摘要

光度立体视觉通过在固定视角下采集目标在不同光照条件下的图像，实现表面法向量恢复，并进一步获取目标的精细三维形状信息。由于其成像配置相对简洁、对局部表面几何细节敏感等特点，光度立体视觉已被广泛应用于三维人脸重建、文物数字化和工业检测等领域。然而，在阴影、高光、全局光照、非朗伯反射和复杂几何等真实成像条件下，现有研究大多将光照视为给定的采集条件，主要关注法向量重建模型本身，而对有限光照预算下如何主动规划光照方向这一问题研究不足。实际上，在稀疏采集条件下，重建效果不仅取决于下游重建算法，也显著依赖于光照观测的选择方式。因此，面向光度立体视觉的光照规划问题具有重要的理论意义和应用价值。

本文围绕面向有限光照预算的学习型光度立体视觉光照规划问题展开研究，将光照从传统意义上的固定采集条件提升为主动感知框架下可控、可选择、可优化的测量设计变量。不同于在既定观测上被动执行表面法向重建，本文强调在采集阶段主动设计观测过程，即通过规划光照方向来提高观测的有效性、信息量与鲁棒性。特别是在有限采集预算和复杂真实成像条件下，不同光照所提供的观测质量存在显著差异，因此光照选择本质上是一个与下游法向估计紧密耦合的任务驱动优化问题。针对现有方法中启发式规则适应性不足、离散候选光照集合存在量化误差，以及缺乏真实系统执行与验证平台等问题，本文开展了从离散序列决策、连续在线控制到真实系统落地的系统研究。本文的主要工作与创新点如下：

(1) 提出了一种基于强化学习的光照规划方法 **ReLeaPS** (**Re**inforcement **Lea**rning-based illumination planning method for **P**hotometric **S**tereo)。针对传统启发式光照选择方法对复杂材质和不同重建模型适应性不足的问题，将光照规划建模为强化学习驱动的序列决策过程，以当前观测状态和已选光照信息作为输入，以光照方向选择作为动作，并以法向量重建质量为奖励信号，实现了面向重建目标的自适应光照选择。该方法能够在多步观测过程中综合利用历史采集信息，动态评估不同光照方向对后续重建的潜在贡献，从而避免局部启发式策略的局限性。实验结果表明，该方法能够在有限光照预算下有效改善多种光度立体方法的法向量重建结果，验证了强化学习用于光照规划问题的有效性和适用性。

(2) 提出了一种连续在线光照规划方法 **COIL-PS** (**C**ontinuous **O**nline **IL**lumination planning method for **P**hotometric **S**tereo)。针对离散候选光照集合所带来的量化误差和性能上限问题，进一步将光照规划从离散候选选择拓展到上半球连续空间中的在线方向预测。该方法利用中间法向量重建结果对后续光照方向进行动态优化，从而实现了连续可控的光照规划。相较于仅能在预定义候选集合中进行选择的离散方法，该方法能够更加灵活地适应当前重建状态，并在更大的搜索空间中寻找更具信息量的光照方向。实验结果表明，该方法能够降低离散候选集合对光照选择精度的限制，在相同光照预

算下获得更优的法向量重建结果，进一步证明了连续光照规划在提升光度立体性能方面的潜力。

(3) 构建了一套面向光照规划的真实光度立体采集与验证系统。针对现有研究主要停留在仿真或离线数据评估、缺乏真实执行闭环的问题，设计并实现了集成光照控制、图像采集、光照标定、HDR 成像、实验记录与结果评估于一体的闭环系统。该系统支持固定光照、启发式规划、离散学习型规划和连续在线规划等多种模式下的统一执行与公平比较。基于该系统进行的实验验证了 ReLeaPS 和 COIL-PS 两种学习型光度立体视觉光照规划方法在实际硬件约束、标定误差和动态范围受限等条件下仍具有较好的稳定性和有效性。

综上，本文将光照规划从传统光度立体中的附属采集设置提升为主动感知中的核心测量设计问题，构建了从离散序列规划、连续在线控制到真实系统验证的完整研究框架。本文主要面向受控主动光源条件下的光度立体采集场景，在该设定下相机、物体与光源之间的关系可以被控制。对于开放场景或自然光照条件下的光度立体问题，环境光干扰、未知光照和动态场景将进一步增加光照规划的难度。本文的研究为有限光照预算下的高效光度立体重建提供了新的思路，也为未来将任务驱动的光照规划扩展至弱受控或非受控环境中的主动光度感知系统奠定了基础。

关键词：光度立体视觉，光照规划，强化学习，连续在线控制，主动感知

ABSTRACT

Photometric stereo (PS) recovers surface normals from images captured under varying illumination conditions from a fixed viewpoint, thereby enabling the reconstruction of fine-scale three-dimensional (3D) surface geometry. Owing to its relatively simple imaging configuration and sensitivity to local surface geometric details, PS is widely applied in areas such as 3D face reconstruction, cultural heritage digitization, and industrial inspection. However, under realistic imaging conditions involving cast shadows, specular highlights, global illumination effects, non-Lambertian reflectance, and complex geometry, most existing studies treat illumination as a given acquisition condition and focus primarily on the reconstruction model itself, while paying limited attention to how illumination directions should be actively planned under a limited acquisition budget. Under sparse acquisition settings, reconstruction quality depends not only on the downstream reconstruction algorithm, but also on the informativeness of the selected illumination observations. Illumination planning (IP) for PS is therefore of both theoretical significance and practical value.

This thesis investigates learning-based IP for PS under limited illumination budgets by treating illumination as a controllable, selectable, and optimizable measurement-design variable in active sensing. To address the limited adaptability of heuristic illumination selection, the quantization-induced limitations of discrete candidate sets, and the lack of real-world execution and validation platforms in existing studies, this thesis develops a unified framework spanning discrete sequential decision-making, continuous online control, and real-world system deployment. The main contributions of this thesis are summarized as follows:

- **A Reinforcement Learning-based illumination planning method for Photometric Stereo, termed ReLeaPS.** To overcome the limited adaptability of conventional heuristic illumination selection methods to complex materials and different reconstruction backbones, IP is formulated as a reinforcement learning-based sequential decision-making problem. The current observations and previously selected illumination directions are treated as the state, the next illumination direction as the action, and normal reconstruction quality as the reward signal. This formulation enables adaptive illumination selection driven by reconstruction objectives. Experimental results show that the proposed method effectively improves surface-normal reconstruction results across multiple PS methods under limited illumination budgets.
- **A Continuous Online ILlumination planning method for Photometric Stereo, termed COIL-PS.** To address the quantization-induced limitations and performance ceiling imposed by predefined discrete candidate sets, IP is further extended from discrete candidate selection to continuous illumination direction prediction over the upper hemisphere. The proposed method dynamically refines subsequent illumination directions based on intermediate normal reconstruction results, thereby enabling continuous online illumination control. Experimental results demonstrate that the proposed method alleviates the quantization-induced limitations of discrete candidate sets and achieves improved surface-normal reconstruction results under the same acquisition budget.

- **A real-world PS acquisition and validation system for IP.** To bridge the gap between simulation-based evaluation and practical deployment, a closed-loop system integrating illumination control, image acquisition, illumination calibration, HDR imaging, experimental logging, and result evaluation is developed. The proposed system supports unified execution and fair comparison across multiple acquisition modes, including fixed-illumination acquisition, heuristic planning, discrete learning-based planning, and continuous online planning. Real-world experiments verify that the proposed learning-based IP methods remain reasonably stable and effective under practical factors such as hardware constraints, calibration errors, and limited dynamic range.

In summary, this thesis elevates IP from a secondary acquisition setting in conventional PS to a central measurement-design problem in active sensing. It establishes a coherent research framework spanning discrete sequential planning, continuous online control, and real-world system validation. The thesis mainly focuses on PS acquisition under controlled active illumination, where the relationship among the camera, object, and light source can be controlled. For PS in open scenes or under natural lighting conditions, ambient light interference, unknown illumination, and dynamic scenes further increase the difficulty of IP. This research provides a new perspective on efficient PS under limited illumination budgets and lays the foundation for extending task-driven IP toward weakly controlled or uncontrolled active photometric sensing systems in the future.

KEY WORDS: photometric stereo, illumination planning, reinforcement learning, continuous online control, active sensing