

基于三维激光点云的枕簧几何尺寸测量方法

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摘要 枕簧是铁路货车减振装置的关键部件,发挥着承载和缓冲的作用,其尺寸直接影响车辆的减振能力与特性。为保证行车安全,铁路货车段修和厂修时必须对枕簧几何尺寸等进行测量与检查。为提高枕簧检修过程中的测量效率,提出了一种基于三维激光点云的枕簧几何尺寸测量方法。该方法采用线激光传感器获取了枕簧三维点云数据,利用下采样和 k -means 聚类等算法实现了点云数据的预处理,然后通过平面拟合利用高度测量算法测量了枕簧高度;经过点云降维、边缘提取、圆分割后利用改进的圆拟合算法测量了枕簧内、外直径。搭建试验平台进行了测量算法的精度、可靠性和重复性试验。结果表明:测量 10 组不同枕簧,最大平均误差在 ± 0.35 mm 内,平均测量时间为 2.7 s;测量 4 组枕簧 10 次,最大平均误差在 ± 0.35 mm 内,重复性小于 3%。测试结果具有良好的精度和稳定性,满足检修规程和检修工艺要求。

关键词 测量; 枕簧测量; 三维点云; 线激光传感器; 平面拟合

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1 引言

在铁路货车运行过程中,减振弹簧和摇枕弹簧(以下称枕簧)承受着主要载荷,各组枕簧的尺寸将直接影响车辆的行驶安全。按照工艺规定,枕簧在组装之前必须经过严格的测量和选配^[1-2]。随着《中国制造 2025》的提出和工业 4.0 时代的到来,为实现铁路货车运输市场快速稳定的发展,迫切需要实现转向架的自动化和智能化检测,同时提高检测效率和检测准确度。枕簧检修作为铁路货车转向架段修项目之一,对于铁路货车检修工艺的发展有着重要的意义^[3]。

在枕簧检测方面,科研人员已经得到一定的研究成果,但多以专利为主,检测方法相关的论文较少。段乐^[4]以 3D 结构光视觉技术为基础,结合机械结构和电气设计及信息处理等技术设计出一套枕簧智能检测系统,完成了枕簧半径及高度检测等项目,但利用该方法采集数据时须停止枕簧运输,效率不足。Liu 等^[5]提出了一种基于单目视觉标定的枕簧测量方法,该方法在测量效率方面有着较大的优势,但是其无法长时间进行稳定的枕簧尺寸测量。李传翔等^[6]研制了一种 3D 视觉检测和智能选配相结合的枕簧检测系统,基于 3D 点云实现了枕簧的高效测量和选配,但关于测量方法的相关描述较少,且测量精度和测量

效率未给出具体数据。目前枕簧测量算法的相关研究仍存在测量效率低、稳定性不足和精度不高等问题。

近年来,随着低成本三维成像设备的出现和专业三维点云采集技术的发展,三维点云处理技术愈发成熟^[7]。高佳月等^[8]提出了一种基于局部边缘特征描述子的自适应边缘检测算法,可以对输入点云特征进行参数自适应调整,增加边缘提取的准确度。Zhao^[9]提出了一种基于曲率和点云密度的精确去噪算法,该算法对点云进行去噪处理时,对公共点云、文物点云和室外点云等数据的去噪效果良好,点云预处理效果有较大提升。Huang 等^[10]以 Pratt、Taubin 和 Hyper 等 7 种圆弧拟合算法为基础,提出了一种将重复性最小截平方和(RLTS)思想与公平平滑函数结合的新型带噪声空间点云圆弧拟合算法,算法具有较高的准确率和再现率,抗噪声能力较强,在精密测量中具有良好的应用前景。Nurunnabi 等^[11]提出了两种适用于存在异常点的不完整三维点云数据的圆拟合算法,算法具有较强的鲁棒性,其处理结果优于 Hyper、LTS 和 LMS 等算法。Shi 等^[12]提出了基于球面目标拟合的一种新的有限随机搜索算法,算法具有较高的精度和效率,适用于多区域点云拟合。上述部分点云处理技术已被用于物体的距离和体积测量^[13-14]。邓磊等^[15]针对交联聚乙烯电缆接头反应力锥参数的测量问题,

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提出了一种基于三维点云的测量算法,通过改进的点云空间划分方法、平面拟合法和拉格朗日函数法,得到了初步测量结果,又提出了基于残差估计的方式并进行了误差校正,进一步提高了测量精度,该方法具有较高的测量精度和鲁棒性。但点云处理技术在枕簧测量工作中的应用并不多,相关枕簧测量方法仍有较大的改进空间。

三维点云技术在物体检测方面的显著优势为枕簧测量方法的研究提供了新思路^[16]。本文根据上述枕簧测量方法的不足以及点云技术的相关应用,提出了一种基于三维点云技术的枕簧测量方法,实现了枕簧的高度和直径测量。该测量方法通过点云聚类^[17]和下采样^[18]算法实现了枕簧点云数据的预处理^[19-22],通过平面拟合^[23]利用高度测量算法测量了枕簧高度,在边缘提取、圆分割后利用改进的圆拟合等算法测量了枕簧直径。测量方法以可靠性和稳定性为目标,保证了枕簧的测量精度和效率。

2 测量系统总体方案设计

2.1 线激光视觉系统

激光视觉测量是一种被广泛应用于工业和非工业领域中的非接触式测量方法之一。线激光传感器的激光视觉测量系统主要由激光发射器、相机和机架组成,如图 1 所示。线激光传感器工作时,激光发射器发射激光,激光通过柱面物镜被扩散为线激光并投射在目标物体表面上形成漫反射,反射光在相机上成像。利用物体位置和形状的变化可测量物体的位移和形状。

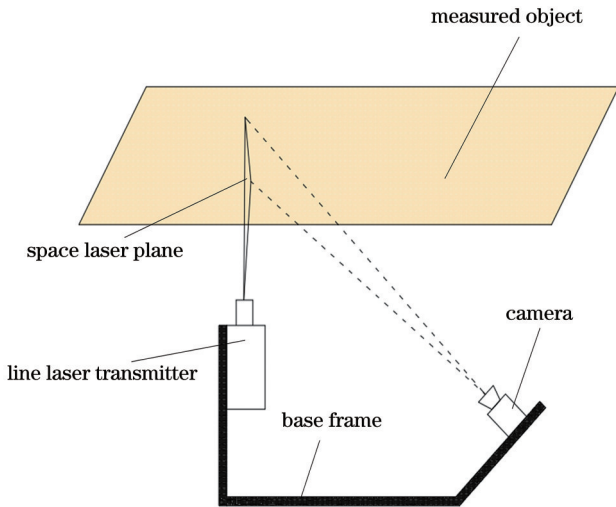


图 1 激光视觉测量系统示意图

Fig. 1 Schematic of laser vision measurement system

2.2 测量系统

枕簧尺寸测量系统主要由六轴机器人、线激光传感器和工控机(IPC)组成,测量系统如图 2 所示。

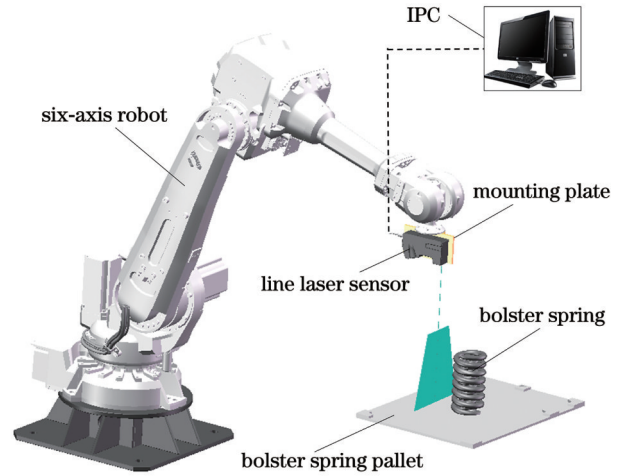


图 2 枕簧尺寸测量系统的示意图

Fig. 2 Schematic of measurement system for size of bolster spring

3 基于三维点云的枕簧几何尺寸测量方法

3.1 测量原理

基于三维点云的枕簧尺寸测量原理如图 3 所示。利用线激光传感器扫描枕簧,将获得的数据传至工控机,利用工控机中的点云算法对点云数据进行下采样和聚类处理。完成点云预处理后,对点云进行平面拟合,利用高度测量算法可得到枕簧高度尺寸;对点云进行降维、边缘提取、圆分割和圆拟合处理,可得到枕簧直径尺寸。

3.2 预处理

3.2.1 点云下采样

线激光传感器可以获取密集的对象特征点云数据,但是其中包含的大量冗余点不仅增加了计算开销,还会影响后续点云处理的结果,因此在保留对象特征的前提下,有必要对点云数据进行精简^[24]。本文使用点云下采样方法对点云进行预处理,基于输入的点云数据创建了三维体素网格。每个体素网格用离中心点最近的点代替该网格的其他点,同时删除其余数据点。其中三维体素网格中心点坐标表示为

$$\begin{cases} X_a = \frac{\sum_{q=1}^g x_q}{g} \\ Y_a = \frac{\sum_{q=1}^g y_q}{g} \\ Z_a = \frac{\sum_{q=1}^g z_q}{g} \end{cases} \quad (1)$$

式中: g 为体素网格中点云数据个数; (X_a, Y_a, Z_a) 为中心点坐标值; (x_q, y_q, z_q) 为第 q 个点的坐标。如图 4 所

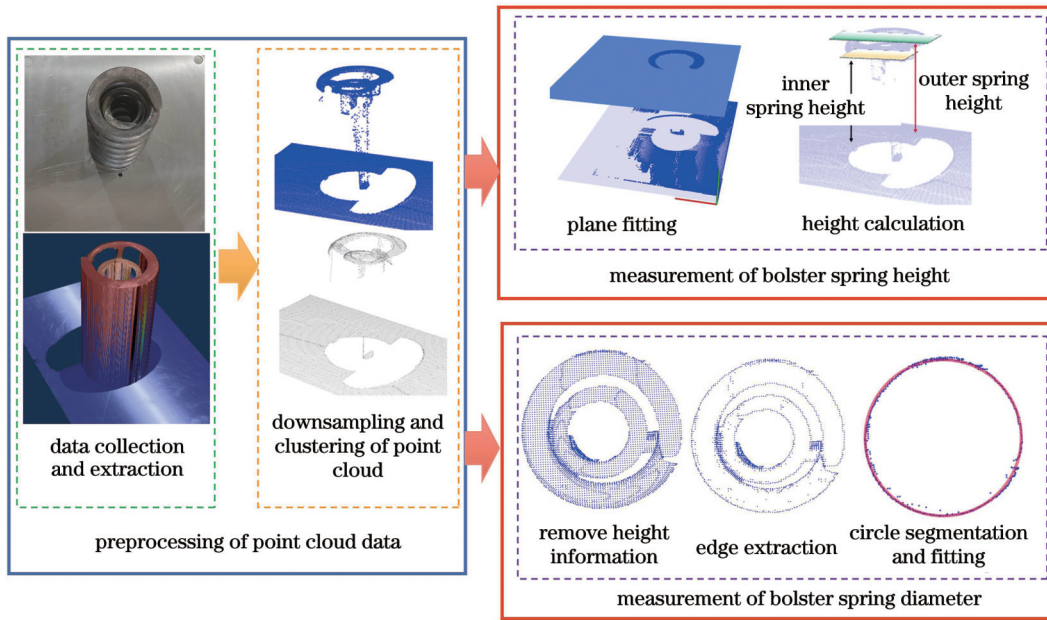


图 3 基于三维点云的枕簧尺寸测量原理

Fig. 3 Measurement principle of bolster spring sizes based on 3D point cloud

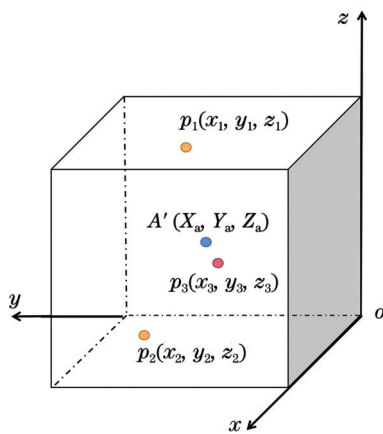


图 4 点云下采样体素网格

Fig. 4 Downsampling voxel mesh of point cloud

示, $A'(X_a, Y_a, Z_a)$ 为中心点, $p_q(x_q, y_q, z_q)$ ($q=1, 2, 3, \dots, g$) 为体素网格内的点, 其中 p_3 离中心点 A' 最近, 该体素网格以 p_3 点为采样保留点。

枕簧测量试验所收集的枕簧点云数量为百万级, 过大的数据量对后续点云处理效率有严重的影响。因枕簧特征清晰、无复杂轮廓, 所以选取尺寸为 $5\text{ mm} \times 5\text{ mm} \times 5\text{ mm}$ 的体素网格对枕簧点云进行采样。将点云数量降至 10000 以下, 此时仍可清晰地保留原有特征, 便于后续处理。

3.2.2 k-means 聚类

k-means 聚类的原理为: 从需要聚类的点云中选取 k 个初始点作为 k 个类别的初始点, 计算所有点与这 k 个点之间的欧氏距离, 根据每个点对应的最小欧氏距离将其放到对应类别中, 重新计算每个类别的质心并作为新的 k 个初始点, 循环执行聚类算法, 直到 k 个样本类别的质心变化很小或不再变化。通过聚类处理初

步过滤枕簧点云, 对枕簧簧圈部分与底部平台部分进行聚类, 增强特征, 聚类距离阈值取 8 mm , 大于下采样体素网格的 5 mm 。

3.3 枕簧高度测量

点云平面拟合是计算枕簧高度尺寸的重要基础, 本文使用最小二乘法进行平面拟合。拟合平面就是找到一个平面, 使该平面距离各个指定离散点最近。对点云进行第一次平面拟合, 得到底部平面方程四个参数 A_1, B_1, C_1, D_1 。将已拟合的底部平面点云移除, 即去除欧式距离小于某个范围值 (本文取 0.1 mm) 的点, 然后进行下一个平面的拟合。

同理进行第二次和第三次平面拟合, 得到 A_2, B_2, C_2, D_2 和 A_3, B_3, C_3, D_3 。其中第二次拟合得到外簧上平面的平面方程, 第三次拟合得到内簧上平面的平面方程, 利用底面和内、外簧上平面三个平面方程分别求取内、外枕簧高度值。

因噪点等因素的影响, 各拟合平面之间不平行且夹角较大, 使用点到平面的欧式距离不能准确求出枕簧高度。为避免这种情况, 对以上方法进行了如下改进。

1) 获取拟合平面时参与拟合的点坐标。

2) 将所有参与第一次拟合的点坐标 (x'_1, y'_1, z'_1) 代入第二次拟合平面的平面方程, 求出各点在第二次拟合平面上的投影点坐标 (x'_1, y'_1, z'_2) :

$$z'_2 = -\frac{A_2 x'_1 + B_2 y'_1 + D_2}{C_2} \quad (2)$$

3) 通过计算参与第一次拟合的各点与其投影点之间的距离 $H = z'_2 - z'_1$, 得到 n' 个距离值 (n' 为拟合底面点数), 然后将 H 从大到小排序, 取排序靠前的若干距离值并求平均以得到枕簧外簧高度尺寸。为满足精

度要求,避免噪声的影响,舍去最大值及其后面若干值,在计算结果中添加高度补偿,得到更精确的测量结果。

4) 将外簧上平面方程更换为内簧上平面方程,重复步骤 1)、2)和 3),得到内簧高度尺寸。

需要说明的是,在步骤 3)中,采集枕簧点云数据时,枕簧摆放位置与激光传感器运动轨迹等各测量条件固定,不同组枕簧所采集的点云数量相近,且不同组枕簧点云数据经预处理后点数量为 5000~10000。其中,底部平面点数量占全部点数量的 60% 左右,内、外簧上平面拟合点数约为全部点数量的 7% 和 10%,其余为无用点。为保证枕簧高度测量值不受取值个数的影响,取内、外簧平面拟合点数的 60% 作为距离值 H 的取值个数。又因点云数据经预处理后噪点较少,为确保高度测量值不受噪点的影响,取内、外簧平面拟合点数的 5% 作为距离值 H 的舍去个数。

在搭建枕簧数据采集试验平台时,存在枕簧放置平台和六轴机器人安装水平度不足等问题,须添加高度补偿值以抵消试验平台安装误差带来的高度测量误差。选取无损枕簧进行 20 次人工测量并取平均值作为标准值,然后针对无损枕簧进行 20 次算法测量,算法测量结果与标准值作差并取平均,以此平均值作为

高度补偿值。

3.4 枕簧直径测量

准确提取点云边缘并识别圆是测量枕簧直径的基础^[25]。枕簧直径测量方法是:首先去除点云高度信息,实现点云降维,然后通过边缘提取算法提取出降维后点云的边缘轮廓,再根据枕簧型号设定不同阈值,分割出每个边界圆,最后通过圆拟合获取枕簧直径尺寸信息。

3.4.1 边缘提取

边缘提取目标为圆环,其轮廓形状规则,采用基于夹角最大值的边缘提取算法进行处理。针对降维后的点云,利用 K 近邻搜索算法找出点云各点 $P_i (i=0, 1, \dots, K)$, 其中 K 为降维后点云中的点数, i 表示第 i 个点) 的近邻点 $N_j (j=0, 1, \dots, K)$, 其中 j 表示第 j 个点), 以 P_i 为起点、 N_j 为终点定义向量 $\overrightarrow{P_i N_j}$, 然后统计各相邻向量之间的夹角。向量和相邻向量夹角的定义如图 5 所示, 其中 r 为 P_i 点所取的圆形邻域半径。相邻向量夹角的差值计算式为

$$\delta_i = \begin{cases} \alpha_{i+1} - \alpha_i, & i = 1, 2, \dots, K-1 \\ 360 + \alpha_1 - \alpha_K, & i = K \end{cases}, \quad (3)$$

式中: δ_i 为相邻向量夹角的差值; α_i 为 P_i 邻域点中两点之间的向量夹角。

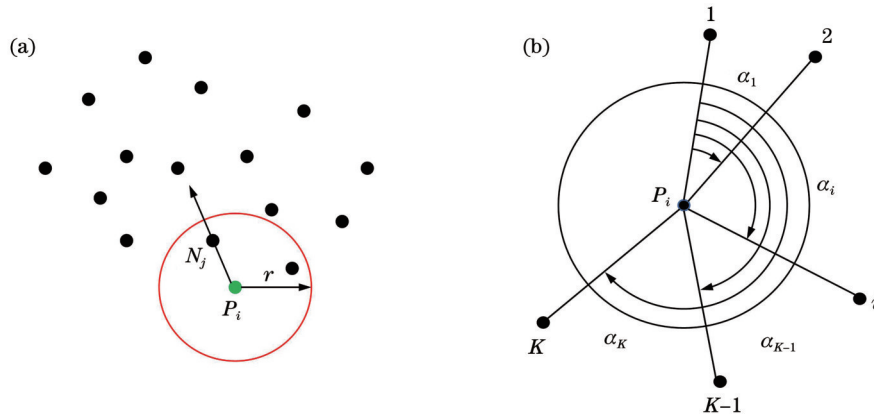


图 5 向量和相邻向量夹角定义。(a) 向量定义; (b) 相邻向量夹角定义

Fig. 5 Definitions of vector and angle between adjacent vectors. (a) Definition of vector; (b) definition of angle between adjacent vectors

将 $K-1$ 个相邻向量夹角进行排序, 选择最大夹角 δ_{\max} 与设定阈值 δ_0 进行比较, 若 δ_{\max} 大于 δ_0 则表明该点

为边界点, 提取出该点, 此处阈值 δ_0 取 $\pi/2$ 。边缘提取结果如图 6 所示。

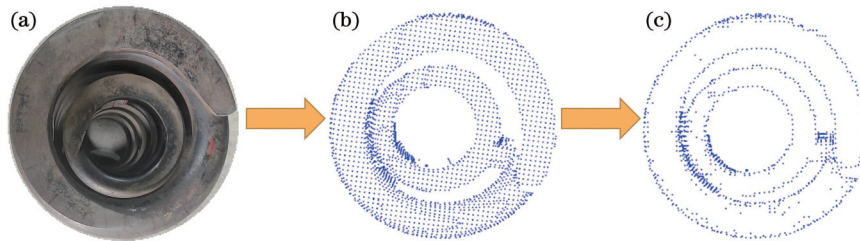


图 6 边缘提取。(a) 枕簧实物俯视图; (b) 枕簧点云降维; (c) 降维点云边缘提取

Fig. 6 Edge extraction. (a) Top view of bolster spring; (b) dimension reduction of bolster spring point cloud; (c) edge extraction of reduced dimension point cloud

3.4.2 圆分割和圆拟合

对降维后的点云数据进行边缘提取,得到两个近似圆环。以枕簧型号为分类依据,为两个近似圆环设置阈值并进行分割。具体分割方法为:测量枕簧时外簧摆放圆心固定,内簧存在圆心偏移,基于前文枕簧高度测量结果判断被测枕簧型号;依据枕簧型号,以内外直径公称尺寸 $\pm 3\text{ mm}$ 作为分割阈值,以外簧圆心作为分割圆心,进行圆分割。但阈值范围选取较大及枕簧摆放位置偏移等因素会导致圆分割后的点云可能存在多余噪点,所以使用上文所述的聚类算法对分割结果进行聚类处理,提取出所分割的圆。分割结果如图 7 所示。

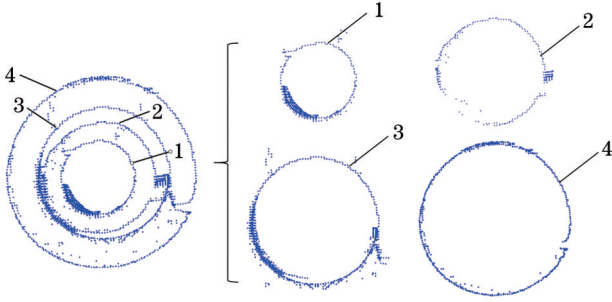


图 7 圆分割

Fig. 7 Circular segmentation

对每个近似圆进行点云圆拟合,得到圆心和直径。

使用RANSAC方法对分割圆点集进行初步过滤处理,去除噪点,从分割圆点集中随机抽取三个点并求解三点所在圆的圆心 (m, n) 和半径 r_0 ,计算所有边界点到圆心的距离 l 。若 $l - r_0$ 大于阈值 ϵ ,则该点为保留点,否则舍去,本文阈值 ϵ 取 0.1。重复上述步骤 N 次,此处 N 取圆点集中圆点数量的 $1/2$ 。选取保留点个数最多时的结果,基于该保留点个数进行圆拟合处理,过程如下。

圆方程表达式为

$$(x - A)^2 + (y - B)^2 = R^2, \quad (4)$$

式中: (A, B) 为圆心坐标; R 为圆的半径。变换后,有

$$R^2 = x^2 - 2Ax + Ax^2 + y^2 - 2By + B^2. \quad (5)$$

令

$$\begin{cases} a = -2A \\ b = -2B \\ c = A^2 + B^2 - R^2 \end{cases}, \quad (6)$$

得到

$$x^2 + y^2 + ax + by + c = 0. \quad (7)$$

参与圆拟合的点云点数为 $M(M \geq 3)$,第 s 个点的坐标为 (x_s, y_s) ,其中 $s=1, 2, \dots, M$ 。为了使每个点到圆心距离的平方值与圆半径平方值的差值 Q 最小,须满足

$$\frac{\partial Q}{\partial l} = 0, \quad (8)$$

式中: $l=a, b, c$ 。由式(8)计算出 a, b, c ,由式(6)计算出所拟合圆的圆心 (A, B) 和半径 R 。

上述最小二乘法拟合的圆存在缺陷,即拟合结果受噪点的影响严重。为减小噪点的影响,引入梯度下降迭代方法。

损失函数表达式为

$$L_{\text{Loss}} = \sum_{s=1}^M \left[\sqrt{(x_s - A)^2 + (y_s - B)^2} - R \right], \quad (9)$$

式中: L_{Loss} 为损失值。对 A, B 求偏导,得到

$$\frac{\partial Q}{\partial A} = \frac{A - x_s}{\sqrt{(x_s - A)^2 + (y_s - B)^2}}, \quad (10)$$

$$\frac{\partial Q}{\partial B} = \frac{B - y_s}{\sqrt{(x_s - A)^2 + (y_s - B)^2}}. \quad (11)$$

取 R 的梯度值为 -1 ,更新 A, B 和 R ,有

$$\begin{cases} A' = A - \alpha \frac{\partial Q}{\partial A} \\ B' = B - \alpha \frac{\partial Q}{\partial B} \\ R' = R + \alpha \end{cases}, \quad (12)$$

式中: α 为学习率。

将最小二乘法拟合得到的圆心 (A, B) 和半径 R 作为初始值代入式(9),求得使 L_{Loss} 最小的圆心和半径,即得到最优值。

4 试验验证与数据分析

4.1 试验平台

为测试提出的基于三维点云的枕簧几何尺寸测量方法的精度、可靠性和稳定性,在图 8 所示的枕簧测量试验平台上开展了可靠性试验和重复性测量试验。枕簧测量试验平台由六轴机器人、线激光传感器、工控机和可编程逻辑控制器(PLC)组成。六轴机器人驱动线激光传感器完成枕簧扫描工作,获取枕簧三维点云数据;工控机作为计算中心,主要负责本文所提方法的具体实现,且实时与 PLC 交互完成数据传递。枕簧测量算法使用 C++ 编程语言,在 Visual Studio 2019 上编写。

4.2 试验结果分析

4.2.1 枕簧检修规范

同一转向架同型号枕簧的自由高度差不得超过 3 mm ,圆钢直径腐蚀、磨耗不得大于 8% ,超限时即报废。本试验选取被测枕簧的最小高度(228 mm)的 0.2% 即 $\pm 0.45\text{ mm}$ 作为高度测量误差范围。将圆钢直径测量转换为枕簧内外直径测量,被测枕簧的最小圆钢直径磨耗为 1.28 mm ,枕簧直径磨耗包括两侧圆钢直径磨耗,因此基于单侧最小磨耗值的 20% ,选取 $\pm 0.4\text{ mm}$ 作为枕簧直径误差测量范围。

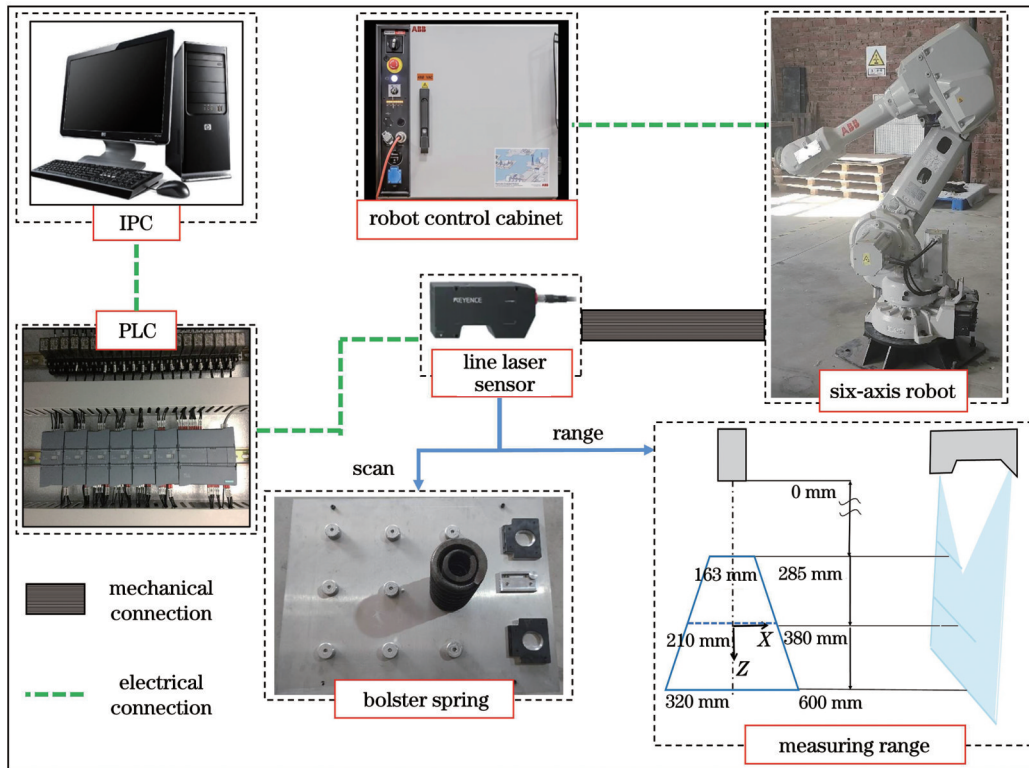


图 8 枕簧测量试验平台

Fig. 8 Test platform for measuring bolster spring

4.2.2 可靠性试验与分析

采用人工测量和线激光扫描两种方式对 10 组枕

簧进行数据采集,人工测量和线激光扫描过程如图 9 所示,点云数据采集和预处理如图 10 所示。

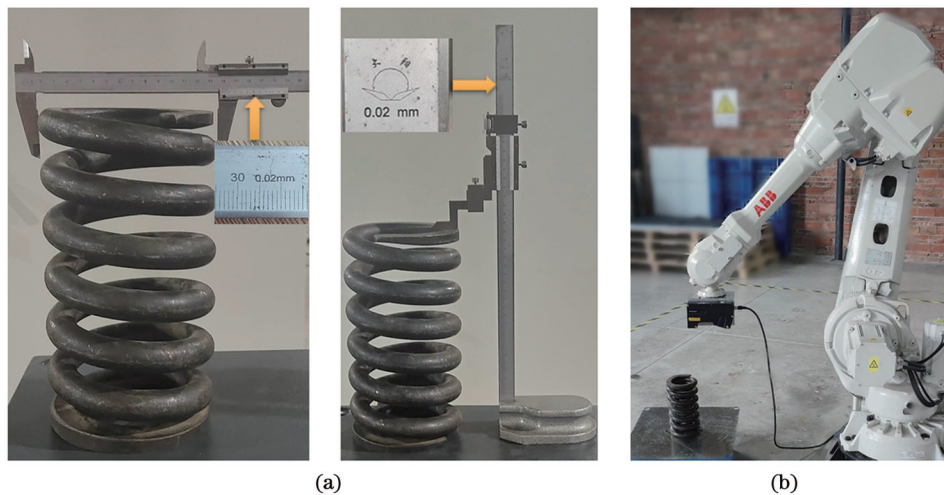


图 9 人工测量和线激光扫描。(a)人工测量;(b)线激光扫描

Fig. 9 Manual measurement and line laser scanning. (a) Manual measurement; (b) line laser scanning

图 9 所示为人工测量过程和线激光测量过程,人工测量时使用的工具为高度测量尺和游标卡尺,精度均为 0.02 mm,线激光传感器的重复性精度为 0.01 mm。图 10 所示为线激光传感器数据采集和点云预处理,共采集 10 组不同枕簧数据。图 10(a)为枕簧三维图像,由线激光传感器数据处理软件生成,图 10(b)为由传感器采集的数据转换的点云数据,图 10(c)为预处理后的点云数据。

针对预处理后的枕簧点云进行高度计算,高度补偿值经校准后取 1.06 mm。利用其中一组点云数据进行高度计算,得到的三个平面方程如表 1 所示。由平面方程计算得到高度值 H 后,外簧高度取值个数为 302,舍去个数为 25,内簧高度取值个数为 156,舍去个数为 13,处理后得到枕簧内、外簧高度值分别为 209.79 mm 和 230.91 mm。对该组点云进行直径计算处理,边缘提取后以公称直径 ± 3 mm



图 10 点云数据采集和预处理。(a)枕簧三维图像;(b)点云数据转换;(c)点云预处理

Fig. 10 Point cloud data acquisition and preprocessing. (a) Three dimensional image of bolster spring; (b) point cloud data conversion; (c) point cloud preprocessing

表 1 平面方程计算结果

Table 1 Calculation results of plane equations

Plane	Plane equation
Upper plane of outer bolster spring	$0.00908485x - 0.999949y + 0.00441526z + 235.798 = 0$
Upper plane of inner bolster spring	$0.0140108x - 0.999783y + 0.0154244z + 209.755 = 0$
Bottom plane	$0.00933259x - 0.999952y + 0.00279845z + 6.8273 = 0$

为阈值进行圆分割,分割后对单个圆进行最小二乘法拟合并求取圆心和直径。外簧外径拟合后圆心为(156.65, 283.70),直径为147.12 mm,将圆心和半径代入迭代算法中继续求解,其中迭代算法学习率取0.1,计算得到圆心为(156.65, 283.79),直径

为147.48 mm,其余直径的测量步骤与外簧外径一致。

基于上述步骤对10组枕簧点云数据进行处理,结果如表2所示,人工测量和点云测量结果的对比如图11所示。

表 2 点云测量结果

Table 2 Measurement results of point clouds

Group No.	Outer bolster spring			Inner bolster spring			Time /s
	Height /mm	Outer diameter /mm	Inner diameter /mm	Height /mm	Outer diameter /mm	Inner diameter /mm	
1	252.79	138.45	91.26	228.49	81.84	50.20	2.258
2	230.42	147.60	95.80	209.52	87.80	50.84	2.387
3	230.93	147.88	95.20	210.08	87.64	51.88	2.569
4	229.93	148.04	96.64	209.85	87.78	52.42	2.293
5	251.93	138.32	91.06	209.81	86.96	52.18	2.811
6	252.13	137.60	90.88	229.70	82.00	50.28	2.857
7	251.19	137.38	90.81	228.8	82.10	50.24	2.899
8	251.40	136.84	90.02	228.36	82.58	49.80	2.962
9	251.61	138.98	91.52	229.08	81.48	49.52	2.728
10	232.01	148.12	96.00	209.74	88.08	51.34	2.931

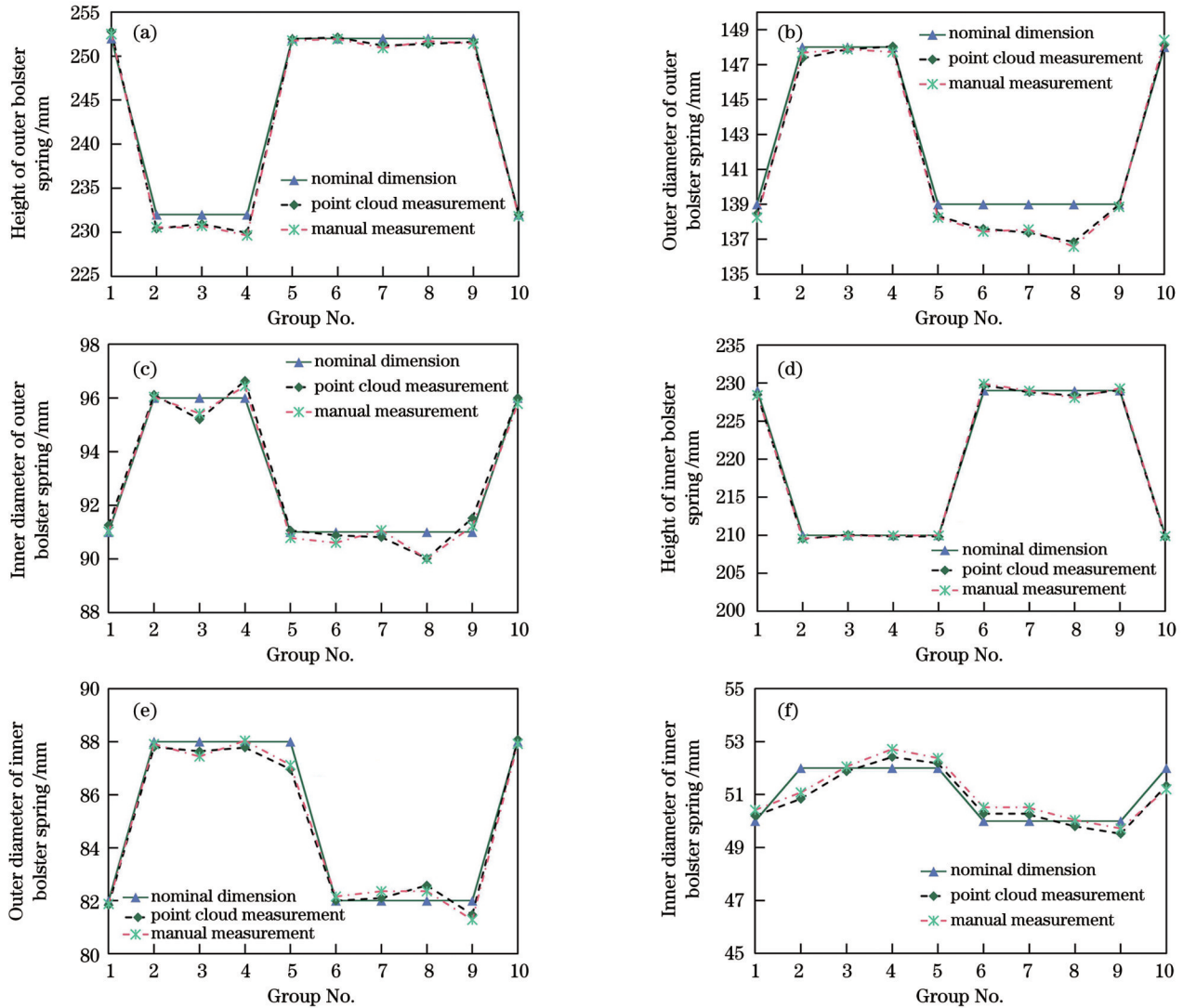


图 11 人工测量和点云测量结果的对比。(a)~(c)外簧;(d)~(f)内簧

Fig. 11 Comparison of manual measurement and point cloud measurement results. (a)~(c) Outer bolster spring; (d)~(f) inner bolster spring

人工测量结果受主观因素影响,试验取 20 次测量结果的平均值作为人工测量值,公称尺寸为枕簧的标准制造尺寸。图 11(a)中外簧高度最大测量误差在 ± 0.3 mm 内,图 11(b)中外簧外径最大测量误差在 ± 0.35 mm 内,图 11(c)中外簧内径最大测量误差在 ± 0.3 mm 内,图 11(d)中内簧高度最大测量误差在 ± 0.35 mm 内,图 11(e)中内簧外径最大测量误差在 ± 0.3 mm 内,图 11(f)中内簧内径最大测量误差在 ± 0.3 mm 内。如表 2 所示,每组枕簧的平均测量时间为 2.7 s,相比人工测量时间 15~20 s 有较大提升,该测量方法满足精度和效率要求且可靠性良好。

4.2.3 重复性试验与分析

测量系统重复性小于 10% 表示测量系统良好,重复性大于 10% 但小于 30% 表示测量系统性能处于临界状态,重复性大于 30% 表示测量系统性能不好。为验证点云测量方法的测量能力,对 4 组 8 个枕簧进行 10 次重复性测量,测量结果如表 3~5 所示,其中 RSD

为相对标准偏差。

由于枕簧的制造误差和使用磨损等因素,枕簧实际尺寸与公称尺寸之间存在偏差,如表 3 中 Group 2 的外簧高度测量结果所示,人工测量值和点云测量值与公称尺寸相差较大,属正常情况。表 3 测量结果显示,枕簧高度测量结果的最大平均误差在 ± 0.35 mm 内,最大标准偏差小于 0.35 mm。表 4 和表 5 测量结果显示,枕簧直径测量结果的最大平均误差在 ± 0.3 mm 内,最大标准偏差小于 0.3 mm。枕簧所有项目的测量重复性均小于 3%,证明该测量方法具有良好的稳定性。

测量结果存在一定误差,但可以满足现有检修规程要求。产生测量误差的主要因素包括:1)线激光传感器存在安装误差;2)六轴机器人驱动传感器扫描时出现抖动,且启动和停止时并非匀速运动;3)枕簧放置基准存在一定的位置和高度误差;4)存在点云预处理和测量算法误差。

表 3 枕簧高度重复测量结果
Table 3 Repeated measurement results of bolster spring height

Experiment No.	Height of outer bolster spring /mm				Height of inner bolster spring /mm			
	Group 1	Group 2	Group 3	Group 4	Group 1	Group 2	Group 3	Group 4
Nominal dimension	252.00	232.00	232.00	252.00	229.00	210.00	210.00	210.00
Manual measurement result	252.50	230.56	230.72	251.76	228.42	209.56	209.92	209.98
1	252.79	230.42	230.93	251.93	228.49	209.52	210.08	209.81
2	252.60	230.97	230.97	252.32	228.37	209.67	209.62	209.52
3	252.49	230.12	230.77	252.17	228.52	209.31	209.80	209.67
4	252.61	230.25	231.34	251.86	228.82	209.98	209.73	210.11
5	252.49	230.91	230.75	252.09	228.55	209.79	210.21	209.95
6	252.67	230.36	230.87	251.88	228.60	209.77	209.73	210.22
7	252.64	230.34	231.21	252.24	228.35	209.34	209.97	209.80
8	252.80	230.48	230.70	252.33	228.59	209.40	209.77	209.85
9	252.47	230.76	230.72	252.02	228.58	210.04	210.39	209.76
10	252.71	230.24	230.83	251.98	228.51	210.27	209.82	210.09
Mean error	0.127	0.102	0.189	0.322	0.118	0.149	0.008	0.102
Standard deviation	0.1195	0.2946	0.2140	0.1759	0.1312	0.3225	0.2453	0.2154
RSD /%	0.047	0.128	0.093	0.070	0.057	0.154	0.117	0.103

表 4 枕簧外径重复测量结果
Table 4 Repeated measurement results of outer diameter of bolster spring

Experiment No.	Outer diameter of outer bolster spring /mm				Outer diameter of inner bolster spring /mm			
	Group 1	Group 2	Group 3	Group 4	Group 1	Group 2	Group 3	Group 4
Nominal dimension	139.00	148.00	148.00	139.00	82.00	88.00	88.00	88.00
Manual measurement result	138.24	147.68	147.38	138.24	81.88	87.91	87.44	87.12
1	138.45	147.60	147.88	138.32	81.84	87.80	87.64	86.96
2	138.54	147.36	147.45	138.07	82.12	87.74	87.72	86.71
3	138.13	147.72	147.38	138.72	82.07	87.52	87.98	87.07
4	138.28	147.56	147.72	138.45	81.97	87.46	87.98	86.55
5	138.40	147.48	147.32	138.69	81.88	87.74	87.35	86.80
6	138.37	147.42	147.55	138.66	81.90	87.42	87.55	86.81
7	138.41	147.34	147.40	138.20	82.01	87.72	87.87	87.22
8	138.32	148.14	147.22	138.74	82.22	88.00	87.81	86.78
9	138.25	147.68	147.61	138.32	82.14	87.98	87.23	87.25
10	138.19	147.56	147.39	138.57	81.91	87.66	87.47	86.93
Mean error	0.094	0.094	0.112	0.234	0.126	0.206	0.220	0.212
Standard deviation	0.1247	0.2324	0.1990	0.2376	0.1274	0.1977	0.2592	0.2233
RSD /%	0.090	0.157	0.135	0.171	0.155	0.225	0.296	0.257

表 5 枕簧内径重复测量结果
Table 5 Repeated measurement results of inner diameter of bolster spring

Experiment No.	Inner diameter of outer bolster spring /mm				Inner diameter of inner bolster spring /mm			
	Group 1	Group 2	Group 3	Group 4	Group 1	Group 2	Group 3	Group 4
Nominal Dimension	91.00	96.00	96.00	91.00	50.00	52.00	52.00	52.00
Manual measurement result	91.02	96.04	95.42	90.78	50.38	51.08	52.06	52.38
1	91.26	95.80	95.20	91.06	50.20	50.84	51.88	52.18
2	90.93	96.12	95.33	90.80	50.46	50.96	52.25	52.11
3	91.15	96.02	95.62	91.22	50.31	51.26	51.96	52.08
4	90.94	96.04	95.41	90.98	50.09	51.00	52.07	52.40
5	90.78	95.98	95.10	90.74	50.40	51.02	52.13	52.17
6	90.97	95.76	95.24	90.89	50.28	51.08	52.05	52.25
7	91.00	95.54	95.73	91.30	50.17	51.10	51.88	52.08
8	91.24	95.88	95.40	90.85	50.28	50.88	52.30	52.26
9	90.86	96.00	95.26	90.94	50.30	51.14	52.14	52.13
10	91.10	96.00	95.12	90.88	50.15	51.26	52.10	52.01
Mean error	0.003	0.126	0.079	0.186	0.116	0.026	0.016	0.213
Standard deviation	0.1598	0.1721	0.2058	0.1798	0.1140	0.1430	0.1410	0.1127
RSD /%	0.176	0.180	0.216	0.198	0.227	0.280	0.271	0.216

5 结 论

提出了一种基于三维点云技术的枕簧尺寸测量方法,通过控制六轴机器人的移动轨迹驱动线激光传感器扫描枕簧,从而得到点云数据。为减少噪点干扰,通过点云下采样和 k -means 聚类算法对枕簧点云进行预处理。预处理后通过最小二乘法平面拟合算法求解枕簧端部及底部的平面方程,结合点投影高度计算方法,实现了枕簧的自由高度测量。通过降维算法去除枕簧点云高度信息,利用夹角最大值边缘提取算法和阈值分割算法对降维后的点云进行圆分割处理,分割后利用 RANSAC 方法过滤噪点,通过圆拟合算法完成枕簧直径计算。为提高直径测量精度,采用梯度下降迭代算法,以圆拟合结果作为初值,迭代出最优直径解,完成枕簧内外簧直径计算。搭建枕簧测量试验平台进行数据采集,在工控机上进行可靠性和重复性试验,对 10 组枕簧进行可靠性试验,结果显示,相比于人工测量,点云测量方法的最大测量误差在 ± 0.35 mm 内,平均测量时间为 2.7 s,测量精度和测量效率均满足测量要求且具有可靠性。对 4 组枕簧进行 10 次重复性测量试验,结果显示,相比于人工测量,点云测量方法的最大测量平均误差值在 ± 0.35 mm 内,测量重复性小于 3%,证明点云测量方法具有良好的稳定性。后续工作是继续优化测量系统和点云测量算法,进一步提高测量精度、测量效率和测量稳定性,将点云测量方法应用到转向架枕簧斜楔的自动测量与分选装备研究中。

参 考 文 献

- [1] 刘桓龙, 李大法, 周建义, 等. 狭小空间内基于线激光的枕簧缺口视觉间接定位[J]. 中国激光, 2022, 49(17): 1704002.
Liu H L, Li D F, Zhou J Y, et al. Visual indirect positioning of bolster spring gap based on line laser in narrow space[J]. Chinese Journal of Lasers, 2022, 49(17): 1704002.
- [2] Li C S, Luo S H, Cole C, et al. Bolster spring fault detection strategy for heavy haul wagons[J]. Vehicle System Dynamics, 2018, 56(10): 1604-1621.
- [3] Li M J, Wang X L, Qiu R S. Study of free length detection for bolster spring of railroad tracks[J]. Advanced Materials Research, 2013, 662: 762-767.
- [4] 段乐. 枕簧智能检测系统[J]. 中国新技术新产品, 2017(24): 32-33.
Duan L. Intelligent detection system of pillow spring[J]. New Technology & New Products of China, 2017(24): 32-33.
- [5] Liu H L, Jiang B, Li D F, et al. Measurement method of pillow spring based on machine vision[J]. Journal of Physics: Conference Series, 2021, 1986(1): 012118.
- [6] 李传翔, 杨兵, 杨顺. 铁路货车转向架弹簧视觉检测及机器人智能选配系统研究[J]. 铁道机车车辆, 2021, 41(6): 35-39.
Li C X, Yang B, Yang S. Research on visual inspection and robot intelligent matching system for bogie-spring of railway freight wagon[J]. Railway Locomotive & Car, 2021, 41(6): 35-39.
- [7] Li L H, Wang R W, Zhang X P. A tutorial review on point cloud registrations: principle, classification, comparison, and technology challenges[J]. Mathematical Problems in Engineering, 2021, 2021: 9953910.
- [8] 高佳月, 许宏丽, 邵凯亮, 等. 基于局部边缘特征描述子的自适应边缘检测算法[J]. 中国激光, 2020, 47(6): 0604003.
Gao J Y, Xu H L, Shao K L, et al. An adaptive edge detection method based on local edge feature descriptor[J]. Chinese Journal of Lasers, 2020, 47(6): 0604003.
- [9] Zhao F Q. Point cloud denoising algorithm with geometric feature

- preserving[J]. *Multimedia Systems*, 2022, 28(5): 1679-1687.
- [10] Huang S, Chen M, Lu S L, et al. A novel algorithm: fitting a spatial arc to noisy point clouds with high accuracy and reproducibility[J]. *Measurement Science and Technology*, 2021, 32(8): 085004.
- [11] Nurunnabi A, Sadahiro Y, Laefer D F. Robust statistical approaches for circle fitting in laser scanning three-dimensional point cloud data[J]. *Pattern Recognition*, 2018, 81: 417-431.
- [12] Shi Y T, Zhao G, Wang M M, et al. An algorithm for fitting sphere target of terrestrial LiDAR[J]. *Sensors*, 2021, 21(22): 7546.
- [13] 林冬云, 卢嘉祺, 李纯明, 等. 基于空间点云三维曲面重建的距离测量[J]. *激光与光电子学进展*, 2022, 59(14): 1415018.
- Lin D Y, Lu J Q, Li C M, et al. Distance measurement based on three-dimensional surface reconstruction of spatial point cloud[J]. *Laser & Optoelectronics Progress*, 2022, 59(14): 1415018.
- [14] 刘金锦, 李浩军. 基于点云切片改进法的不规则物体体积测量[J]. *光学学报*, 2021, 41(23): 2312003.
- Liu J J, Li H J. Volume measurement of irregular objects based on improved point cloud slicing method[J]. *Acta Optica Sinica*, 2021, 41(23): 2312003.
- [15] 邓磊, 刘桂华, 邓豪, 等. 基于三维点云处理的交联聚乙烯电缆接头反应力锥参数测量算法[J]. *中国激光*, 2023, 50(6): 0604003.
- Deng L, Liu G H, Deng H, et al. Measurement algorithm of anti-stress cone parameters of XLPE cable joint based on three-dimensional point cloud processing[J]. *Chinese Journal of Lasers*, 2023, 50(6): 0604003.
- [16] Zhang Z P. A new measurement method of three-dimensional laser scanning for the volume of railway tank car (container) [J]. *Measurement*, 2021, 170: 108454.
- [17] Mahdaoui A, Sbai E H. 3D point cloud simplification based on the clustering algorithm and introducing the Shannon's entropy[J]. *Proceedings of SPIE*, 2021, 11605: 116050N.
- [18] Lin Y J, Benziger R R, Habib A. Planar-based adaptive down-sampling of point clouds[J]. *Photogrammetric Engineering & Remote Sensing*, 2016, 82(12): 955-966.
- [19] Shuang M, Zhou C J, Zhang L D, et al. Depth image denoising and key points extraction for manipulation plane detection[C]// *Proceeding of the 11th World Congress on Intelligent Control and Automation*, June 29-July 4, 2014, Shenyang, China. New York: IEEE Press, 2014: 3315-3320.
- [20] Wang J L, Zhang H Y, Gao J X, et al. Dust removal from 3D point cloud data in mine plane areas based on orthogonal total least squares fitting and GA-TELM[J]. *Computational Intelligence and Neuroscience*, 2021, 2021: 9927982.
- [21] Irfan M A, Magli E. Joint geometry and color point cloud denoising based on graph wavelets[J]. *IEEE Access*, 2021, 9: 21149-21166.
- [22] Han X F, Jin J S, Wang M J, et al. A review of algorithms for filtering the 3D point cloud[J]. *Signal Processing: Image Communication*, 2017, 57: 103-112.
- [23] 张中岳, 周惠兴, 王舜, 等. 基于RANSAC的WTLS平面拟合算法研究[J]. *国外电子测量技术*, 2022, 41(6): 93-98.
- Zhang Z Y, Zhou H X, Wang S, et al. Research on algorithm of plane fitting of RANSAC-WTLS[J]. *Foreign Electronic Measurement Technology*, 2022, 41(6): 93-98.
- [24] 赵夫群, 汤慧. 层次化的散乱点云简化算法[J]. *激光与光电子学进展*, 2022, 59(18): 1811006.
- Zhao F Q, Tang H. Hierarchical simplification algorithm for scattered point clouds[J]. *Laser & Optoelectronics Progress*, 2022, 59(18): 1811006.
- [25] 李皓宇, 杨蕴杰, 杨皓, 等. 基于点云法线与投影融合的三维圆孔识别算法[J]. *激光与光电子学进展*, 2022, 59(8): 0820002.
- Li H Y, Yang Y J, Yang H, et al. Three-dimensional circular hole recognition algorithm based on point cloud normal and projection fusion[J]. *Laser & Optoelectronics Progress*, 2022, 59(8): 0820002.

Geometric Dimension Measurement Method for Bolster Spring Based on Three-Dimensional Laser Point Clouds

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Abstract

Objective Damping springs and bolster springs (hereinafter referred to as bolster springs) are important components of a railway freight car bogie, which carry the main load when the vehicle is running. According to the relevant regulations, bolster springs need to be repaired and replaced regularly. Moreover, the driving safety of the vehicle is directly affected by the dimensions of each group of bolster springs. Thus, it is necessary to disassemble the bolster spring and perform maintenance on each part separately, and the qualified and unqualified products need to be distinguished and classified based on their dimensions. Under the traditional operation mode, the model and type of bolster spring are determined by measuring the height of the bolster spring using a free height ruler, measuring the diameter of the round steel of the bolster spring using a spring diameter gauge, and through manual visual inspection. Typically, several bolster springs of different types are used in railway freight cars. Thus, the use of the manual detection method is inefficient, labor intensive, and vulnerable to human interference, making it difficult to meet the current maintenance needs of bolster springs. To develop an intelligent maintenance system for bolster springs that can replace manual operation, a key technical problem, namely, the design of a stable and efficient detection algorithm for bolster springs, needs to be urgently solved. Through investigations and analyses, researchers have made certain advancements in the field of bolster spring detection; however, most of them include patents and very few are related to detection algorithms. Therefore, a point cloud detection method for the bolster spring size is proposed in this paper based on 3D laser point cloud technology to achieve the stable, high-precision, and efficient detection of the bolster spring size.

Methods In this study, the bolster spring point cloud data were collected using a line laser sensor and the size of the bolster spring was measured using point cloud processing technology. First, the bolster spring measurement test platform was set up, and the three-dimensional point cloud data of the bolster spring were obtained via linear laser sensor scanning and uploaded into an industrial computer for processing. For the bolster spring point cloud data, the point cloud density was reduced and the noise was removed using the point cloud down sampling algorithm and k -means clustering algorithm. Subsequently, the free height of the bolster spring was measured using the plane fitting algorithm and point projection height calculation method based on the processed point cloud. Finally, the inner diameter and outer diameter of a group of internal and external bolster springs were calculated using the point cloud dimension reduction algorithm combined with the edge extraction, circle segmentation, and circle fitting. Through experimental research, the accuracy and efficiency of the bolster spring measurement algorithm based on point cloud technology were discussed, and the reliability and stability of the method were verified.

Results and Discussions The manual measurement results and bolster spring point cloud data were obtained via manual measurement and the linear laser sensor scanning for 10 groups of bolster springs, respectively (Fig. 9), and the sparse point cloud data with reserved features were obtained by processing the bolster spring data using a point cloud preprocessing algorithm (Fig. 10). Furthermore, the reliability test for the height and diameter measurement was conducted on 10 groups of bolster spring data. The results show that the maximum measurement error of the point cloud measurement method is in the range of ± 0.35 mm compared with that of the manual measurement, and the average measurement time is 2.7 s, which is much shorter than the manual measurement time. Additionally, the measurement accuracy and measurement efficiency are both reliable and meet the measurement requirements (Table 2 and Fig. 11). The four groups of bolster springs were measured 10 times. The results show that compared with that of the manual measurement, the maximum average error value of the proposed algorithm is in the range of ± 0.35 mm, and the measurement repeatability is less than 3%, which proves that the proposed algorithm has good stability (Tables 3–5). Thus, the obtained reliability and repeatability test results are acceptable and meet the requirements stipulated in existing maintenance regulations.

Conclusions In this study, a method for measuring the size of the bolster spring based on 3D point cloud technology was proposed. The point cloud data were obtained by controlling the driving line laser sensor of a six-axis robot when scanning the bolster spring. To reduce noise interference, the bolster spring point cloud data were preprocessed via sampling using the point cloud sampling algorithm and k -means clustering algorithm. After preprocessing, the point cloud data were used to solve the end and bottom plane equations of the bolster spring using the least square plane fitting algorithm. Based on the plane equation and point projection height calculation method, the free height measurements of the bolster spring were obtained. Subsequently, the bolster spring point cloud height information was removed using the dimension reduction algorithm. The reduced dimension point cloud was then circular-segmented using the maximum included angle edge extraction algorithm and threshold segmentation algorithm. Subsequently, the noise points of the segmented point cloud were filtered using the RANSAC method, and the diameter of the bolster spring was calculated using the circle fitting algorithm. To improve the diameter measurement accuracy, the gradient descent iterative algorithm was used to iterate the optimal diameter solution using the circle fitting results as the initial values, marking the end of the calculation of the inner and outer spring diameters of the bolster spring. The bolster spring measurement test platform was then set up for data collection, conducting reliability and repeatability tests on the industrial computer, and conducting reliability tests on 10 groups of bolster springs. The results show that the maximum measurement error of the point cloud measurement method is in the range of ± 0.35 mm compared with that of the manual measurement, and the average measurement time is 2.7 s. Moreover, the measurement accuracy and measurement efficiency were reliable and met the measurement requirements. The measurement tests on the 4 groups of bolster springs were repeated 10 times, and the results show that compared with that of manual measurement, the maximum average measurement error value is in the range of ± 0.35 mm, and the measurement repeatability is less than 3%, which proves that the point cloud measurement method has good stability. Follow-up work should be conducted to optimize the measurement system and point cloud measurement algorithm, to further improve the measurement accuracy, measurement efficiency, and measurement stability, and to apply the point cloud measurement method to the research on the development of automatic measurement and sorting equipment for bogie bolster springs and wedges.

Key words measurements; bolster spring measurement; three-dimensional point cloud; line laser sensor; plane fitting