马斯·R·沃尔特等人利用无人机在飓风前后对同一场地进行测量及三维重建，获取反映地表状况的多种模型，用于监测与研究灾害前后地质变化[37]。苏蒂里斯·凡科尼奥迪斯等对地震导致的滑坡体进行了无人机测量与三维重建，并与地震前的三维点云数据进行对比，以确定滑坡体位置、体积并研究其形成机制[38]。

基于无人机的气候研究仍在初步探索阶段，但已经展现出其潜能。海诺·克鲁范尼等使用无人机作为移动平台，在芬兰赫尔辛基的城市街道峡谷中测量肺沉积表面积（LDSA）浓度的垂直剖面结构[39]。杨宇喆等基于消费级无人机飞行平台开发了空气质量指数检测系统，并在二维和三维模拟场景中进行了试验测量与计算[40]。安德莱斯·M·卡德纳等研发了一款可搭载无人机的小型空气质量监测仪器，能测量臭氧、甲烷、二氧化碳、一氧化碳、二氧化氮、细颗粒物的浓度，并在哥伦比亚共和国完成了试验性飞行[41]。

无人机在其他领域的应用可能会为景观设计带来新的启发。如无人机货运及载人运输可能会对未来人居环境的空间结构产生影响，改变高密度城市空间或偏远地区的交通模式。对无人机运输的关键技术——自主路径规划算法的进一步研究，将促进传感器数据的融合研究，提高无人机的环境感知能力，同时也能促进城市三维环境信息数

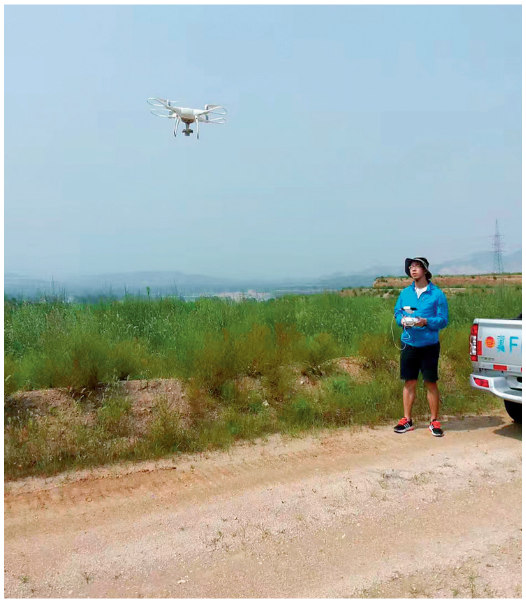
with true color cameras and infrared cameras[31]. By using UAV monitoring platforms and the decision tree algorithm, Han Dong et al. realized an automatic and instant classification of vegetation types and the vegetation coverage at a landscape scale[32]. Wang Guifang et al. used UAV measurement to acquire land-use images with a resolution of 0.09 m for quantitative analyses of the scale effect of landscape pattern in Luohe City, Henan Province, combining with GIS spatial analyses[33].

UAVs also have great prospects for monitoring, 3D analysis, and visualization of urban spaces. Park Keunhyun and Reid Ewing conducted the monitoring and statistical analysis of human activities in urban parks through UAV low-altitude shooting[34]. Liang Huilin et al. conducted the statistics of 3D green quantity of urban park based on orthophotos acquired by UAVs[35]. Tarek Rakha and Alice Gorodetsky used UAVs with infrared sensors to measure and 3D-visualize the thermal radiation of a building[36].

The mobility of UAVs make them an ideal tool for dynamic monitoring and responses to disasters and emergencies. Thomas R. Walter et al. used UAVs to measure a same site before and after hurricanes and studied the geological changes with surface models derived from 3D reconstructions[37]. Sotiris Valkaniotis et al. explored the location, volume, and formation mechanism of landslides by comparing the 3D point clouds before and after earthquakes[38].

Climate research based on UAVs is still in preliminary tests but has shown great potentials. Heino Kuuluvainen et al. used UAVs as mobile platforms to measure the vertical profile structure of lung deposition surface area (LDSA) concentrations in urban street canyons in Helsinki, Finland[39]. Yang Yuzhe et al. developed an air-quality index (AQI) detection system based on a consumer UAV platform, and conducted measurements and calculations of AQI in both 2D and 3D scenarios[40]. Andrés M. Cárdenas et al. developed a small airborne air-quality monitoring device to measure the concentration of various air quality indicators such as ozone, methane, carbon dioxide, carbon monoxide, nitrogen dioxide, and fine particles matter, and piloted it in Republic of Colombia[41].

The application of UAVs in other fields may have cross-over with Landscape Architecture. For example, UAV transportation may affect the spatial structure of future human settlements by changing the traffic modes in high-density urban environments or remote areas. As a key technology of UAV transportation, the autonomous path planning algorithm is expected to be further studied to promote the research of sensor data fusion, improving UAV's sensing ability and the development of urban 3D environmental databases. The application of UAVs in



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据库的构建。无人机在休闲娱乐场景的应用可以为景观设计提供新的创作与表现手段，例如通过将无人机与虚拟现实相结合，能够提供沉浸式的飞行体验，以空中视角审视和体验建成环境与自然环境；无人机群飞行表演所使用的群控技术也有望促进无人机群同步测量技术的发展，进一步提升无人机的测量效率和空间精确度。

3 案例

北京大学建筑与景观设计学院数字科技与地理设计实验室将无人机作为工作平台，完成了数个课题的测量、数据计算、可视化及分析工作。课题涵盖城市设计、乡村建设、灾后重建、生态评估等多种内容，研究区域涉及城市、乡村，以及开垦中的荒地等多种环境。测量工作采用“大疆创新”精灵4系列专业版（DJI Phantom 4 Pro）作为飞行平台（图5），使用其默认搭载的摄像头进行拍摄，详细的测量表现可参考表1；飞行测量航路由Pix4D Capture移动端设定并作为地面站；计算由基于SFM算法的Agisoft Metashape（原PhotoScan）完成，计算环境配置可参考表2。

3.1 山东省王坟镇：灾后测量与重建

2018年8月，受台风“温比亚”影响，山东潍坊多地连降暴雨，多个水库泄洪引发的洪灾导致其下辖的青州及寿光多地相继被淹，造成巨大的经济损失。2018年9月，中国城市规划设计研究院及北京大学组成的联合项目组受托对青州市王坟镇的灾后社区重建和生产恢复工作进行评估和规划。由于需要尽快开展相关重建工作，场地现状调研必

leisure and entertainment can provide new ways of expressing landscape architecture. For example, the combination of UAV and VR can provide an immersive flight experience, creating an aerial perspective to examine the built and natural environments. In the future, the control technology of UAV fleet performance may promote the development of synchronous measurement technology, further improving the efficiency and spatial accuracy of UAV measurements.

3 Application Cases

The Digital Technology and Geo-Design Laboratory of the College of Architecture and Landscape (CALA), Peking University has been using the UAV as a working platform in

表1：“大疆创新”精灵4专业版飞行测量表现
Table 1: Flight and measurement performance of DJI Phantom 4 Pro

项目 Item	参数 Performance
单电池标称最大飞行时间 Nominal maximum flight time of single battery	约 30 分钟 About 30 minutes
单电池可供飞行测量时间 Measuring time of single battery	约20-25分钟 About 20~25 minutes
标称信号有效距离（无干扰，无遮挡） Nominal effective distance of signal (without intervention or obstacle)	2,000 ~ 7,000 m
地面站稳定控制最远距离 Maximum distance for stable control of ground station	直线距离1 000m~1 500m 1,000 ~ 1,500 m (straight distance)
单次飞行较理想的测量网格大小 Best grid size for single flight	120m高度下控制在500m × 500m以内 Smaller than 500 m × 500 m at height of 120 m

表2：案例使用的计算环境配置
Table 2: Environment configuration for calculation of cases in this paper

部件 Item	型号及参数 Model and parameter
CPU	Intel Xeon Gold 5118 * 2 单CPU十二核心，二十四线程 / Single CPU, 12 cores, 24 threads CPU主频 / Base Frequency：2.3GHz 动态加速频率 / Max Turbo Frequenc：3.2GHz
内存 RAM	128GB（16G*8）2,666MHz
GPU	NVIDIA Quadro P5000 显存 / VRAM：16GB GDDR5X 浮点计算能力 / FP32 Performance: 8.9 TFLOP 支持CUDA / CUDA Enabled
硬盘 Hard drive	Samsung PM961 512GB M.2 NVMe SSD + Western Digital 4TB HHD
系统 Operation system	Windows 10 Pro

5. 使用大疆精灵4系列专业版作为飞行平台
6. 王坟镇案例测量区位信息图

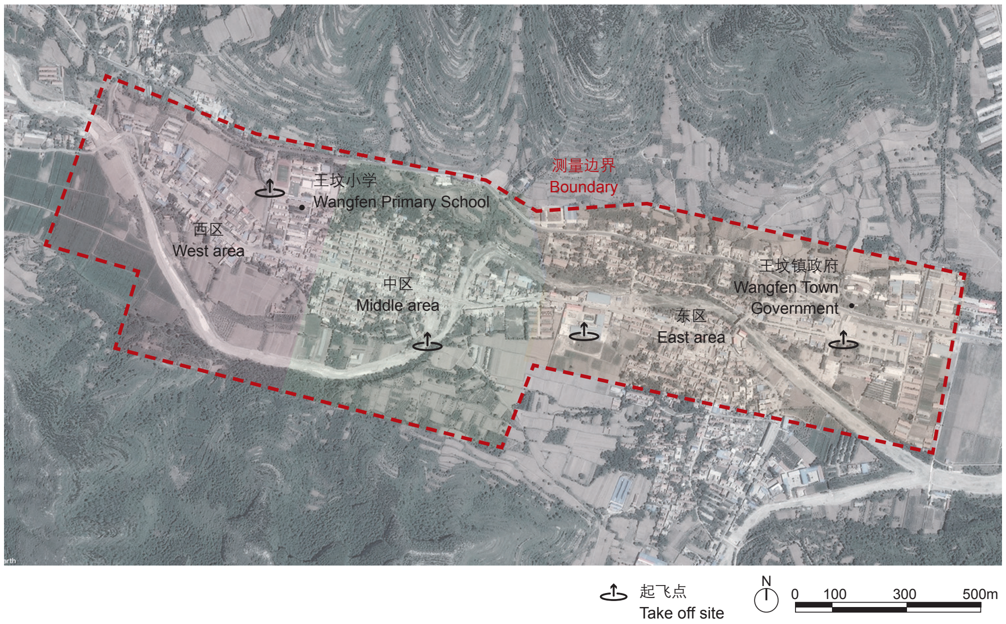
5. DJI Phantom 4 Pro adopted as the flight platform
6. The site for measurement of the Wangfen Town case

须在较短时间内完成。考虑到卫星影像更新周期长、分辨率低，利用全站仪进行场地测量花费时间长、成本较高，项目组决定使用无人机进行测量，以快速获得相关基础资料。

无人机测量的飞行高度取决于被测景观的具体类型。在本案例中，对于地物稀疏、地形变化较小的河道、农田等地段，采用100m的飞行高度；对于建筑密集的村落及镇区街道等地段，则采用50m的飞行高度。获得数据后，先进行整体的相片对齐，形成连接点；再将场地分为东、中、西三个区段，在每个区段使用相应的相片进行密集点云的计算；最后通过整体连接点和相片对齐数据，进行整体密集点云数据的融合（图6）。

经过上述处理获得的密集点云包含场地内所有物体的三维结构信息，可以依此构建DSM。通过对密集点云数据进行筛选与属性分类，可得到多种地物的专题模型与DTM。其中，由于被植被、建筑遮挡的地面点信息很难通过空中俯拍获取，故在生成DTM时需采用插值运算，补全缺失的信息，以获得连续的DTM。在该案例中，树丛连续遮挡情况较少，且建筑结构简单，故采信了插值获得的DTM（图7）。

该案例在一周的时间内便完成了测量及初步计算工作（表3），获得了多种精确度较高的场地现状图成果（图8），体现了无人机在获取存在安全隐患场地空间数据方面的效率优势。其中，DSM、DTM可以直接用于规划研判，且为水文分析、植被分析等专项研究提供了数据支



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missions of site measurement, data calculation, visualization, and analysis, covering urban design, rural construction, post-disaster rebuilding, and ecological assessment in cities, villages, or even wastelands. All the measurement tasks used DJI Phantom 4 Pro as the flight platform (Fig. 5) and the default camera (Table 1). Pix4D Capture Applet was used as a ground station for route setting. The calculation was done by Agilsoft Metashape (formerly PhotoScan) based on SFM algorithm (Table 2).

3.1 Wangfen Town, Shandong Province: Measurement for Post-Disaster Rebuilding

In August 2018, Typhoon “Wambia” in Qingzhou and Shouguang City of Weifang, Shandong Province saw heavy rains and severe floods, causing huge economic losses. In September 2018, a joint team of the China Academy of Urban Planning and Design and Peking University was asked to develop an assessment and a planning scheme for the post-disaster rebuilding of the attacked communities and campuses of Wangfen Town, Qingzhou City. For speed and a lower cost, the project team decided to use UAV measurement to acquire high-resolution images of the site.

Given various landscape types, different flying heights were adopted during the measurement: for the rivers and farmlands with sparse terrain, the flight height was set at 100 meters; for areas with dense buildings and streets, the flight height was set at 50 meters. Following field measurement, the photos were aligned to generate an overall connection point network. The site was then divided into east, middle, and west sections. For each section, the corresponding photos were used to reconstruct a dense point cloud model. Finally, three dense point clouds were merged into a unity via the connection point network (Fig. 6).

The unity dense point cloud model contains 3D structural data of all objects on the site, which can be transformed into a DSM directly. The point cloud data can further be screened and classified into different features to generate diverse subject models and a DTM. Due to the aerial shooting, it was difficult to acquire images of the ground features obscured by vegetation or structures, making interpolation calculations necessary. If there is not so much vegetation blocking or many complex structures on the site, the interpolated DTM can be accepted as was in the Wangfen case (Fig. 7).

Using the UAV, the project completed the measurement and preliminary calculations of the site in a week (Table 3), illustrating a great efficiency in acquiring data on hazardous sites, and obtained several high-accuracy maps for various research purposes (Fig. 8). For example, the DSM and DTM were

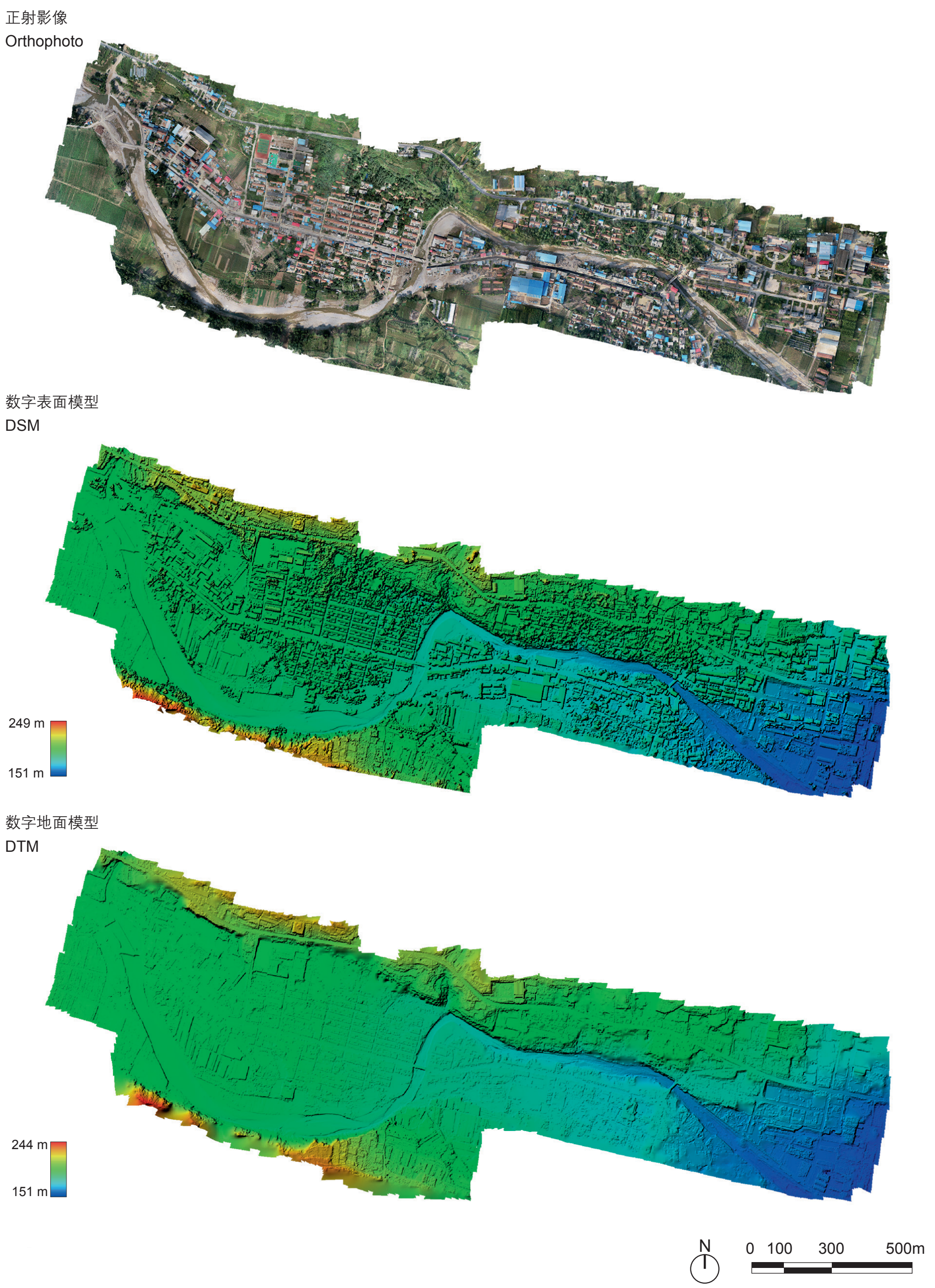

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表3：王坟镇案例场地测量信息
Table 3: Information of the measurement task in Wangfen Town

场地面积 **Site area**	约1.4km² About 1.4 km²
单次飞行区域大小 **Single flight extent**	400m × 500m（100m飞行高度）、150m × 200m（50m飞行高度） 400 m × 500 m (flying height: 100 m), 150 m × 200 m (flying height: 50 m)
飞行次数 **Number of flight**	14
飞行高度 **Flying height**	镇中心区域距离起飞点①50m，其他区域100m 50 m above the launching point① (for the town center); 100 m above the launching point (for the rest of the site)
测量总时间 **Measuring period**	2天 2 days
总相片数量 **Number of acquired photos**	5 377 5,377
密集点云总数② **Volume of the unity dense point cloud②**	409 341 107个点 409,341,107 points
密集点云运算时间③ **Calculation period of dense point cloud③**	约35个小时 About 35 hours

注：

① 起飞点指无人机起飞时的位置点。在测量任务中，无人机会根据起飞点的位置及设定的高度来确定测量任务的飞行平面，在一个固定的海拔高度上飞行。在实际测量过程中，受场地限制，测量任务可能会选择从地面、屋顶或汽车顶棚上开始。

② 密集点云数量与相片数量、分辨率、计算设置都有关系。

③ 运算时间仅指从相片对齐至计算出不带顶点颜色的密集点云的时间，其他工作（如准备工作、数据清洗、专题成果制作等操作）所花费的时间未计入内。

Notes:

① Launching point is where the UAV takes off. During a measurement task, the UAV flies at a fixed flying plane determined by the launching point and the preset flying height. In practice cases, the UAV may have to take off on the ground, a roof, or an automobile's calash according to the site conditions.

② The volume of dense point cloud is determined by the number, resolution, and calculation setting of the photos.

③ The calculation period here refers to the duration from the photo alignment begins to the calculation of dense point cloud without color finishes. The time spent on other operations such as preparation, data cleaning, and production is not included.

持；DSM及正射投影图为受灾情况的详细调查及各类分析的可视化提供了依据。

3.2 安徽省西溪南村：村落建筑与街道测绘

西溪南村位于安徽省黄山市徽州区西部，是一个拥有1 200多年历史的古村落，当地建筑肌理及水系统均保存完好。2018年春季学期，

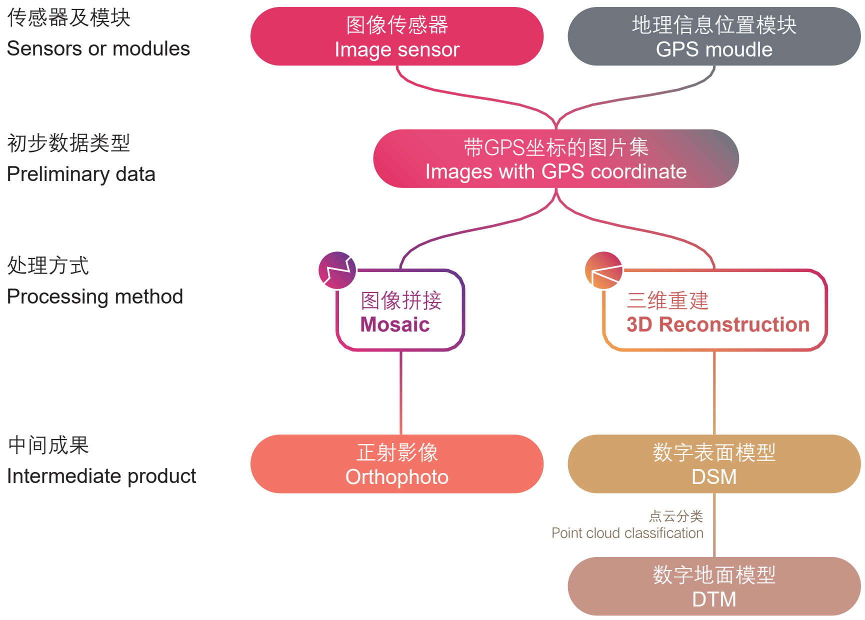
directly used for planning research and provided data support for further research on hydrology and vegetation. The DSM and orthophoto created a visual basis for various analyses of detailed damages.

3.2 Xixinan Village, Anhui Province: Mapping of Village Buildings and Streets

Xixinan is a well-preserved 1,200-year-old village located in the west of Huizhou District, Huangshan City, Anhui Province

7. 通过无人机获取的数据计算而成的正射影像、DSM与DTM。
8. 王坟镇案例应用路径

7. The orthophoto, DSM, and DTM generated through calculation of the UAV images.
8. The workflow of UAV application in the Wangfen Town case



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北京大学建筑与景观设计学院将西溪南村作为基地，开设了以“美丽乡村建设”为主题的设计研讨课程。

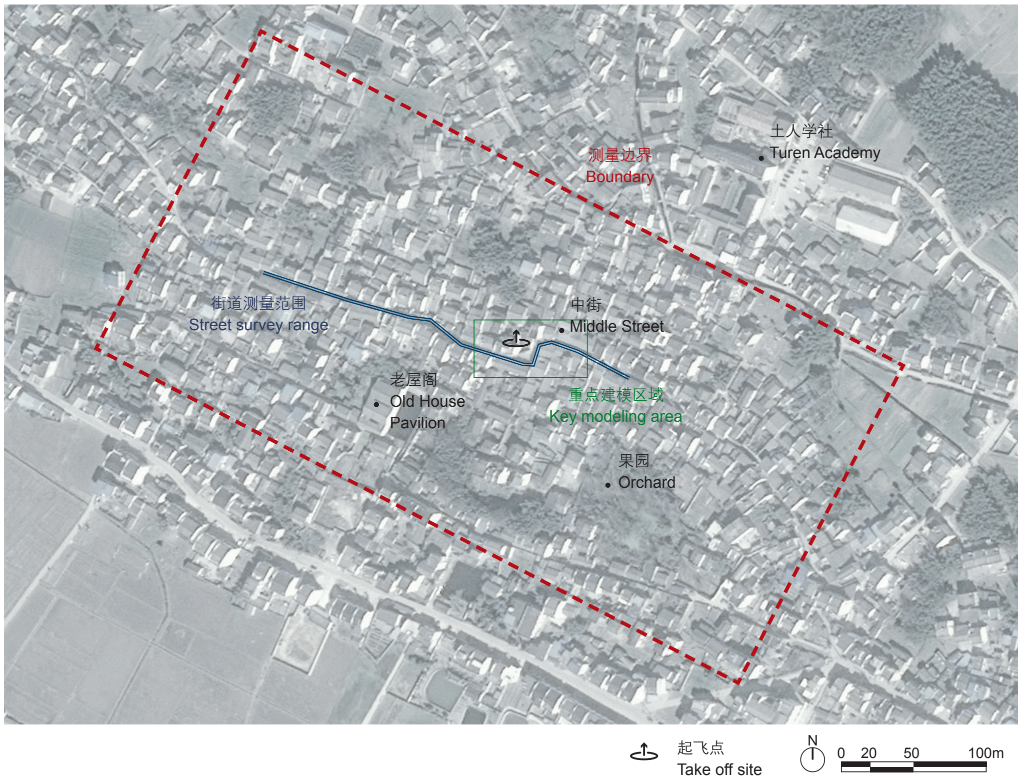
课程要求获取村落及其附近环境的地理信息。由于场地内地物种类繁多且分布情况复杂，故采用多次但有细微高度差的方式对场地进行测量，相互补充以获取更完整的信息。同时，课程还要求对村落内的街道立面进行测绘，用作街道环境设计的基础资料。由于村落内建筑排列紧密，道路狭窄，仅依靠无人机飞行无法完整捕获街道内图像，故采用无人机拍摄与地面拍摄结合的方式进行测量（图9）。

通过不同设备获取的影像数据因拍摄角度不一致，需要进行额外的对齐和融合处理。首先对相片进行初步处理，利用语义分割算法将天空、人、车、开敞水面等后期建模不需要的要素剔除，再对两种不同设备获取的数据分别进行建模，获得村落整体模型及街道区域模型，作为模型对齐等后续处理的基础，并检查影像数据的完整度。接着通过人工比对的方式，选择较为开放的空间作为主要控制节点进行定位点的详细标注，并在地面拍摄路线的沿途设置辅助控制点。人工标注完成后，将两部分模型进行基于控制点的对齐、合并及点云的重新计算，以对齐并融合不同设备获取的数据（图10）。数据融合后，从地面拍摄的街道数据将继承无人机拍摄数据所带的精确地理坐标，形成高精确度的三维点云数据。

and enjoys a sound conservation. In the spring of 2018, CALA organized a design studio course there themed on “Construction of Beautiful Countryside.”

The course collected geographic information from the village and its surrounding countryside at first. Given the complexity and variety of objects on the site, the UAV flew the site several times at slightly different heights to acquire enough images that cover all the necessary information. The mapping of street facades was conducted to inform alley design of the village. Because some of the alleys were too narrow for the UAV photography, ground photography was also adopted (Fig. 9).

Since the UAV photography and ground photography were taken in varied shooting angles, an additional alignment and mergence was required: Firstly, a semantic segmentation algorithm and exclusion masks were used to eliminate unnecessary elements such as sky, people, cars, and open water surface. Secondly, UAV images and ground-photographed images were transformed into point cloud models of the whole village and all the alleys, respectively, then the image integrity was verified. Thirdly, through manual comparison, several open spaces were marked as the main control nodes with auxiliary control nodes set along the ground photography route. With all these control nodes, the two models were aligned, merged, and recalculated (Fig. 10) to let the ground photography data inherit the precise geographic coordinates of the UAV data, forming a 3D point cloud dataset with high accuracy.



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9. 西溪南村案例测量区位信息图
10. 通过控制点的无人机数据与地面数据的融合
11. 使用融合数据生成的带有地理信息及尺寸信息的街道立面模型
12. 使用融合数据生成的人视角的街道点云（左）、多面体模型（中）及贴图模型（右）。

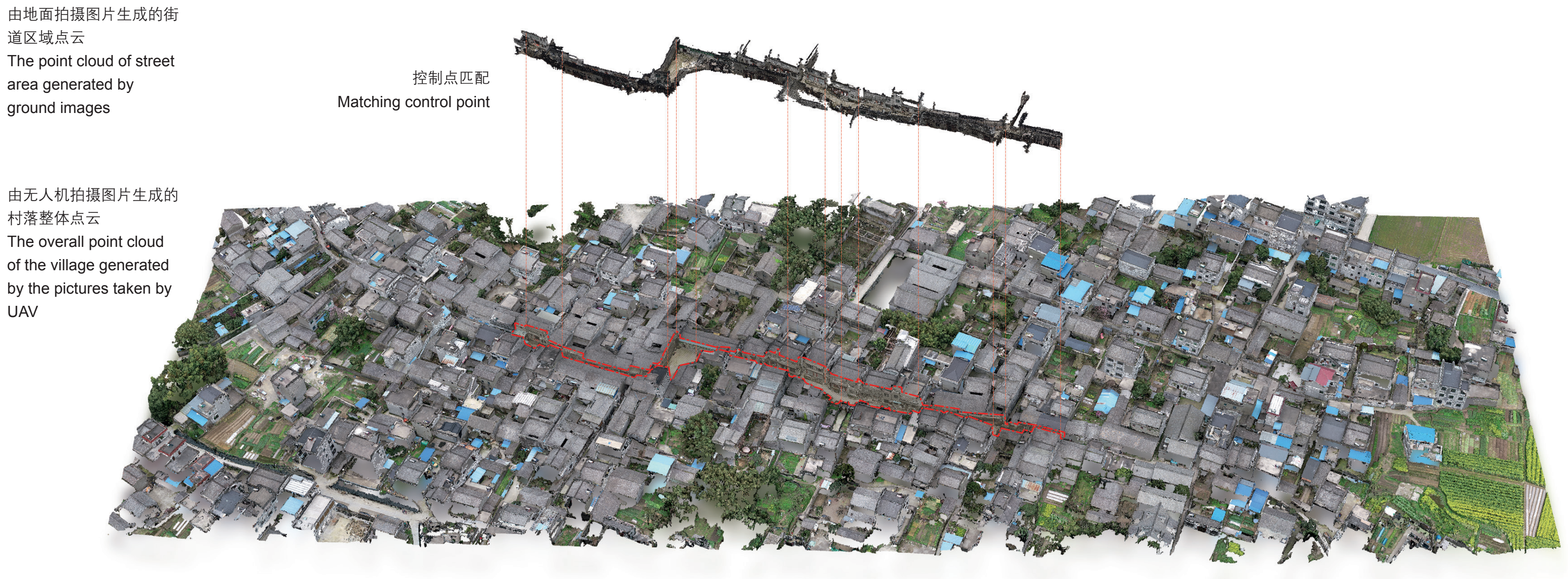
9. The site for measurement of the Xixinan Village case
10. Fusion of the UAV image data and the ground photography data through control nodes
11. The street facade model with geographic and size information generated from the data fusion
12. The point cloud (left), multi-facet model (middle), and textured model (right) in a human perspective, generated from the data fusion.

由于整体的三维点云数据集十分庞大，需结合具体工作要求，选择适当尺度与精确度的点云数据进行进一步的数据处理。使用村落整体点云数据加工成村落DSM及正射投影图，作为绘制村庄肌理及街道肌理的设计底图；通过对街道区域点云数据的拆分、三维联结和纹理投影，获得具有地理空间坐标及物体详细尺寸的街道立面图，用作细部测绘基础资料（图11）；选取部分重点区域的点云加工成带材质的三维模型，供方案设计、展示使用（图12）。

使用传统方法建立精确度的村落与街道场景模型，需要投入大量时间与人力进行测绘与人工建模。通过无人机拍摄与地面摄影相结合的测量方式与计算机辅助下的半自动化数据加工，可以在较短的时间内完成外业测量任务，并快速建立精确度较高的场景模型，显著压缩了时间和人力成本（表4）。同时，通过无人机空中影像及地面人视角影像数据的融合，可在单个数据集中集成不同尺度与精确度的二维及三维数据（图13），为后期设计与研究工作提供基础材料与分析参考。

Given the large volume of the overall 3D point cloud dataset, only a few parts of it were selected for further study at different scales and accuracies. The village's overall point cloud data was processed into a DSM and an orthophoto as base maps for buildings and alley fabric drawings. By splitting, 3D linking, and texture projection, the point cloud data of the alleys generated a facade model with spatial position and size information of all objects, becoming reference for detailed mapping tasks (Fig. 11). Point clouds of some key areas were processed into 3D models with texture information for other design and display purposes (Fig. 12).

In this case, a combination of UAV and ground photography completed the field measurements, helping generate high-accuracy site models and significantly reducing time and labor costs, compared with traditional manual working modes (Table 4). Moreover, the merging of UAV and ground photography images realized a combination of 2D and 3D data at different scales and accuracies into an integrated dataset (Fig. 13), providing a significant basis and reference for design and research.



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4 结论与讨论

使用无人机可以以较低成本获取高精确度、高分辨率和高时效的场地数据，并进一步将其加工为正射投影图、DSM、DTM等产品，以辅助相关研究和设计工作；还可以生成三维模型，为场地立体分析与设计、三维景观数字系统构建等提供基础。但目前该方法存在一定的局限和问题：

首先，国内外民用无人机管理目前仍处于探索阶段，故在飞行过程中要尤其注意潜在的安全及法律风险。景观设计领域的无人机测量作业往往尺度较大、飞行高度较高，无法以肉眼进行实时监测；在执行任务的过程中，由于地面站接管了无人机的飞行控制系统，机内自主避障系统往往处于关闭状态，会增加碰撞事故的风险；在城市中，净空环境、电磁波环境等较农村及野外更为复杂，无人机飞行会面临更多的不确定因素。在飞行前一定要注意当地航空器材管理条例及限制飞行区域公告，认真履行必要的申报手续，取得合法飞行许可。同时也应提前与测量区域的管理人员及当地居民进行积极沟通，避免发生误解和冲突。

其次，三维数据的存储、分析和渲染技术存在提升空间。对于点云和多面体模型，目前业界尚未形成具有统一地理坐标标准、可供赋值和参数调整的通用文件格式。基于图像产生的三维点云数据需要高性能计算机进行计算和渲染，得到的三维模型面数也往往过高，以目前的逆向工程算法还无法达到理想的减面效果。就景观设计领域而言，常用的设计软件无法对点云及高面数模型进行便捷的赋值和更改，也无法直接利用三维数据辅助分析和设计。而针对高面数模型开发的软件无法完整支持研究分析和设计工作。因此在实际工作过程中，往往不得不将三维数据降维成二维数据进行分析和使用，或将三维模型用于简单展示。

无人机测量在景观设计科研与实践中的应用前景将越来越广阔。通过无人机行业与政府部门的努力，无人机的飞行申报与管理工作将进一步完善，使无人机应用于更多场景；无人机设计制造技术的发展可进一步提升无人机的集成程度，减小其体积、降低生产成本；无人机群控技术的发展、内建传感器的升级、路径计算能力的增强，以及三维地图精确度的提升有望进一步增强无人机的自主控制能力，为无人机的广泛使用奠定基础；在计算机领域，点云数据库、多细节层次（LOD）、可视角度渲染、逆向工程、三维GIS分析等技术的进一步发展可帮助提升设计行业对三维数据的赋值、分析与修改能力。

景观设计领域也应进一步挖掘无人机适用的新场景，在数据收集、信息反馈、使用后评估以及人与环境互动等方面创造新的价值，并努力推进景观设计与相关研究的方法革新。这些发展都将有助于构建功能完善的景观数字信息平台，提高景观设计信息化和数字化程度，助力未来数字三维环境下的景观设计和研究工作。**LAF**

表4：西溪南村案例场地测量信息
Table 4: Information of the measurement task in Xixinan Village

场地面积 **Site area**	约10hm^2 About 10 hm^2
单次飞行区域大小 **Single flight extent**	500m × 200m 500 m × 200 m
飞行次数 **Number of flight**	3
飞行高度 **Flying height**	距离起飞点50~60m 50 ~ 60 m above the launching point
街道长度 **Length of the street**	300 m
测量总时间 **Measuring period**	4小时（无人机与地面拍摄同时） 4 hours (when the UAV and ground photography were conducted simultaneously)
总相片数量 **Number of acquired photos**	1 092张无人机相片+761张地面相片 1,092 UAV photos and 761 ground photos
密集点云总数 **Volume of the unity dense point cloud**	466 765 689个点 466,765,689 points
密集点云运算时间 **Calculation period of dense point cloud**	约26个小时 About 26 hours

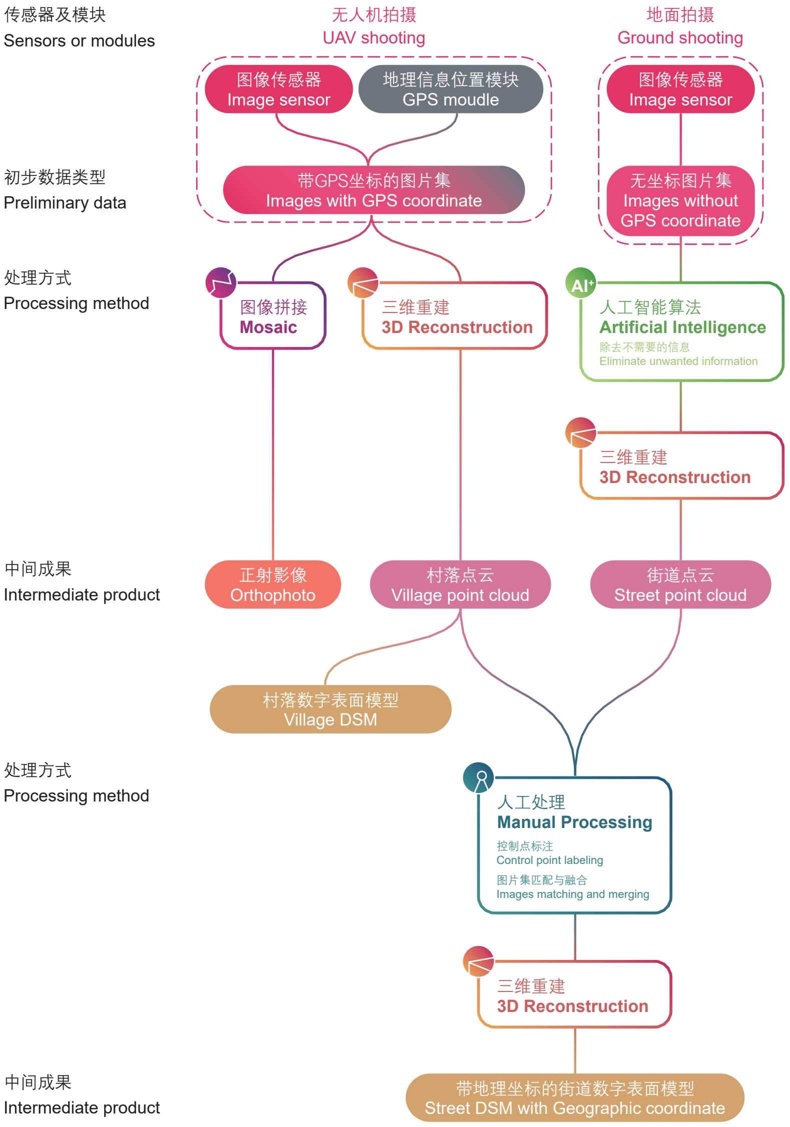
4 Conclusion and Discussion

Using the UAV can efficiently and economically acquire site data with high accuracy and resolution. The data can be processed into orthophoto, DSM, DTM, and other formats compatible with the existing landscape research and design process; it can also be reconstructed as 3D models for further 3D analysis and design, and the construction of 3D digital landscape systems. However, there are some lessons learned from the authors' authentic experience and the precedent practices.

First, because there has not been an established protocol for civil UAVs globally, operators should be vigilant for potential safety and legal risks during the flight. In landscape architecture measurement, UAVs usually fly quite high for a large-size site investigation that is hard to monitor with the naked eyes; since the UAV flight is usually controlled by its ground station, the on-board obstacle avoidance system will automatically turn off which would increase the crash risk. In urban environment where the clearance and the electromagnetic conditions are often more complicated than those in rural areas or the wild, the UAV measurement faces a number of uncertainties. Therefore, before each task, it is necessary to obtain the legal flight license according to local restrictions and get public permission from the communities on the site.

13. 西溪南村案例应用路径

13. The workflow of UAV application in the Xixinan Village case



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Secondly, storage, analysis, and rendering technologies of 3D data need to be improved. There is still not any broadly accepted 3D file format which supports the value assignment and parameter adjustment under a universal geographic coordinate system. Besides, the large volume of 3D point cloud dataset built on images requires a high-performance computer for calculation and rendering. The number of facet of the derived multi-facet model is considerable that cannot be well refined with existing reverse engineering algorithms. At present, however, common landscape design software still does not allow assignment or editing of 3D models, or any direct analysis or design of them. Specialized software for multi-facet modeling offers little help during other stages of the research, analysis, and design workflow. Therefore, in actual analysis and design scenarios, 3D data usually has to be reduced into 2D formats, or can simply be used for display.

In the future, the application of UAV measurement in landscape architecture research and practice might be much broader. Through the efforts by the UAV industry and government departments, the application and management regulations on UAV flights will be further established. The development of UAV design and manufacturing technologies is expected to improve the integration level of UAV while reducing its size and cost. The advances of UAV fleet control technology, built-in sensors, and path calculation, as well as the accuracy enhancement of 3D maps can improve the automatic control of UAVs. In addition, the development of point cloud database, Level of Detail (LOD), visual perspective renderings, 3D GIS analysis can support the analyses and editing of 3D data in design tools.

Besides, new scenarios of UAV application should be explored continuously in landscape architecture industry to encourage new methodologies of design and research as well as technique innovation in data collecting, information feedback, post-occupancy evaluation, and interaction between people and the environment with UAVs. These developments will contribute to the construction of sound multi-functional digital landscape information platforms, supporting the landscape digital design and research in 3D environment. **LAF**

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