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石河子大学

硕士学位论文

基于无人机的棉田残膜污染在线评估系统设计与研究

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申请学位门类级别　专业硕士
学科、专业名称　机械
研究方向　机械工程
所在学院　机械电气工程学院

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Design and Research of Online Evaluation System for Cotton Field Residual Film Pollution Based on UAV

A Dissertation Submitted to

Shihezi University

In Partial Fulfillment of the Requirements

for the Degree of

Master of Engineering

By

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Mechanical

(Mechanical Engineering)

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摘 要

棉花是我国重要工业原料与战略资源，对保障民生、稳定纺织产业、维护产业链安全意义重大。目前棉花种植广泛采用覆膜技术，长期使用造成残膜在土壤中持续累积，导致耕地质量下降、作物减产，并引发土壤白色污染，残膜污染治理已刻不容缓。治理过程中，除研发回收机具外，残膜污染快速精准评估同样关键。传统人工采样评估劳动强度大、效率低、时效性差，无法满足大面积棉田快速评估需求。无人机技术为残膜污染在线评估提供了新思路，但实际应用中仍有以下不足，无人机一体化自动快速在线评估未完全实现，不规则棉田采样点布设不合理，不同光照会干扰残膜分割精度，且缺乏浅层残膜污染预测方法，这些均影响评估质量与效率。本文以棉田残膜污染精准高效在线评估为目标，构建一体化在线评估系统，为残膜污染治理与棉田生态可持续发展提供技术支撑。主要研究内容与结论如下：

(1) 系统总体架构设计。针对棉田残膜污染高效在线评估的实际需求，本研究明确系统核心功能与设计方向，构建涵盖软硬件、核心算法及系统集成的完整技术框架。选用 DJI Mavic 3M 行业级多光谱无人机作为数据采集终端，负责棉田残膜图像及相关参数采集。借助 DJI 上云 API，设计“端边云用”四层架构，构建棉田残膜污染评估 APP 与 Web 端开发框架，满足棉田在线评估系统的实际应用需求。

(2) 无人机采样及路径规划研究。针对传统五点采样法布点不均、地块边界适应性差、样本代表性不足的问题，本研究设计适用于大面积不规则棉田的基于几何中心的辐射式采样方法，实现采样点自动均匀布设。将采样点与作业起始点共 6 个点位抽象为规模 N=6 的旅行商问题，完成无人机飞行路径规划及算法实现并开展对比试验。结果表明，Held-Karp 算法在该小规模 TSP 路径规划中兼顾路径质量与规划效率，可稳定找到全局最优路径，平均规划时间 0.06963 s，能有效应用于无人机棉田残膜污染评估路径规划，显著提升评估效率与精准度。

(3) 基于无人机的棉田表层残膜检测方法研究。针对新疆棉田残膜污染评估中，现有分割方法漏检率高、抗光照干扰弱的问题，本研究以新疆典型棉区为研究区域，采集多地块、多光照条件下的残膜数据，经预处理构建标准化数据集。在原始 U-Net 基础上，嵌入改进 ASPP 模块、引入 CBAM 注意力机制并融合 InceptionV4 结构，构建 AIC-UNet 残膜分割模型，通过对比实验与消融实验验证模型性能。结果表明，该模型分割性能优异（Pa 99.78%、F1-Score 90.34%、mIoU 88.59%），单幅图像分割耗时增幅较小，预测覆盖度与真实值相关性良好（R^2 0.968、*RMSE* 0.07318、*PCC* 0.98393）。本研究提出的 AIC-UNet 模型有效解决了复杂场景下残膜分割精度低的问题，为棉田残膜污染量化评估提供了可靠技术支撑。

(4) 基于无人机的棉田浅层残膜含量预测方法研究。棉田浅层残膜含量是评估残膜污染程度的核心指标，现有基于人工采样称重的含量测算方法存在劳动强度大、效率低、空间代表性差等问题，难以满足规模化棉田残膜污染精准管控需求。研究以棉田浅层残膜重量及无人机地表残膜图像为对

象，建立无人机图像特征与重量预测技术途径。通过实验发现 300 个样本的残膜覆盖率与重量呈正相关（R^2=0.79635，*PCC*=0.89239），RDTR-Net 模型凭借 ResNet50、Transformer、Dice-CE Loss 及岭回归融合优势实现的预测模型表现最优（R^2=0.853，*RMSE*=0.1009）。该方法较传统人工采样大幅缩短评估时间、降低成本且无损土壤，为棉田残膜污染大规模高精度监测及精准治理提供技术支撑与数据支持。

(5) 基于无人机的棉田残膜污染在线评估系统开发及田间验证。设计并开发一套基于无人机平台的棉田残膜污染在线评估系统，并通过田间试验对系统性能与应用效果进行验证。将系统各功能模块进行整合，集成了基于几何中心的辐射采样点布设与 Held-Karp 路径规划算法、AIC-UNet 模型以及 RDTR-Net 模型。前端采用 Vue.js 框架搭建棉田残膜污染在线评估平台的网页界面，并基于 Android Studio 完成无人机采样移动端 APP 的设计与开发。后端以 Spring Boot 为核心框架，实现了系统各功能模块与数据库的构建，同时通过系统测试验证了整体功能的可靠性与运行稳定性。实现无人机采样、数据传输、模型解算与污染评估全流程自动化一体化作业。田间试验结果表明，系统评估平均相对误差为 8.2%，单区域平均评估时长 412 s，可有效弥补传统残膜评估方法存在的不足，为棉田残膜污染实现快速、精准、高效的在线评估提供有力技术支撑。

关键词：棉田残膜污染；路径规划；信息预测；深度学习；无人机系统

Abstract

Cotton is an important industrial raw material and strategic resource in China, which is of great significance to protect people 's livelihood, stabilize the textile industry and maintain the safety of the industrial chain. At present, film mulching technology is widely used in cotton planting. Long-term use has caused the continuous accumulation of residual film in the soil, resulting in the decline of cultivated land quality, crop yield reduction, and soil white pollution. It is urgent to control residual film pollution. In the process of treatment, in addition to the development of recycling equipment, rapid and accurate assessment of residual film pollution is also critical. Conventional manual sampling-based evaluation entails substantial labor input, low efficiency and poor timeliness, which cannot meet the needs of rapid evaluation of large-area cotton fields. UAV technology provides a new idea for on-line assessment of residual film pollution, but there are still the following shortcomings in practical application. The integrated automatic and rapid on-line assessment of UAV is not fully realized. The layout of sampling points in irregular cotton fields is unreasonable. Different illumination will interfere with the accuracy of residual film segmentation, and there is a lack of prediction methods for shallow residual film pollution, which all affect the quality and efficiency of assessment. Aiming at the accurate and efficient online assessment of residual film pollution in cotton fields, this thesis constructs an integrated online assessment system to provide technical support for residual film pollution control and ecological sustainable development of cotton fields. The main research contents and conclusions are listed below:

(1) The overall system architecture design. Aiming at the actual needs of efficient online evaluation of residual film pollution in cotton fields, this study clarifies the core functions and design directions of the system, and constructs a complete technical framework covering software and hardware, core algorithms and system integration. The DJI Mavic 3M industry-level multispectral UAV is selected as the data acquisition terminal, which is responsible for the collection of cotton field residual film images and related parameters. With the help of DJI 's cloud API, a four-layer architecture of ' end-to-end cloud use ' was designed to construct a cotton field residual film pollution assessment APP and Web-side development framework to meet the practical application requirements of the cotton field online assessment system.

(2) Research on UAV sampling and path planning. Aiming at the problems of uneven distribution of traditional five-point sampling method, poor adaptability of plot boundary and insufficient representativeness of samples, this study designed a radial sampling method based on geometric center suitable for large-area irregular cotton fields to realize automatic and uniform layout of sampling points. A total of 6 points from the sampling point and the starting point of the operation are abstracted as a traveling

salesman problem with a scale of $N = 6$. The UAV flight path planning and algorithm implementation are completed and comparative experiments are carried out. The results show that the Held-Karp algorithm takes into account the path quality and planning efficiency in the small-scale TSP path planning, and can stably find the global optimal path. The average planning time is 0.06963 s, which can be effectively applied to the path planning of residual film pollution assessment in UAV cotton field, and significantly improve the evaluation efficiency and accuracy.

(3) Research on detection method of surface residual film in cotton field based on UAV. In the evaluation of residual film pollution in cotton fields in Xinjiang, the existing segmentation methods have the problems of high missed detection rate and weak resistance to light interference. In this study, the typical cotton area in Xinjiang was taken as the research area, and the residual film data under multi-plot and multi-light conditions were collected. After preprocessing, a standardized data set was constructed. On the basis of the original U-Net, the improved ASPP module is embedded, the CBAM attention mechanism is introduced, and the InceptionV4 structure is integrated to construct the AIC-UNet residual membrane segmentation model. Extensive comparative and ablation experiments are carried out to validate the performance of the proposed model. The results show that the model has excellent segmentation performance (Pa 99.78 %, F1-Score 90.34 %, mIoU 88.59 %). The time-consuming increase of single image segmentation is small, and the predicted coverage has a good correlation with the real value (R^2 0.968, *RMSE* 0.07318, *PCC* 0.98393). The AIC-UNet model proposed in this study effectively solves the problem of low segmentation accuracy of residual film in complex scenes, and provides reliable technical support for quantitative evaluation of residual film pollution in cotton fields.

(4) Research on prediction method of shallow residual film content in cotton field based on UAV. The content of shallow residual film in cotton field is the core index to evaluate the degree of residual film pollution. The existing content measurement methods based on manual sampling and weighing have the problems of high labor intensity, low efficiency and poor spatial representativeness, which are difficult to meet the needs of precise control of residual film pollution in large-scale cotton fields. The research takes the weight of shallow residual film in cotton field and the image of UAV surface film as the object, and establishes the technical way of UAV image feature and weight prediction. Through experiments, it was found that the residual film coverage of 300 samples was positively correlated with weight ($R^2 = 0.79635$, $PCC = 0.89239$). The RDTR-Net model performed best with the advantages of ResNet50, Transformer, Dice-CE Loss and ridge regression ($R^2 = 0.853$, $RMSE = 0.1009$). Compared with traditional manual sampling, this method greatly shortens the monitoring time, reduces the cost and does not damage the soil, and provides technical support and data support for large-scale high-precision monitoring and precise treatment of residual film pollution in cotton fields.

(5) Development and field verification of online evaluation system for residual film pollution in

cotton field based on UAV. An on-line evaluation system for residual film pollution in cotton fields based on UAV platform was designed and developed, and the performance and application effect of the system were verified by field experiments. The functional modules of the system are integrated, and the radiation sampling point layout and path planning algorithm based on geometric center, AIC-UNet model and RDTRNet model are integrated. The Vue.js framework is used to build the web interface of the online evaluation platform of cotton field residual film pollution, and the design and development of the UAV sampling mobile APP is completed based on Android Studio. The back-end uses Spring Boot as the core framework to realize the construction of each functional module and database of the system. At the same time, the reliability and operation stability of the overall function are verified by system test. The automatic integration of UAV sampling, data transmission, model calculation and pollution assessment is realized. The results of field experiments showed that the average relative error of system evaluation was 8.2 %, and the average evaluation time of single area was 412 s, which could effectively make up for the shortcomings of traditional residual film evaluation methods and provide strong technical support for rapid, accurate and efficient online evaluation of residual film pollution in cotton fields.

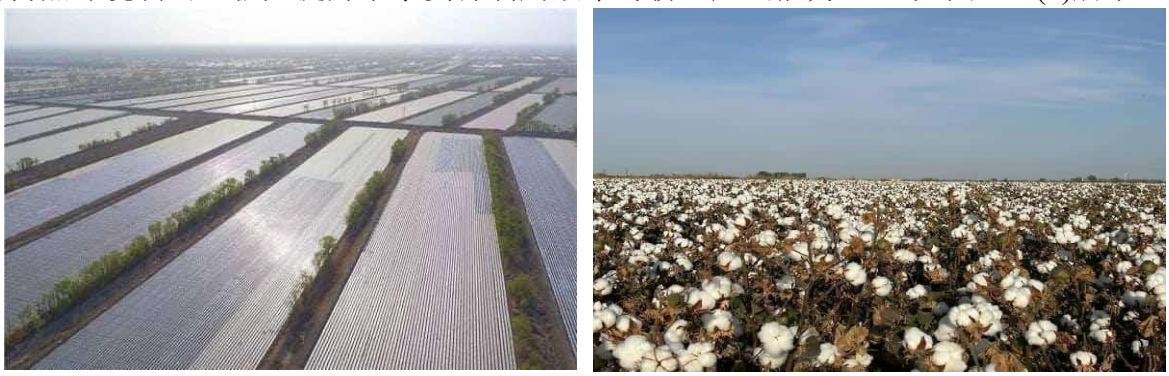
Key words: cotton field residual film pollution; path planning; information prediction; deep learning; UAV system

目 录

第 1 章 绪论

1.1 研究背景及意义

在现代农业生产体系中，地膜已成为仅次于种子、化肥、农药的第四大核心农业生产资料，对保障作物产量、提升农业生产效益具有不可替代的重要作用[1]，覆膜种植技术作为保障棉花高产稳产的关键措施，在我国棉花主产区广泛应用，如图 1-1 (a)所示。其中新疆作为我国最大的优质棉生产基地，棉花种植面积与产量均居全国首位，地膜覆盖普及率更是高达 95%以上，地膜的大规模应用有效抵御了新疆干旱少雨、昼夜温差大的自然环境制约，极大提升了水资源利用效率与耕地产出能力[2-4]，如图 1-1 (b)所示。

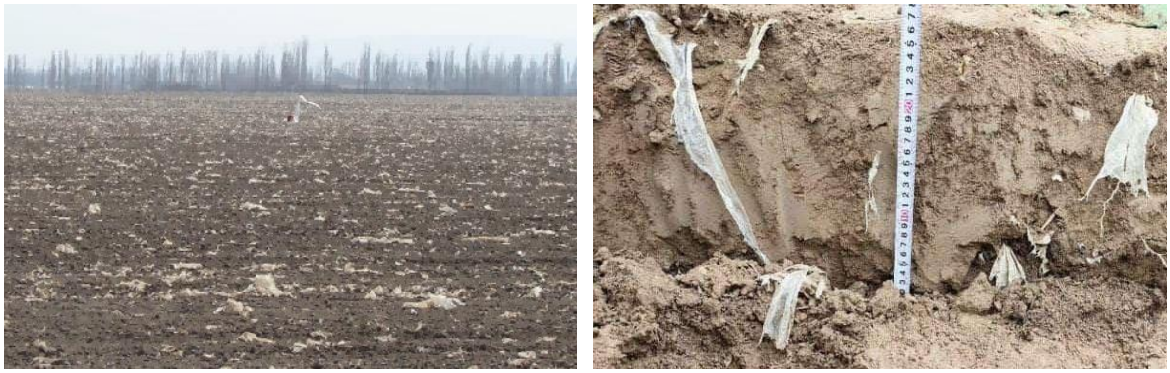


(a) 地膜覆盖种植技术 (b) 新疆棉花主要产区

图 1-1 新疆棉区地膜覆盖种植模式

Fig.1-1 The plastic film mulching planting model in Xinjiang cotton-growing areas.

但长期以来，受地膜材质、回收技术、种植模式等多重因素影响，新疆棉田地膜回收利用率偏低，大量残膜在土壤中逐年累积，引发土壤水分运移受阻、微生物群落改变、作物产量下降、环境污染等问题，形成了突出的棉田残膜污染问题[5-8]，如图 1-2 所示。



(a) 表层残膜污染 (b) 耕层残膜污染

图 1-2 棉田残膜污染情况

Fig.1-2 The pollution situation of residual plastic films in cotton fields.