基于编码结构光的高铁轮轨姿态三维重建

3D Reconstruction of high-speed rail-wheel based on coded structured light

项目概况 OVERVIEW

2019/04-2020/07
国家级大学生创新训练计划项目
项目依托于国家重大科研仪器研制项目——基于高精度结构光的高速铁路轮轨动态接触姿态检测系统，轨道交通智能检测与监测研究所

项目团队 TEAM OF 5

唐麒(Qi Tang)、罗瑶(Yao Luo)、赵彦阳(Yanyang Zhao)
指导教师(Advisor)：尹辉(Hui Yin)、黄华(Hua Huang)

主要工作 MY ROLE

项目负责人，完成结构光编码、解码方案设计、可视化软件设计、构建与编码
Principal Investigator, Design and encode structured light pattern,decoding algorithm and software

核心技术 CORE TECHNOLOGY

相机标定、三维重建、点云渲染；软件基于 C++、QT+OpenCV+PCL 开发
Camera calibration, 3D reconstruction, point cloud rendering; software development based on C++ and QT+OpenCV+PCL.

项目目标 GOAL

对基于空间编码结构光的三维重建方法进行研究，根据项目应用场景提出自己的解决方案，提取高铁轮轨的稠密点云，重建轮轨三维模型，并完成软件的构建编码与封装。
Research the 3D reconstruction method based on spatially coded structured light. Propose our own solution according to the application scenario, and extrcat the dense point cloud of high-speed rail-wheel, reconstruct the 3D model of rail-wheel and design a visualization software.

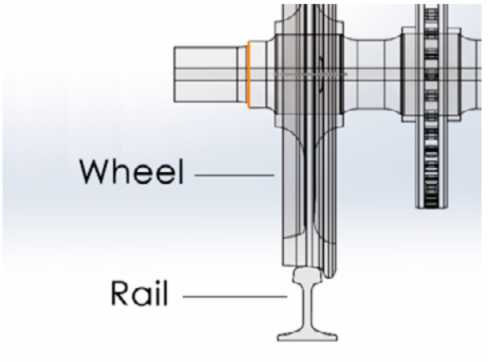
- √ 亚像素级条纹中心的提取
  Extractaction of stripe center at sub-pixel level
- √ 小波变换增加点云稠密度
  Increase the density of point cloud by wavelet transform
- √ 构建三维重建全流程平台
  Construct the whole process platform of 3D reconstruction

近年来，中国高铁发展迅速，高铁技术不断走出国门。我国已经成为运营里程最长，动车组运行最多的国家。

In recent years, China's high-speed rail has developed rapidly, and high-speed rail technology has gone abroad. China has become the country with the longest operating mileage and the largest number of EMUs.

保障高铁运行安全是铁路部门的重中之重。

Ensuring the safety of high-speed rail is the top priority of the Ministry of Railways.



正常轮轨姿态

Normal wheel-rail interaction

轮轨姿态反映着列车运行中轮轨间复杂的动态相互作用和约束关系，掌握高铁轮轨姿态是保障高铁安全运营的基础。

The wheel-rail interaction of high-speed rail reflects the complex dynamic interaction and constraint relationship between wheel and rail and is an important foundation to ensure the safey of high-speed railway.

仅从二维图像上获取轮轨姿态不精确，故需提取轮轨表面特征点，重建出三维模型。

It is not accurate to obtain the wheel-rail interaction only from 2D images, so it is necessary to extract the feature points of the wheel-rail surface and reconstruct the 3D model.

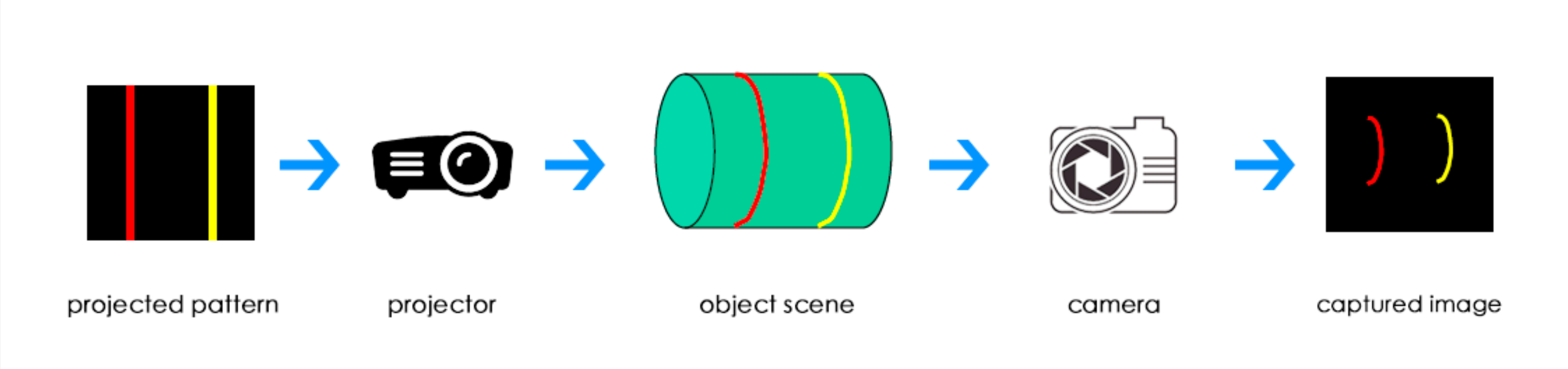
2D->3D

编码结构光法

Structured Light Projection

由投影仪将编码图案投影到被测物体的表面，摄像机在另一个角度对进行同步拍摄，再将捕获的结构光图像输入计算机，进行解码处理，最后再根据系统标定的结果来计算特征点的三维坐标。空间编码可以单次投影完成三维重建。

The projector projects the structured light coding pattern onto the surface of the measured object, then the camera shoots the image at another angle. Then the captured image was input into the computer for decoding. Finally, the three-dimensional coordinates of the feature points are calculated according to the results of the system calibration. Space Codification can complete 3D reconstruction by one shot.



Pattern Encoding/Decoding

编码结构光三维重建步骤

Proposed 3D Reconstruction Steps and Algorithm

系统标定 System Calibration

系统由摄像机、投影仪和计算机组成，标定的目标是计算摄像机和投影仪内参矩阵、镜头畸变系数和两者之间相对位置的外参矩阵。

The system consists of a camera, a projector and acomputer. The goal of calibration is to calculate the internal parameter matrix and the lens distortion coefficient of the camera and the projector and the external parameter matrix of the relative position between the two.

结构光编码 Structured Light Encoding

通过编码的方式使投影图像每一点的“身份”可以被识别。

The "identity" of each point of the pattern can be identified through coding.

图像获取 Image Capture

投影仪向物体投射编码结构光图案，图案会随物体表面形状的调制而发生畸变，摄像机拍摄被物体调制过的结构光图像。

The projector projects the coded structured light pattern on the surface of the target, and the pattern will be distorted with the modulation of the surface shape of the object. What is captured by the camera is the structured light image modulated by the object.

结构光解码 Structured Light Decoding

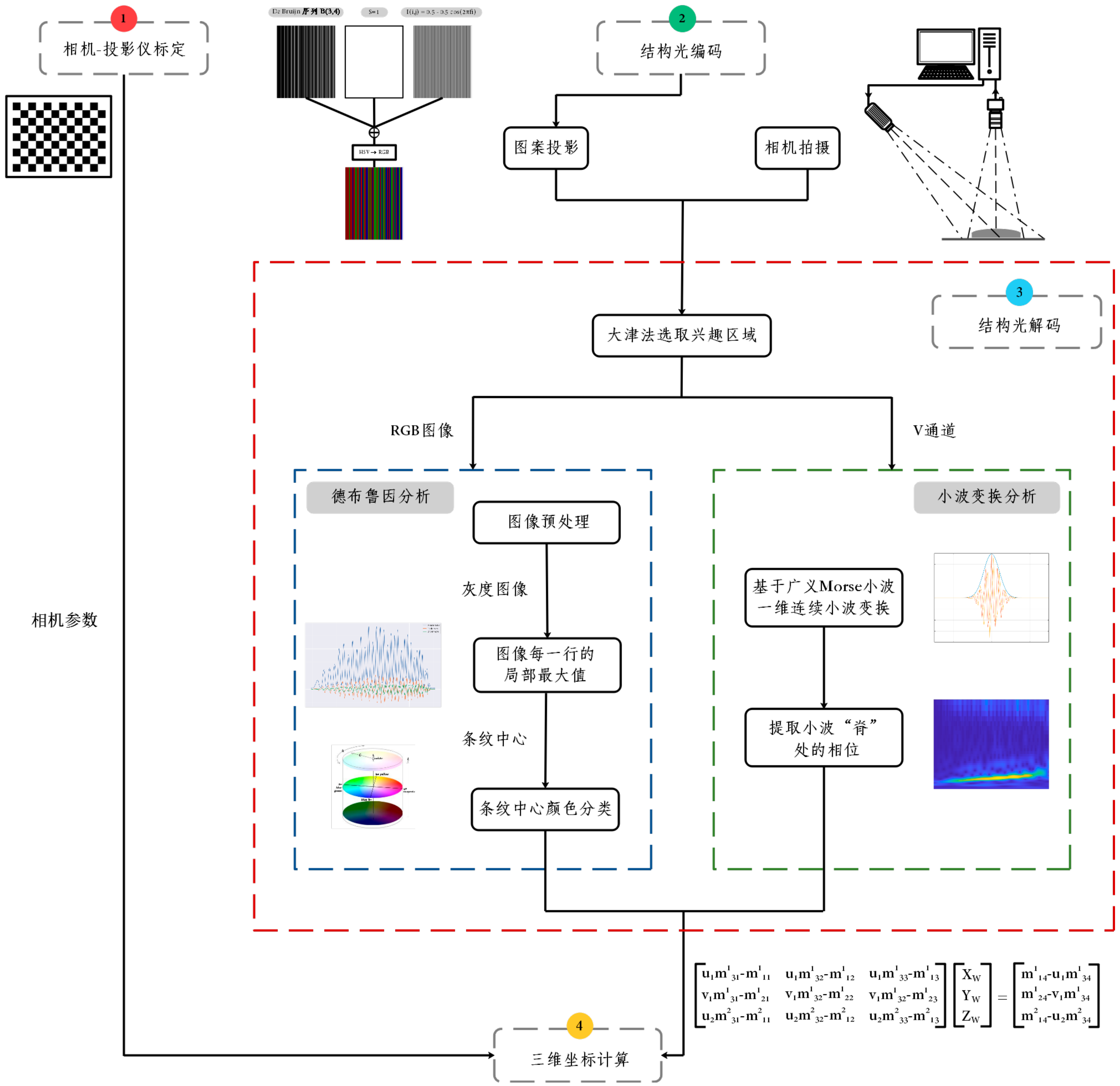
对捕获的结构光图像进行解码，解码的方法取决于编码的方法，目的是建立相机平面和投影平面特征点之间的对应关系。

Decode the captured structured light image, the decoding method depends on the encoding method.The purposeis to establish the correspondence between the feature points of the camera plane and the projection plane.

三维坐标计算 3D Coordinate Calculation

利用解码算法得出的特征点对应关系和系统标定结果，基于三角测量原理求出特征点的三维信息。

Using the corresponding relationship between the feature points and the calibration results, the 3D information of the feature points are obtained based on the principle of triangulation.



基于空间编码结构光的稠密重建算法

One Shot and Dense Reconstruction Algorithm

图案设计 Pattern Creation

图案由彩色正弦条纹图案组成，不同条纹的颜色(H 通道)遵循 De Bruijn序列，对于图案的所有像素，S通道均设置为1，V通道由余弦函数计算得到。

The pattern consists on a colored sinusoidal fringe pattern, where the color of the different fringes follows a De Bruijn sequence, which maps the value of H channel. The S channel is set to 1 for all pixels the V channel is calculated by the sinusodial signal.

德布鲁因分析 DeBruijn Analysis

为获得条纹中心点的位置，采用局部最大值算法从类似“高斯”形状的条纹灰度图像中提取图像每一行的局部最大值（以亚像素精度检测），并在 Lab 颜色空间下对中心点的颜色进行分类。

To extract the center point of the stripes, a local maximum algorithm is applied to searching local maxima (detected with sub-pixel precision) of each row of the image from the strips which is present a gaussian-like shape, and the color of center point is classified in the Lab space.

小波变换分析 Wavelet Transform Analysis

捕获图像的V通道包含了条纹的相位，比较了一维、二维的加窗傅里叶变换和小波变换后，选择基于广义 Morse 小波的小波变换方法分析，可以获得条纹的包裹相位。将DeBruijn分析与小波分析的结果结合，即可获得非条纹中心点的位置。

The V channel of the captured image contains the phase of the fringe. After comparing the 1D and 2D WFT and WT, the WT whose mother wavelet is generalized Morse wavelet to analyze. The wrapped phase is obtained. Combining the results of DeBruijn analysis and wavelet analysis, the position of the non-center point can be obtained.

评价指标 Evaluating Indicator

95mm的球体，提取表面点云17W+，半径误差0.678mm，运算时间10-15s。

For a sphere with a radius of 95 mm, the 17W+ surface point cloud is extracted, the radius error 0.678mm, and the calculation time is 10-15s.

结构光三维重建软件

Structured-Light 3D Reconstruction Software

核心技术 Core Technology

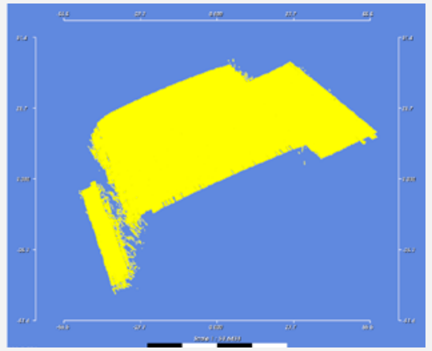
软件以 C++ 作为开发语言并基于 QT 框架进行界面开发，依赖于 OpenCV 和 PCL (Point Cloud Library) 进行图像和点云数据处理。在开发上采用了单例模式、责任链模式等设计模式。

The software uses C++ as the development language and the interface development is based on the QT framework, which relies on OpenCV and PCL (Point Cloud Library) for image and point cloud data processing. It adopts some design patterns such as singleton pattern and chain of responsibility pattern, etc.

主要功能 Main Function

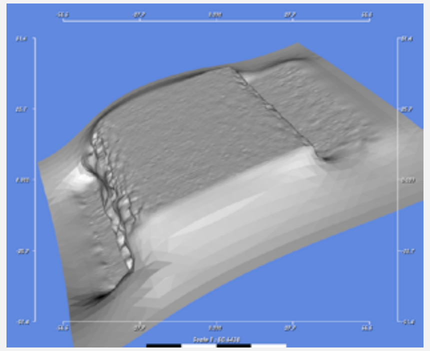
软件集三维重建整个流程为一体，主要实现系统（相机与投影仪）标定、三维重建和点云渲染三个功能。

The software integrates the entire process of 3D reconstruction, and implements the three functions of system calibration, 3D reconstruction and point cloud rendering.



铁轨点云渲染展示

Rail Point Cloud Display



铁轨泊松重建结果

Rail Poisson Reconstruction Result

软件功能展示 - 重建球体

Function Display-Reconstruct a Sphere

系统标定

Calibration

三维重建

3D Reconstruction

点云渲染

Point Cloud Rendering