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基于近地遥感的林木参数精细获取进展简述

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摘要:林木树冠自动分割、胸径、树高、冠幅、冠面积、材积等精细林木参数快速准确提取是森林生产力和碳储量等参数高精度估算的基础。近地遥感技术可以快速高效获取多视角高分辨率数据,具有高精度自动获取林木参数的潜力。对国内外利用地面和有/无人遥感技术开展森林精细调查的情况进行总结,全面阐述基于近地遥感的林木参数精细获取研究现状,重点讨论不同近地遥感平台多光谱和激光雷达数据中获取森林参数的效果与能力,并对比其应用场景和优劣性。近地遥感技术具备低成本、高效获取森林精细参数的能力,可为森林管理培育和经营决策、加快推进美丽中国建设提供重要技术支持。

关 键 词:林木参数;地面观测;近地观测;高分辨率影像;LiDAR点云
中图分类号:S712;TP79 **文献标志码**:A **文章编号**:1004-0323(2025)04-1015-11

1 引 言

森林作为陆地生态系统重要的组成部分,在全球碳循环、水循环和能量交换、气候变化以及人类文明的发展中扮演重要角色[1-3]。作为森林资源管理和监督的基础工作,森林资源调查在为林业经营服务的过程中起到了重要的作用[4-5]。传统通过实地人工测量进行样地调查的方式耗时费力、效率低、成本高,且调查精度受调查人员经验影响[6-9],例如树高、冠幅测量存在“看不到、测不准”的问题[10-12],难以满足新形势下自然资源调查监测体系中森林资源调查技术的要求。鉴于我国森林资源分布广、森林情况复杂、生长受干扰强的状况[13-14],实现调查样地自动、高效、准确信息提取对于促进森林资源的可持续发展、规划造林育林方案、提高森林质量与固碳能力、加强生态环境保护至关重要,已成为现阶段研究和应用的重要方向。

当前,遥感技术的发展已构成多平台(卫星、有/无人机、地基)、多角度、多模式(光学、LiDAR等)的立体观测体系[15-16],特别是近地遥感技术(包括有/无人机和地面平台)为精准、高效森林样地调查提供一种可行和通用的方法[17-20]。无论是数据获取速度还是数据精度都能够满足森林结构参数的精细化监测需求,这使得近地遥感技术在林业调查中快速得到应用[2,21-22]。目前,国内外学者针对森林单木参数遥感精细监测方面的研究已开展较多,例如应用光学遥感、LiDAR技术提取单木位置、胸径、冠幅、冠面积、材积、生物量等信息[3,7-8,18,21,23-25],这些研究也证明了近地遥感技术在单木参数提取方面的潜力,但对于复杂林分情况下的样地调查仍存在一定的难度和挑战。

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本研究聚焦于如何从不同技术重建的林木三维场景中提取单木参数这一主题内容，简要概述近地遥感技术不同观测方法的特点和适用场景，综述基于地面/近地 LiDAR 技术、摄影测量技术以及地面-近地多模态数据联合的林木精细参数获取的研究现状，并总结近地遥感林木参数提取技术发展方向。

2 近地遥感在森林资源精细监测中的应用

近地遥感技术包括有/无人机和地面平台两种，采集数据的方式及不同平台数据特点如图 1 所示。地面平台，即地面近距观测（Terrestrial Close-Range Observation，TCRO）重建的点云数据能够获取完整的树干及林下地形，因而可以准确获取树干、胸径等树木下部信息。星载、空地高分辨率影像或者无人机（Unmanned Aerial Vehicle，UAV）近距观测（UAV Close-Range Observation，UCRO）数据能够较好重建出树冠上部结构，因此树顶点和树高信息提取精度较高。但由于树冠的遮挡影响，单一平台观测存在不同程度林木三维全景描述能力不足的问题（图 1）。

2.1 有/无人机遥感在森林资源精细监测中的应用

空地观测或 UCRO 获得的高空间分辨率多角

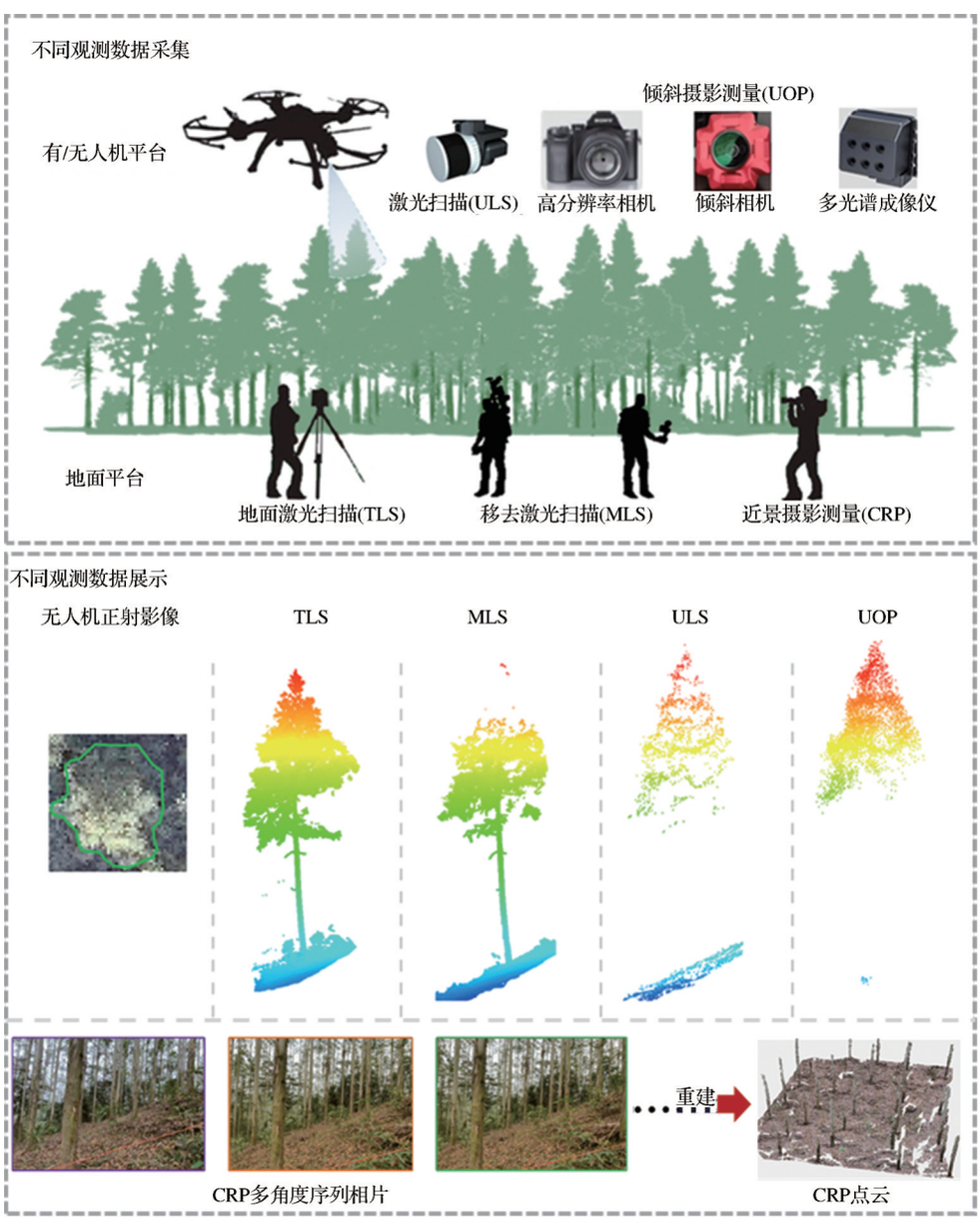

图 1 近地遥感数据采集及其特点

Fig.1 Near-ground remote sensing data acquisition and its characterization

度影像[26]、光探测和测距(Light detection and ranging, LiDAR)点云数据[5,27]已成为获取林木参数的主要数据源。空地或近地光学成像技术可从森林及其环境上方不同角度获取高空间分辨率影像,具有成本低、范围广、获取方便等优势[7,26],但对于郁闭度或密度高导致的影像上树冠重叠、冠型复杂以及树冠和背景之间相似易出现混淆的林分,树冠提取精度不高[3,18];且由于无法获取冠层以下林木参数以及复层林树冠参数,对于复杂森林环境下树冠信息提取难以实现[7,17]。

LiDAR技术是一种主动遥感方式,能够准确获取森林三维点云或波形数据[2,28,29],与光学遥感技术相比可以提供更多的森林垂直空间结构信息,在样地尺度、单木尺度、甚至叶片尺度的科学研究和实际林业调查工作中具有明显优势[30]。目前,利用机载激光扫描(Airborne Laser Scanning, ALS)数据提取森林树高的精度较高[31,32]。无人机激光扫描(UAV Laser Scanning, ULS)相较于ALS,灵活、高效、成本较低且具有较高的准确性[20]。然而有人机或UAV LiDAR扫描时由于相对较低的点密度易使树顶点信息遗漏导致树高测量偏低[33],且点云数据归一化处理易受地形坡度影响导致树冠变形扭曲及树高测量误差[34-35]。此外,树冠遮挡无法获取完整的树干结构以及生长竞争导致的多树重叠树冠、不规则的树冠形状等复杂森林环境,使得树冠参数提取仍存在一定的难度和限制[31,36]。

随着计算机视觉技术的发展,UAV倾斜摄影测量(UAV Oblique Photogrammetry, UOP)技术可以将垂直和倾斜不同视角同步采集的高分辨率多角度影像进行三维重建得到森林三维点云模型,进而获取林木空间位置信息以及结构信息[21,23,37],凭借其效率高、成本低的优势,在森林树高、树冠参数持续性监测方面具有独特优势[23,38]。但由于光学影像不具备穿透能力,因此在林分郁闭度较大的区域无法突破树冠遮挡严重的问题,影响了单木参数的提取精度[21,39]。

2.2　地面遥感在森林资源精细监测中的应用

TCRO技术主要包括地面激光扫描(Terrestrial Laser Scanning, TLS)、移动激光扫描(Mobile Laser Scanning, MLS)和近景摄影测量(Close-Range Photogrammetry, CRP)[40]。TLS点云数据提供了详细的森林三维结构信息[29,33,41],在低密度林分提取胸径、树高、冠幅、冠面积等单木参数方面具有较高的精度[33,42-43]。然而,在高密度森林环境由于树冠遮挡导致树冠上部信息缺少,造成了树高以及多树重叠情况下树冠参数无法准确提取[3,18,27]。此外TLS设备携带不便、多站扫描模式也限制了其在林业调查中的使用[29,44]。

随着即时定位与建图技术(Simultaneous Localization And Mapping, SLAM)解决了林下定位问题[45-46],MLS技术具备森林场景点云数据快速采集能力,并缓解一定程度树木遮挡效应[45,47],凭借背负式[48]、手持式[49]、头戴式[50]等多种数据采集方式,提升了林业调查中LiDAR技术的实用性[51-53]。但由于目前算法的限制,MLS点云密度和精度相对于TLS均存在一定差距[47],且无法完整采集树冠信息。

随着计算机视觉技术及消费级图像采集传感器技术的提升和普及,CRP技术可以对获取的多角度森林序列图像进行高度解释并提取特征[54-55],通过建立二维图像和三维真实场景之间的相关性获取描述森林场景地形和三维结构的点云信息[3,8,18],进而实现林木参数快速有效提取[56]。与TLS相比,CRP不仅能够提供相似的产品,还具有数据采集灵活便捷、效率高、成本低的优势[40,54],为林业调查提供一个实用、有效的解决方案。然而,由于图像采集过程中枝叶遮挡、光线昏暗、视角狭窄等影响,在密度高和地形复杂的林分,通过CRP技术重建生成的三维森林场景中缺少树木冠层信息[3,57]。

3　林木参数精细获取研究进展

根据数据类型和获取方式,本文将基于近地遥感技术的林木参数获取研究归纳为LiDAR技术(地面和近地平台)、UOP技术(近地平台)和CRP技术(地面平台)等3类。本章内容主要聚焦于从不同技术重建的三维场景提取林木参数的总体进展进行总结。

3.1　基于LiDAR技术的森林单木参数提取

近年来,随着LiDAR数据获取成本不断降低,应用于林业方面的研究也越来越多[2,18,28-29,58]。其中ALS/ULS提供了大面积和多种地形条件下森林自上而下的观测视角,通过获取的高分辨率点云描绘准确、详细的森林三维结构[18,31,59-60],已成为提取单木参数最有效、常用的技术手段之一。

针对ALS/ULS数据,研究者们开发了众多自上而下的方法,例如基于冠层高度模型(Canopy

Height Model, CHM)的局部最大值方法识别树顶点,结合分水岭分割[61-62]、山谷跟踪[63]、边缘检测[64]、形态学重建[65]、区域生长算法[21]、模板匹配[66]和深度学习[24,67-68]等算法实现单木分割,不同场景单木分割精度*F1*得分为0.70~0.95之间(*F1*得分介于0~1之间,值越大表示精度越高),然而这些方法对于有明显树顶点的针叶树效果较好,树冠不规则的阔叶树效果较差。此外对于具有隐藏特征的矮小亚冠层树不能较好提取[18,31]。为此,基于点云数据开发了k均值聚类[69]、均值漂移[23,27,70]、体素间距[71]、基于密度的空间聚类[72]、条件欧氏距离聚类[73]等方法以提高不规则树冠的检测率。但由于树冠遮挡无法获取完整的树干结构,在林分密度高、树冠形状不规则、边界不确定的相互连接树冠提取方面受到限制[3]。此外,相对较低的点云密度易造成树顶点的遗漏,影响树高测量精度及树冠检测能力[27,74-75]。

TLS从树冠下方观察森林垂直结构信息,通过生成数百万个激光脉冲创建高分辨率点云[2,76],提供了详细的森林三维结构和极其精细的毫米级几何度量特性[28-29,33,41],并能够直接测量或估计单木参数,包括胸径、树高、冠幅、冠面积、生物量和体积[2,33,42-43],成为ALS/ULS信息的重要补充。由于TLS点云偏向树木下部,因此更适合自下而上的单木自动分割方法,例如圆柱拟合获取树枝的连通性[31],修正节点相似计算的归一化分割方法[77]。然而,这些方法复杂、缺乏实用性,并且在多树冠重叠情况不能准确检测树冠边界[78-79]。此外,它们对点云数据质量具有严格要求,例如点密度和树干的完整性[79]。这无疑增加了数据获取成本(需要更多站TLS扫描),特别是复杂高密度森林环境,使其难以普及到林业调查中[29]。

MLS技术通过移动扫描的方式能够快速获取森林结构数据且一定程度上避免了树木遮挡效应[45,80],林木检测率方面优于TLS[81],同时MLS具有多种携带方式[47-50],例如背包激光扫描(Backpack Laser Scanning, BLS)、手持激光扫描(Hand-held Laser Scanning, HLS)等,增加了应用于林业调查中的适用性。然而,MLS通过集成SLAM算法实现林下定位[45,47,50],森林场景中相似的特征易导致路径漂移现象[45],因此MLS点云精度及参数测量精度均低于TLS(3%~10%)[82]。此外,MLS数据依赖于调查人员携带设备行走在森林中采集,数据获取能力相较于ULS仍有限,特别是对于地形复杂、高密度森林环境。

综上,LiDAR三维点云数据可以准确刻画森林垂直结构特征,但由于树冠的遮挡影响,单一平台LiDAR并不具备林木三维全景描述及单木完整检测能力,特别是在剧烈变化地形和高密度复杂林分条件中。综合使用ULS和TLS/MLS系统具有描绘完整森林场景以及准确获取单木参数的潜力,但目前仍鲜有该方面的研究工作。此外,LiDAR数据获取成本仍相对高昂,研究能够提供类似点云数据且低成本的技术(例如UOP、CRP),协同LiDAR技术构建三维模型及单木参数信息提取方法具有重要的应用价值。

3.2 基于倾斜摄影测量技术的森林单木参数提取

近年来,许多学者对UOP技术在森林参数提取方面的研究较为关注[21,38,83-85]。由于UOP技术获取的树冠表面点云提供了与ALS/ULS相似的产品,因此可以参考ALS/ULS数据处理方法提取单木参数信息。例如,Che等[83]将高分辨率UOP多角度像片进行三维重建获取三维点云、正射影像(Digital Orthophoto Map, DOM)及数字表面模型(Digital Surface Models, DSM),采用局部最大值算法获取树顶点计算树高,结果表明利用UOP像片获取的三维点云密度高于LiDAR点云2.7~3.1倍,树高提取R^2为0.91,rRMSE为16%,证明了UOP可以获得高密度点云及相对完整的冠层信息。利用运动恢复结构(Structure from Motion, SfM)技术重建的落叶松和油松林三维点云、DOM及DSM,提取树高、冠面积等参数精度均优于80%[38],表明UOP技术能够准确提取不同树种的单木参数,可满足大规模低成本林业调查的要求。由于UOP像片空间分辨率与飞行高度相关,直接决定了数据的获取效率,有必要确定最优空间分辨率,对于飞行参数确定以及减少数据冗余等方面具有重要意义[23,37]。因此,Yin等[21]使用UOP像片对杉木林进行三维重建,在提出的UOP单木参数提取框架的基础上,探究了不同空间分辨率影像对单木参数提取的影响,结果表明当空间分辨率为0.25 m时树高、冠面积提取效果较好。然而,这些研究中使用的数字地形模型(Digital Terrain Model, DTM)数据均通过LiDAR数据获取,原因在于UOP是一种被动遥感技术,在低郁闭度林分UOP点云生成的DTM与LiDAR点云生成DTM差异不大,而对于高郁闭度林分UOP

DTM精度相对较差。

总体上,UOP具有数据采集灵活便捷、效率高、成本低的优势,结合SfM技术可重建森林真实场景,可视化效果较好,也能够获得比ULS更密集的点云,并且还能提供森林冠层的光谱和纹理信息。但由于UOP多角度像片无法穿透至密林内部,导致高郁闭度林分林下地形、树高和树冠参数提取受限,因此更适用于疏林区域的单木分割及单木参数获取。此外,已开展直接使用DSM数据提取单木树冠参数的研究[86],但算法的适用性仍需进一步验证。

3.3　基于近景摄影测量技术的森林单木参数提取

随着计算机视觉技术以及消费级图像采集硬件的提升和普及,CRP技术能够将多角度林分序列相片进行特征点检测和点云加密处理,提取图像中林木位置和结构等特征信息,生成准确度较高的三维点云数据(图1),并可以提供地形信息以及林木空间点云信息[3,8,57]。与TLS相比,CRP技术不仅能够提供相似的产品,还具有数据采集灵活便捷、效率高、成本低的优势[54],正在成为林业调查中快速、高效提取林木参数的解决途径。例如,结合SfM和多视图立体摄影测量技术可以实现单木三维模型重建以及胸径、材积等单木参数的准确提取[87],精度可以达到95%。但由于这些研究中仅使用较小的树木,且在实际地面调查时对样地全部树木逐个拍摄耗费时间过长,因此该方法已经不能满足快速获取样地林木信息的要求。

近年来,研究者们开始挖掘利用CRP技术提取样地尺度单木参数方面的潜力,例如利用搭载RTK(Real-Time Kinematic)技术和电荷耦合器件CCD相机的设备采集林分序列相片,能够准确提取单木位置和胸径信息[88]。针对光照不均匀导致图像质量低的问题,提出一种利用多尺度Retinex增强图像、Harris+SURF算子进行特征匹配、基于几何约束的平面三角测量网络迭代插值算法重建三维模型进而提取单木位置和胸径的框架[55],并证明了利用消费级相机/移动手机采集序列图像重建的三维点云具有准确提取树位置和胸径的能力[54,89],胸径提取精度优于94.5%,材积提取精度优于90%。然而,由于林分中枝叶遮挡、光线以及视线角度等因素,在利用CRP技术完成序列图像数据的林地三维点云重建后,其生成的三维点云模型缺乏优质的林木冠层信息,导致无法高精度提取林木树高及树冠参数[3,55]。特别是在地形复杂、密度高的林分,重建的点云模型虽然对于树木位置和胸径具有较好的表现,但是树冠信息表达不足,因此现阶段对于CRP提取树高、树冠方面的研究很少。

总的来说,CRP技术为林木参数调查提供了低成本、快速的解决方案,在单木位置、胸径提取方面具有较大优势,但对于复杂森林环境下树高、树冠信息提取无法实现。研究如何充分发挥CRP技术准确提取单木位置、胸径的独特优势协同考虑林木竞争估算树冠参数的方案具有重要意义。

3.4　地面—近地主被动遥感技术联合的森林单木参数提取

TCRO(包括TLS、MLS和CRP)和UCRO(包括ULS和UOP)数据可以准确刻画森林结构特征,但由于树冠的遮挡影响,单一平台观测及参数提取技术存在不同程度林木三维全景描述能力不足的问题。目前,基于有限树冠点云或枝干信息的计算机模拟方法获取缺失的树冠信息,例如光线追踪算法[90]、点—线交点算法[91]等,一定程度上能够解决由于树冠遮挡导致单木树冠/树干信息获取不完整的问题[92],但这些方法针对相对简单环境和特定树种、模型参数复杂且模拟结果具有不确定性、对真实森林场景和竞争关系刻画困难[90,93]。

协同TCRO、UCRO从多个扫描视角观察的森林场景数据构建三维全景模型,可以从根本上解决单木完整检测和刻画的问题,为不同森林环境下单木分割及参数提取提供可能[94]。该技术结合TCRO准确获取地形、树位置、胸径及树冠下部信息和UCRO准确获取树顶点、冠层结构信息的优势,能够实现单木测树因子的准确、快速提取[95-96],特别是对于高郁闭度森林、复层林等复杂森林环境贡献巨大,因此现有近地多平台数据融合的单木参数提取精度达到95%以上。然而,树冠对生长空间的竞争导致树冠结构在垂直和水平方向上均存在异质性[2,97],而当前的单木分割技术未考虑参数间的相互关系,因此对于多树冠重叠、不规则对称的树冠形状等情况下树冠参数提取仍然具有一定挑战。

此外,需要注意的是,TCRO数据采集范围及效率取决于调查人员,因此TCRO数据覆盖范围一定程度上会影响TCRO和UCRO协同应用于大范围林木参数调查的实用性。

4 结 语

本研究对地面和有/无人机等不同平台搭载的多角度高分辨率相机和激光扫描仪等不同类型传感器获取的近地遥感数据，提取单木尺度胸径、树高、树冠、材积、生物量等精细林木参数信息的国内外先进技术方法进行综述整理。研究发现：

(1)TCRO和UCRO数据及其构建的三维模型，获得的数据包含的信息各有优势和限制，不同观测技术适宜于提取不同的单木和样地参数。TLS/MLS数据适用于提取树木冠层下部林木参数，如胸径、材积；ALS/ULS数据适用于提取树木冠层上部林木参数，如树高、冠幅、冠面积等；UOP和CRP技术虽然获取成本和效率相较于LiDAR点云具有优势，但由于不具备穿透冠层的能力，无法获取树高等参数；协同TCRO和UCRO数据具备高精度林木多参数联合获取的能力，但TCRO数据的获取范围限制了使用场景。

未来研究将继续以提高森林调查效率、代替人工调查为目标，研制可林冠上、林冠下自由飞行的无人机或者复杂环境中可自由行进的机器人/狗等关键技术和设备，对于森林资源调查业务具有重要应用价值。

(2)由于不同观测平台、传感器和观测角度具有较大差异，且存在误差的不确定性，尚未考虑参数间的相互关系等限制，因而仍面临单木参数提取能力缺乏的问题。此外，由于环境因素(光照、风等)、不同管理干预、林木竞争导致不规则树冠、多树冠重叠以及复层林等复杂森林环境，应用近地遥感技术提取单木参数仍面临挑战。

随着深度学习、计算机视觉、人工智能等技术发展，未来研究将重点协同前沿技术，从包含丰富空间纹理—光谱—垂直结构以及语义信息的近地多模态全景三维模型中提取精准且丰富的单木信息，对于提升森林资源调查和生态系统评估具有重要意义。

(3)目前参数提取仍然根据数据结构简单测量，例如通过树顶点到所在地面的长度计算树高，而实际森林环境中树木倾斜生长现象普遍存在，复杂地形环境中上述方法增加了树高测量的不确定性，从而导致生物量、碳储量等其他参数的估算误差。但目前鲜有将数据与树木生长特征协同考虑进行单木参数提取的研究工作。

因此，未来研究需充分发挥CRP、UOP、LiDAR等遥感技术获取单木参数的优势，协同实际森林场景下的林木生长及生物学特征，构建单木参数高精度提取方法，实现低成本、高效的森林精细调查，可为森林管理培育和经营决策、加快推进美丽中国建设提供重要技术支持。

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Brief Review on the Progress in Fine-scale Acquisition of Forest Parameters based on Near-ground Remote Sensing

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Abstract: Automatic crown segmentation, rapid and accurate extraction of diameter at breast height, tree height, crown width and crown area are the basis for high-precision estimation of forest productivity and carbon stocks. Near-ground remote sensing technology allow rapid and efficient acquisition of high-resolution data from multiple views, which have the potential for high-precision acquisition of forest parameters. Summary of domestic and international forest fine survey using ground and manned /unmanned aircraft remote sensing technology. Comprehensive description of the current status of research on fine acquisition of forest parameters based on near-ground remote sensing. Discussions focus on the algorithms for acquiring forest parameters based on near-ground remote sensing platform multispectral and LiDAR data, and compare their application scenarios and advantages and disadvantages. Near-ground remote sensing technology possesses the capability to acquire detailed forest parameters with low costs and high efficiency, providing crucial technical support for forest management, cultivation, operational decision-making, and accelerating the advancement of building a Beautiful China.

Key words: Forest parameters; Ground-based observations; Near-earth observations; High-resolution imagery; LiDAR point cloud