同行专家业内评价意见书编号：20250854477

附件1

浙江工程师学院（浙江大学工程师学院）
同行专家业内评价意见书

姓名： 龚凡崴

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申报工程师职称专业类别（领域）： 电子信息

浙江工程师学院（浙江大学工程师学院）制

2025年06月05日

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一、个人申报

（一）基本情况【围绕《浙江工程师学院（浙江大学工程师学院）工程类专业学位研究生工程师职称评审参考指标》，结合该专业类别(领域)工程师职称评审相关标准，举例说明】

1.对本专业基础理论知识和专业技术知识掌握情况(不少于200字)

在电子信息工程领域，我系统掌握了光通信技术、数字信号处理、数字电路设计等核心理论知识。在光通信方向，深入理解激光通信的物理特性（高方向性、低发散角、抗干扰性等），熟练掌握光模块工作原理、掺铒光纤放大器（EDFA）增益原理及光功率预算分析方法。在数字信号处理方面，具备DSP芯片开发能力，熟悉Mcbsp多通道缓冲串口协议设计，能实现复杂外设的数据交互控制。在数字电路设计领域，精通FPGA逻辑架构设计，掌握VHDL硬件描述语言，可完成千兆以太网MAC层通信模块开发及时序优化，具备高速数据流拆帧组包、时钟域交叉处理等关键技术能力。针对无线通信系统，掌握误码率（BER）测试、眼图分析等通信质量评估方法，并可通过Matlab进行通信链路仿真验证。通过项目实践，我将理论知识与工程应用深度融合，特别是在激光通信系统的高速数据传输协议适配等方向形成了完整的技术知识体系。

2.工程实践的经历(不少于200字)

在威海激光通信先进技术研究院的工程实践中，我主导完成了激光通信系统的三大核心模块开发：首先，基于Xilinx Artix-7
FPGA平台，设计实现千兆以太网MAC层通信系统，创新采用双时钟域（125MHz/200MHz）架构，通过CRC32校验与流量控制机制将误码率降至10^-
12量级，满足G.709光传输标准。其次，开发光模块通信适配系统，攻克不定长以太网帧与880字节定长光通信包的转换难题，设计具有动态缓冲管理的package_split/package_joint模块，实现零丢包率的千兆光通信。同时，构建主控上位机与DSP-
FPGA的协同控制系统，开发基于Modbus-
TCP协议的指令解析，实现CCD光斑定位、步进电机闭环控制、EDFA增益调节的多设备联动。在工程实施中，完成系统级联调测试12次，编写自动化测试脚本实现长时间压力测试，最终使通信系统在威海海域实测中实现千兆速率稳定传输，相关成果已应用于某型卫星激光通信终端研制。

3.在实际工作中综合运用所学知识解决复杂工程问题的案例（不少于1000字）

在参与点对点激光通信系统研发过程中，我主导完成了基于FPGA的千兆通信系统设计与实现，成功解决了高速数据传输、多协议异构系统协同、动态帧长转换三大技术难题。项目初期面临的核心挑战在于如何构建满足可靠的通信架构：千兆以太网管理通道存在物理层抖动与MAC层缓存溢出的双重风险，传统测试方法无法量化评估实际链路性能；主控指令需跨越Windows上位机、FPGA、DSP、外设四层异构协议栈，时钟域失步导致指令传输延迟波动超过5μs；而SFP光模块所需的880字节定长包与标准以太网变长帧结构冲突，直接截断或填充方案分别造成12.7%数据丢失或23%带宽浪费。针对这些复杂问题，我通过系统性技术创新实现了工程突破。
在通信性能评估方面，我创新设计了分层监测架构，将物理层CRC32校验、MAC层AXI4流控计数器、应用层序列号比对进行数据融合。通过在FPGA内部构建BRAM双端口存储器实现纳秒级时间戳对齐，最终测得系统稳定传输阈值为867Mbps，较行业通用方案有较大提升。测试模块成功捕捉到PHY芯片在893MHz时钟下的周期性误码现象，该发现直接指导了硬件电路的时序优化，使千兆通道实际传输速率达到950Mbps（误码率<1e-
9），为激光通信载荷提供了可靠的数据通道。

针对多协议协同难题，我构建了跨时钟域指令传输体系。通过设计三级缓冲机制——125MHz AXI时钟驱动的2KB环形缓冲区、100MHz
McBSP时钟域的双端口RAM缓存，将指令重传率从2.1%降至0.03%。为解决DSP端偶发的指令位翻转问题，开发了包含序列号连续性检测与时间戳比对的复合校验协议，使端到端指令延迟从15ms压缩至2.3ms（抖动<200μs）。
为突破光通信与以太网数据适配瓶颈，我通过设计一套数据帧的拆帧组包和拆包组帧的机制管理以太网数据流，将以太网的不定长数据帧进行动态切割，在FPGA中实现帧头特征识别与数据帧重组逻辑。发送端通过给下发的以太网数据帧按照880字节进行切割，并给切割后的帧填加报头、帧计数、分片计数、校验码等信息。接收端根据切割后的定长帧的帧头和帧尾信息对数据帧还原成不定长的以太网数据帧。经长时间实测验证，该方案使有效数据利用率达到98.2%，误码率<1e-9，较传统方案有较大提升。
本项目实施过程中，我综合运用了FPGA时序约束优化、AXI4总线协议栈开发、跨时钟域信号同步等专业技术，特别是在解决光模块定长包转换问题时，创造性将计算机网络中的滑动窗口协议与硬件描述语言相结合，实现了通信效率与可靠性的双重突破。通过严格的眼图测试、边界条件压力测试，系统最终达到星载设备指标要求。此次工程实践不仅验证了千兆激光通信系统的可行性，更培养了我对复杂系统问题的分析能力——
从最初的问题定位、中期的算法创新到最终的全链路验证，形成了完整的工程技术闭环，为后续承担更大型通信系统研发奠定了坚实基础。

（二）取得的业绩（代表作）【限填3项，须提交证明原件（包括发表的论文、出版的著作、专利证书、获奖证书、科技项目立项文件或合同、企业证明等）供核实，并提供复印件一份】

1. 公开成果代表作【**论文发表、专利成果、软件著作权、标准规范与行业工法制定、著作编写、科技成果获奖、学位论文等**】

成果名称	成果类别 [含论文、授权专利（含发明专利申请）、软件著作权、标准、工法、著作、获奖、学位论文等]	发表时间/授权或申请时间等	刊物名称/专利授权或申请号等	本人排名/总人数	备注
Asymmetric lens distortion compensation method based on linear reconstruction of feature points	会议论文	2024年12月06日	SPIE	1/2	EI会议收录
特征点投影变换引导线性重构的非对称镜头畸变补偿方法	发明专利申请	2024年08月28日	申请号：202411191188 2	1/2	进入实质性审查

2.其他代表作【主持或参与的课题研究项目、科技成果应用转化推广、企业技术难题解决方案、自主研发设计的产品或样机、技术报告、设计图纸、软课题研究报告、可行性研究报告、规划设计方案、施工或调试报告、工程实验、技术培训教材、推动行业发展中发挥的作用及取得的经济社会效益等】

本人在威海激光通信先进技术研究院中参与设计和开发点对点激光通信设备样机，通过主控上位机与 FPGA 板卡以及各种外设(如CCD相机、电机、光模块等)之间的信息交互，实现设备之间点对点的远距离激光通信。

/

<table>
<tr><td colspan="2">（三）在校期间课程、专业实践训练及学位论文相关情况</td></tr>
<tr><td>课程成绩情况</td><td>按课程学分核算的平均成绩： 82 分</td></tr>
<tr><td>专业实践训练时间及考核情况(具有三年及以上工作经历的不作要求)</td><td>累计时间： 1.2 年（要求1年及以上）
考核成绩： 81 分</td></tr>
<tr><td colspan="2">本人承诺</td></tr>
<tr><td colspan="2">个人声明：本人上述所填资料均为真实有效，如有虚假，愿承担一切责任，特此声明！

申报人签名：[signature]</td></tr>
</table>

72260100

二、日常表现考核评价及申报材料审核公示结果

日常表现考核评价	非定向生由德育导师考核评价、定向生由所在工作单位考核评价： ☑优秀 □良好 □合格 □不合格 德育导师/定向生所在工作单位分管领导签字（公章）：2025 年 6 月 5 日
申报材料审核公示	根据评审条件，工程师学院已对申报人员进行材料审核（学位课程成绩、专业实践训练时间及考核、学位论文、代表作等情况），并将符合要求的申报材料在学院网站公示不少于5个工作日，具体公示结果如下： □通过 □不通过（具体原因： ） 工程师学院教学管理办公室审核签字（公章）： 年 月 日

浙 江 大 学 研 究 生 院

攻读硕士学位研究生成绩表

学号：22260100	姓名：龚凡崴	性别：男	学院：工程师学院	专业：电子信息	学制：2.5年

毕业时最低应获：26.0学分	已获得：28.0学分	入学年月：2022-09	毕业年月：

学位证书号：	毕业证书号：	授予学位：

学习时间	课程名称	备注	学分	成绩	课程性质	学习时间	课程名称	备注	学分	成绩	课程性质
2022-2023学年秋季学期	新时代中国特色社会主义理论与实践		2.0	89	公共学位课	2022-2023学年春季学期	研究生英语基础技能		1.0	79	公共学位课
2022-2023学年秋季学期	工程技术创新前沿		1.5	76	专业学位课	2022-2023学年春季学期	电子与通信工程领域前沿讲座		2.0	77	跨专业课
2022-2023学年秋季学期	数值计算方法		2.0	85	专业选修课	2022-2023学年春夏学期	移动互联网智能设备应用设计与实践		3.0	80	专业学位课
2022-2023学年秋冬学期	工程伦理		2.0	94	公共学位课	2022-2023学年夏季学期	自然辩证法概论		1.0	70	公共学位课
2022-2023学年秋冬学期	研究生论文写作指导		1.0	87	专业学位课	2022-2023学年夏季学期	物联网信息安全技术与应用基础		2.0	83	专业学位课
2022-2023学年秋冬学期	高阶工程认知实践		3.0	89	专业学位课	2022-2023学年春夏学期	研究生英语		2.0	70	公共学位课
2022-2023学年冬季学期	产业技术发展前沿		1.5	82	专业学位课		硕士生读书报告		2.0	通过	
2022-2023学年冬季学期	物联网操作系统与边缘计算		2.0	90	专业选修课						

说明：1. 研究生课程按三种方法计分：百分制，两级制（通过、不通过），五级制（优、良、中、及格、不及格）。

2. 备注中“*”表示重修课程。

学院成绩校核章：

成绩校核人：张梦依

打印日期：2025-06-03

浙江大学研究生（60）成绩校核章

ICGIP 2024 ACCEPTANCE LETTER

Dear Fanwei Gong and Jie Zhong,

Congratulations!

Based on the recommendations of the reviewers and conference program committees, we are delighted to inform you that your paper identified below has been accepted for **presentation and publication** after a double-blinded peer review process. You are cordially invited to present the paper at 2024 16th International Conference on Graphics and Image Processing (ICGIP 2024) in Nanjing, China during November 8-10, 2024.

Finally, we would like to further extend our congratulations to you again and look forward to seeing you in Nanjing, China!

Paper ID: G4P099

Paper Title: Asymmetric lens distortion compensation method based on linear reconstruction of feature points

Publication Information:

The Proceedings of ICGIP 2024 will be included in **SPIE Digital Library** and provided to the Web of Science Conference Proceedings Citation Index-Science, Scopus, Ei Compendex, Web of Science (CPCI), Inspec, Google Scholar, Microsoft Academic Search, and others, to ensure maximum awareness of the Proceedings.

Registration Instructions:

1. Revise paper according to review comments and paper template: Paper Template ; Formatting Instruction | SPIE Manuscript Specifications

2. Finish registration and upload final paper by below link before October 15, 2024:

http://conference123.mikecrm.com/wyL7WQB

Any problems about registration, please contact: icgip_conf@vip.163.com

Final Conference Program will be available at the website in October, 2024. For the most updated conference information, please check the conference website at: www.icgip.org

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AUTHOR

Paper Title: **Asymmetric lens distortion compensation method based on linear reconstruction of feature points**

Paper No. **ICG24-38**

Tracking No. **ICG24-ICG24-38**

Proceedings Coordinator: **Alphonsa, Rennie** (Rennie.Alphonsa@spie.org)

MANUSCRIPT

Status: Manuscript version 2 submitted and approved.	**Due Date**
Submit Manuscript Revision or Update Presentation Details	06 December 2024
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Submission History

Asymmetric lens distortion compensation method based on linear reconstruction of feature points

Fanwei Gong, Jie Zhong*
College of Engineers, Zhejiang University, Hangzhou, China

ABSTRACT

This paper proposes a new method to compensate for asymmetric lens distortion through feature point projection transformation and linear reconstruction. The method involves traversing the world coordinates of calibration image feature points using a minimum reference grid and calculating the composite projection transformation error of all grids. The composite projection error is obtained through weighted calculations based on linear constraints, cross-ratio constraints, and parallel line constraints. After a second screening, the reference grid area with the minimum projection error is identified. Subsequently, the optimal reference grid is optimized with the goal of minimizing the composite error. Finally, the optimized feature point coordinates are solved with the corresponding world coordinates to derive the homography matrix. This allows the linear reconstruction of the entire calibration image's feature points through projection transformation, and the parameters of the asymmetric lens distortion model are optimized. Consequently, a high-precision asymmetric lens distortion model is obtained, allowing for compensation and correction of the asymmetric distortion.

Keywords: Camera calibration, distortion compensation, linear projection transformation, target optimization.

1. INTRODUCTION

Camera calibration technology plays a crucial role in various fields, including computer vision, robotic navigation, autonomous driving, 3D reconstruction, and virtual reality. Its primary task is to determine the internal and external parameters of the camera to accurately map points from the 3D world onto a 2D image plane[1]. However, due to manufacturing and installation imperfections in the camera lens[2], various types of distortions are inevitable. These distortions not only affect image quality but also significantly reduce measurement accuracy. Lens distortions can be broadly categorized into two types: radial distortion and tangential distortion[3]. Radial distortion refers to the radial bending of light as it passes through the lens, causing a disproportionate scaling effect between the image center and edges. Tangential distortion occurs due to imperfections in lens assembly, causing a shift in the light rays[4].Typically, polynomial fitting or other mathematical models are used to correct these distortions, restoring the true geometry of the image.

As camera lens usage scenarios become increasingly complex, the demand for calibration precision continues to rise. In certain scenarios, such as long-focus lenses, wide-angle imaging, or lens optical axis deviation, distortions exhibit asymmetric characteristics[5]. Existing distortion models struggle to handle these complex cases and fail to achieve ideal fitting results, resulting in a significant decrease in calibration accuracy[6]. Therefore, improving lens correction accuracy in asymmetric distortion environments has become an urgent problem that needs to be addressed.

To solve this problem, this paper proposes a method for asymmetric lens distortion compensation based on feature point projection transformation and linear reconstruction. The method involves traversing the world coordinates of feature points in calibration images and calculating the composite projection transformation error for the minimum reference grid. The projection error is computed through weighted calculations based on linear constraints, cross-ratio constraints, and parallel line constraints. The optimal grid area is then optimized, and the projection coordinates are converted into world coordinates through linear reconstruction, enabling compensation for the asymmetric lens distortion.

2. CAMERA CALIBRATION MODEL AND LINEAR PROJECTION TRANSFORMATION CONSTRAINTS

2.1 Camera Calibration model

2.1.1 Linear Projection Transformation Model

The linear camera model is one of the simplest models. To determine the position information of a point existing in the objective world in a linear camera model[7], it is only necessary to perform coordinate transformations based on the relationships between different coordinate systems[8].

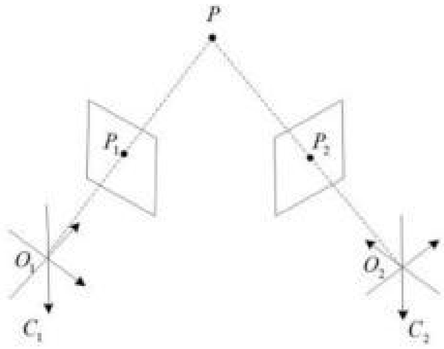

Figure 1. Schematic diagram of the projection of a linear camera model.

Assuming that there is a point P in the world with world coordinates(x_W,y_W,z_W,1), and its projection on the camera image coordinates is point P_1, with camera coordinates (x_C,y_C,z_C,1). The transformation between these two coordinates can be represented as following equation (1):

$$\begin{pmatrix} X_C \\ Y_C \\ Z_C \\ 1 \end{pmatrix} = \begin{pmatrix} R & T \\ 0^T & 1 \end{pmatrix} \begin{pmatrix} X_W \\ Y_W \\ Z_W \\ 1 \end{pmatrix} = \begin{pmatrix} r_{11} & r_{12} & r_{13} & t_x \\ r_{21} & r_{22} & r_{23} & t_y \\ r_{31} & r_{32} & r_{33} & t_z \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} X_W \\ Y_W \\ Z_W \\ 1 \end{pmatrix} \quad (1)$$

Where R represents the rotation vector and T represents the translation matrix. The projection of the point in the camera coordinate system onto the image coordinate system can be expressed by the following equation (2):

$$\begin{cases} x = f\frac{X_C}{Z_C} \\ y = f\frac{Y_C}{Z_C} \end{cases} \quad (2)$$

The focal length f represents the distance from the focal point to the lens center 0_1. The coordinates of this point in the image coordinate system are represented as (x,y), and in the camera coordinate system as (x_C,y_C,z_C). The normalized form of equation (3) is as follows:

$$Zc\begin{pmatrix} x \\ y \\ 1 \end{pmatrix} = \begin{pmatrix} f & 0 & 0 & 0 \\ 0 & f & 0 & 0 \\ 0 & 0 & 1 & 0 \end{pmatrix} \begin{pmatrix} Xc \\ Yc \\ Zc \\ 1 \end{pmatrix} \quad (3)$$

The relationship between the pixel coordinate system (u,v) and the image coordinate system (x,y) equation (4) can be expressed as:

$$\begin{cases} u = \frac{x}{dX} + u_0 \\ v = \frac{y}{dY} + v_0 \end{cases} \quad (4)$$

Using homogeneous coordinates, the equation(5) is expressed as:

$$\begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = \begin{bmatrix} 1/dX & 0 & u_0 \\ 0 & 1/dY & v_0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix} \quad (5)$$

Based on the above formulas, the relationship between the world coordinates of any point in the three-dimensional world and the pixel coordinates can be derived as the equation(6):

$$Z_C\begin{pmatrix}u\\v\\1\end{pmatrix}=\begin{pmatrix}\frac{1}{dX} & 0 & u_0\\ 0 & \frac{1}{dY} & v_0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}f & 0 & 0 & 0\\ 0 & f & 0 & 0\\ 0 & 0 & 1 & 0\end{pmatrix}\begin{pmatrix}R & T\\ 0^T & 1\end{pmatrix}\begin{pmatrix}X_W\\Y_W\\Z_W\\1\end{pmatrix}$$
$$=\begin{pmatrix}f_x & 0 & u_0 & 0\\ 0 & f_y & v_0 & 0\\ 0 & 0 & 1 & 0\end{pmatrix}\begin{pmatrix}R & T\\ 0^T & 1\end{pmatrix}\begin{pmatrix}X_W\\Y_W\\Z_W\\1\end{pmatrix}=AM\begin{pmatrix}X_W\\Y_W\\Z_W\\1\end{pmatrix}=N\begin{pmatrix}X_W\\Y_W\\Z_W\\1\end{pmatrix} \quad (6)$$

Solving the N matrix completes the camera calibration[9]. In the case where all parameters appearing in the above the equation (6) are known, for any point existing in the objective world, the corresponding point on the image can be found through this transformation relationship.

Explanation of relevant symbols:

A — Camera intrinsic matrix, size 3 ×4;

M — Camera projection transformation matrix, size 4 ×4;

N — Camera projection transformation matrix, size 3 ×4, and N=AM;

u_0 — The x-coordinate of the origin (principal point) of the image coordinate system;

v_0 — They-coordinate of the origin (principal point) of the image coordinate system;

f_x — The effective focal length of the u-axis in the pixel coordinate system;

f_y — The effective focal length of the v-axis in the pixel coordinate system;

dX— The unit length per pixel in the x-direction of the image coordinate system;

dY— The unit length per pixel in they-direction of the image coordinate system.

2.1.1 Asymmetric Distortion Model

In general, the ideal imaging model satisfies a linear relationship, but in practice, errors are unavoidable[10]. Due to manufacturing processes and assembly deviations in industrial lenses, distortion occurs during the imaging process, causing nonlinear distortion[11]. This means that there is a certain offset between the ideal projection point of a spatial point and its actual imaging point on the image plane. Nonlinear distortion mainly includes radial distortion and tangential distortion[5].The formulas for describing radial distortion and tangential distortion are shown in formulas(7)(8).

$$x_{distorted} = x(1 + k_1r^2 + k_2r^4 + k_3r^6) \quad (7)$$

$$y_{distorted} = y(1 + k_1r^2 + k_2r^4 + k_3r^6) \quad (8)$$

Where (x,y) are the undistorted normalized coordinates, (xdistorted,ydistorted) are the distorted coordinates, and r is the distance from the point to the center of the image. k1, k2, k3 are the radial distortion coefficients.

The expression for tangential distortion is shown in the formulas(9)(10):

$$x_{distorted} = x + (2p_1y + p_2(r^2 + 2x^2)) \quad (9)$$

$$y_{distorted} = y + (p_1(r^2 + 2y^2) + 2p_2x) \quad (10)$$

Where p1 and p2 are the tangential distortion coefficients.

For complex lens distortion cases, such as periscope long-focus lenses and fisheye lenses, in addition to considering radial and tangential distortion, asymmetric distortion factors and edge over-distortion factors also need to be introduced.

Thus, an asymmetric distortion model is constructed for this case. The formula for the asymmetric distortion model is shown in the equation(11)(12)(13):

$$\lambda^2 = (u'_\varphi - c_1)^2 + (v'_\varphi - c_2)^2 \quad (11)$$

$$\tilde{u}_{\varphi} = u^{I}_{\varphi}(1 + k_1\lambda^2 + k_2\lambda^4 + k_3\lambda^6) + (2p_1 v^{I}_{\varphi} + p_2(\lambda^2 + 2{u^{I}_{\varphi}}^2)) + c_3 e^{c_4\lambda^2} \quad (12)$$

$$\tilde{v}_{\varphi} = v^{I}_{\varphi}(1 + k_1\lambda^2 + k_2\lambda^4 + k_3\lambda^6) + (p_1(\lambda^2 + 2{v^{I}_{\varphi}}^2) + 2p_2 u^{I}_{\varphi}) + c_3 e^{c_4\lambda^2} \quad (13)$$

Where λ is the distance between the feature point in the distorted image coordinate matrix and the distortion center point (c1,c2). k1, k2, k3 are the radial distortion coefficients, p1, p2 are the tangential distortion coefficients, c3 and c4 are the edge∼disto rtion coefficients, and u^{I}_{φ}, v^{I}_{φ} are the coordinates of the φ-th feature point in the distorted image coordinate matrix. u_{φ}, v_{φ}~are the predicted distorted feature point coordinates.

2.2 Linear Projection Transformation Constraints

During the perspective projection transformation, if the points in the scene are structured, the collinearity and correlation of the scene will be preserved. Therefore, the world coordinates of feature points after projection transformation should satisfy invariance of cross-ratio, line invariance, and parallel lines intersecting at a common point. If a set of 4x4 chessboard image feature point coordinates is taken as the reference grid R, the line error E_{st}, cross-ratio error E_{cr}, and parallel line error E_{pa} corresponding to the reference grid R are defined.

The formula for calculating the line error E_{st} of the reference grid is shown in the equation(14)(15)(16)(17):

$$E_{st} = \frac{\sum_{m=1}^{r}\sum_{n=1}^{s}(v_{m,n}-\hat{v}_{m,n})^2}{r\times s} \quad (14)$$

$$\hat{v} = \hat{a}_m u + \hat{b}_m \quad (15)$$

$$\hat{a}_m = \frac{\sum_{n=1}^{s}(u_{dm,n}-u_{dm})(v_{dm,n}-v_{dm})}{\sum_{n=1}^{s}(u_{dm,n}-u_{dm})^2} \quad (16)$$

$$\hat{b}_m = v_{dm} - \hat{a}_m u_{dm} \quad (17)$$

Where $v_{m,n}$represents the vertical coordinate of then-th feature point online l_m, and $\hat{v}_{m,n}$ represents the fitted vertical coordinate of then-th feature point online l_m. r is the number of lines in each reference grid, and s is the number of feature points in each reference grid. $\hat{v}$ is the vertical coordinate calculated by the fitted line l_m using the horizontal coordinate u. $\hat{a}_m$ and $\hat{b}_m$ are the slope and intercept of the fitted line l_m, respectively. $u_{dm,n}$ and$v_{dm,n}$ are the horizontal and vertical coordinates of thennn-th point online lm, and $u_{dm,n}$ and$v_{dm,n}$ are the averages of the horizontal and vertical coordinates of the s points online l_m.

For each row and column of feature points in reference grid R, the straight line lml_mlm can be fitted using the least squares method to obtain the regression linear equation of line l_m.

The formula for calculating the cross-ratio error function E_{cr} of the reference grid is shown in the equation(18)(19)(20)(21)(22)(23):

$$E_{cr} = (E_{crh} + E_{crv})/8 \quad (18)$$

$$E_{crh} = \sum_{m=1}^{r}\sum_{n=1}^{s-3}(F_{cr}(q_{dm,n}, q_{dm,n+1}, q_{dm,n+2}, q_{dm,n+3}) - F_{cr}(P1, P2, P3, P4))^2 \quad (19)$$

$$E_{crv} = \sum_{m=1}^{s}\sum_{n=1}^{r-3}(F_{cr}(q_{dm,n}, q_{dm,n+1}, q_{dm,n+2}, q_{dm,n+3}) - F_{cr}(P1, P2, P3, P4))^2 \quad (20)$$

$$F_{cr}(P1, P2, P3, P4) = \frac{d_{13}\cdot d_{24}}{d_{14}\cdot d_{23}} \quad (21)$$

$$q_{dm,n} = (u_{dm,n}, v_{dm,n}) \quad (22)$$

$$d_{ij} = (u_{dm,i} - u_{dm,j})^2 + (v_{dm,i} - v_{dm,j})^2 \quad (23)$$

Where E_{crh} is the sum of cross-ratio errors calculated for each row of the reference grid, and E_{crv} is the sum of cross-ratio errors calculated for each column. r is the number of lines in each reference grid, and s is the number of feature points in each reference grid. P1, P2, P3, P4 represent the non-distorted world coordinates of four points $q_{dm,n}, q_{dm,n+1}, q_{dm,n+2}, q_{dm,n+3}$ in the world coordinate system.$F_{cr}(\,)$represents the cross-ratio function. $u_{dm,n}$ and$v_{dm,n}$ are the horizontal and vertical coordinates of then-th point online l_m. d_{ij} represents the distance between point $q_{d_{m,i}}$ and $q_{d_{m,j}}$, where i = 1、2，j = 3、4.

Since each feature point is an intersection of horizontal and vertical lines, the calculation of cross-ratio errors in the reference grid must be performed for both horizontal and vertical directions.

After fitting the equations of the straight lines for each row rrr and each column sss in the reference grid, according to the intersection properties of parallel lines, the two groups of parallel lines (rows and columns) will intersect at different vanishing points.

The formula for calculating the parallel line error E_{pa} of the reference grid is shown in the equation(24)(25)(26)(27):

$$E_{pa} = \sum_{m=1}^{r} \left(\hat{b}_m - (-\hat{a}_m \cdot \hat{u}_v + \hat{v}_v)\right)^2 \quad (24)$$

$$\begin{bmatrix} -\hat{a}_1 & 1 \\ -\hat{a}_2 & 1 \\ \cdots & \cdots \\ -\hat{a}_r & 1 \end{bmatrix} \begin{bmatrix} \hat{u}_v \\ \hat{v}_v \end{bmatrix} = \begin{bmatrix} \hat{b}_1 \\ \hat{b}_2 \\ \cdots \\ \hat{b}_r \end{bmatrix} \quad (25)$$

$$A = \begin{bmatrix} -\hat{a}_1 & 1 \\ -\hat{a}_2 & 1 \\ \cdots & \cdots \\ -\hat{a}_r & 1 \end{bmatrix}, \quad \hat{q}_v = \begin{bmatrix} \hat{u}_v \\ \hat{v}_v \end{bmatrix}, \quad b = \begin{bmatrix} \hat{b}_1 \\ \hat{b}_2 \\ \cdots \\ \hat{b}_r \end{bmatrix} \quad (26)$$

$$\hat{q}_v = (A^T A)^{-1} A^T b \quad (27)$$

Where r is the number of lines in the reference grid, $\hat{a}_m$ and $\hat{b}_m$ are the slope and intercept of them-th fitted line l_m (with m=1,2,…,r), A is the coefficient matrix, $\hat{q}_v$ is the assumed vanishing point where the first tor-th parallel lines intersect, $\hat{u}_v$ and $\hat{v}_v$ are the horizontal and vertical coordinates of the vanishing point $\hat{q}_v$, b is the constant matrix, and T represents the transpose.

3. FEATURE POINT LINEAR RECONSTRUCTION AND DISTORTION COMPENSATION

3.1 Feature Point Linear Reconstruction

The image feature point coordinate matrix is constructed based on the feature points of the chessboard calibration image. Using the sub-pixel feature point detection method based on the Harris operator, all feature points of the chessboard calibration image are detected, obtaining the coordinates of each feature point and the size of the chessboard. Based on the chessboard size, a grid point coordinate matrix is initialized, and the detected feature point coordinates are stored in the grid point coordinate matrix as a two-dimensional grid and recorded as the distorted image coordinate matrix.

A sliding grid extraction is performed on the distorted image coordinate matrix using the reference grid R, resulting in a set of reference grids U. For each reference grid in the setU, the line error E_{st}, cross-ratio error E_{cr}, and parallel line error E_{pa} are calculated. Reference grids where E_{st}, E_{cr}, or E_{pa} exceed the preset error threshold are removed, leaving the pre-screened set of reference grids U′. The formula for the comprehensive error E_δ of the δ-th reference grid in theset U′ is shown in the equation(28):

$$E_\delta = \lambda_{cr} E_{cr} + \lambda_{st} E_{st} + \lambda_{pa} E_{pa} \quad (28)$$

Where λ_{cr} 、 λ_{st} 、 λ_{pa} are the weight coefficients corresponding to the three constraints.

The weight coefficients corresponding to the line error E_{st}, cross-ratio error E_{cr}, and parallel line error E_{pa} are generated and recorded as a weight coefficient combination. For each reference grid in the pre-screened set U′, the comprehensive error is calculated, and the reference grid with the smallest comprehensive error is selected as the optimal reference grid R_t for the current weight coefficient combination. By changing the values of the weight coefficients, the optimal reference grid R_t corresponding to different weight coefficient combinations is obtained. The deviation error E_p between each optimal reference grid R_t and the standard distortion center is calculated, and the reference grid R_t with the smallest deviation error E_p is selected as the final optimal reference grid R_t.

The coordinates of each grid point are denoted as $(x_{\alpha\beta}, y_{\alpha\beta})$, where i and j represent the row and column of the grid (with α, β=1,2,3,4). The formula for calculating the deviation error E_p is shown in the equation(29):

$$E_p = \frac{1}{16}\sum_{\alpha=1}^{4}\sum_{\beta=1}^{4}\sqrt{(x_{\alpha\beta}-x_0)^2+(y_{\alpha\beta}-y_0)^2} \tag{29}$$

The comprehensive error function E_t of the final optimal reference grid R_t is used as the objective function. A nonlinear optimization method is applied to optimize the coordinates of each feature point in the final optimal reference grid R_t, resulting in the optimized optimal reference grid R_t.

Based on the optimized feature point coordinates of the optimal reference grid and their corresponding world coordinates, a linear equation system is constructed to solve the homography matrix. Assuming there are n point pairs, a matrix P with 2n rows must be constructed. Let the solution vector of the homography matrix be $h = [h_{11}, h_{12}, h_{13}, h_{21}, h_{22}, h_{23}, h_{31}, h_{32}, h_{33}]^T$. For each feature point's world coordinates (x_w, Y_w) and image coordinates (u, v), the linear equation system for solving the homography matrix is shown in the equation(30):

$$\begin{bmatrix} X_w, Y_w, 1,0,0,0, -uX_w, -uY_w, -u \\ 0,0,0, X_w, Y_w, 1, -vX_w, -vY_w, -v \end{bmatrix} h = 0 \tag{30}$$

The linear equation system for the homography matrix is solved using the Singular Value Decomposition (SVD) method. The eigenvector corresponding to the smallest singular value is taken as the solution vector h, and the homography matrix H is reshaped from this solution vector.

The world coordinate vectors of the feature points are extended into homogeneous coordinates, resulting in the extended homogeneous coordinate matrix w_h, expressed as the equation(31):

$$\mathbf{W_h} = \begin{bmatrix} X_1 & Y_1 & 1 \\ X_2 & Y_2 & 1 \\ \vdots & \vdots & \vdots \\ X_n & Y_n & 1 \end{bmatrix} \tag{31}$$

The homography matrix H is applied to the extended homogeneous coordinate matrix w_h for perspective transformation, resulting in the transformed homogeneous coordinates T_h, expressed as the equation(32)(33):

$$T_h = Hw_h^T \tag{32}$$

$$T_h^T = \begin{bmatrix} X_1' & Y_1' & Z_1' \\ X_2' & Y_2' & Z_2' \\ \vdots & \vdots & \vdots \\ X_n' & Y_n' & Z_n' \end{bmatrix} \tag{33}$$

The transformed homogeneous coordinates T_h are then converted into non-homogeneous coordinates, resulting in the non-homogeneous coordinate vector T, which serves as the undistorted image coordinate matrix. The φ-th coordinate $(u'_{\varphi}, v'_{\varphi})$ in the non-homogeneous coordinate vector T corresponds to the undistorted image feature point coordinates for each image feature point (u, v).

The effect of the linear reconstruction is shown in Figure 2, which displays the optimized optimal reference grid R_t and the linearly reconstructed feature points.

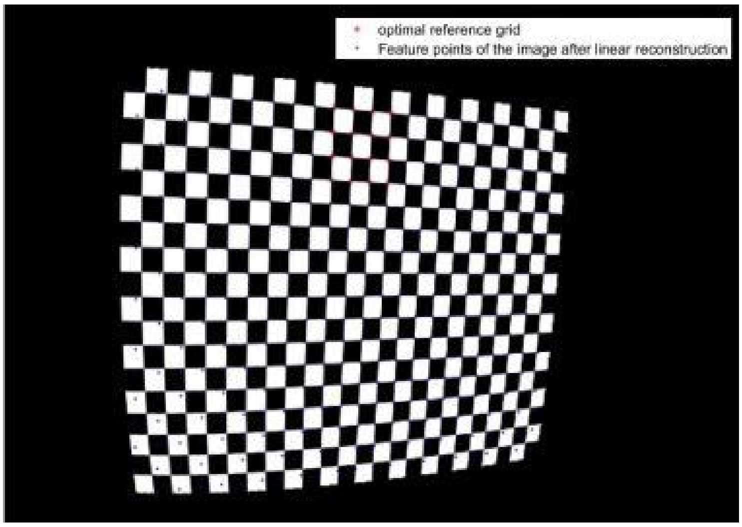

Figure 2. The resolution chart of optimal reference grid selection and linear reconstruction feature point.

3.2 Distortion Compensation

After substituting the feature point coordinates from the undistorted image feature point coordinate matrix into the asymmetric distortion model, the predicted distorted feature point coordinates are obtained, as indicated by the blue markers in Figure 3.

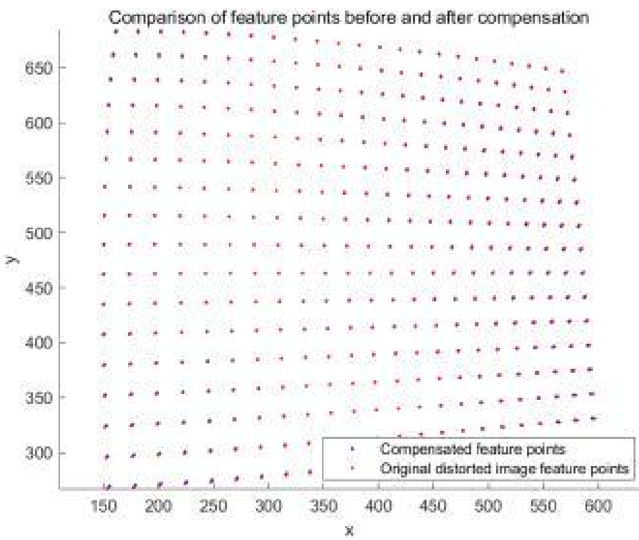

Figure 3. Comparison of feature points before and after compensation.

The error function E_{dis} of the distortion model is used to calculate the error between the predicted distorted feature point coordinates and the angular coordinates in the distorted image feature point coordinate matrix. The interior-point nonlinear optimization method is employed to iteratively adjust the parameters of the asymmetric distortion model (k_1, k_2, k_3, p_1, p_2, c_1, c_2, c_3, c_4) until the error is minimized, resulting in an optimized asymmetric distortion model. This optimized model can perform high-precision compensation and correction for complex distortion scenarios, such as lenses with asymmetric distortion. Figure 3 illustrates the compensated image feature point matrix and the original image feature point matrix in the case where the error is minimized after parameter optimization.

To demonstrate the compensation effect of the proposed method, four calibration chessboard images taken from different angles were tested. Figure 5 shows the average compensation error for each image, and these errors were compared with those obtained using current mainstream methods in MATLAB for the same four images. The results are shown in Figure 4.

The formula for the error function E_{dis} of the distortion model is as follows the equation(34):

$$E_{dis} = \frac{1}{n}\sum_{\varphi=1}^{n} [(\tilde{u}_\varphi - u_\varphi)^2 + (\tilde{v}_\varphi - v_\varphi)^2] \quad (34)$$

Where u_φ, v_φ are the coordinates of the φ-th feature point in the distorted image coordinate matrix, nnn represents the number of feature points, and $\tilde{u}_\varphi$, $\tilde{v}_\varphi$ are the compensated distorted feature point coordinates.

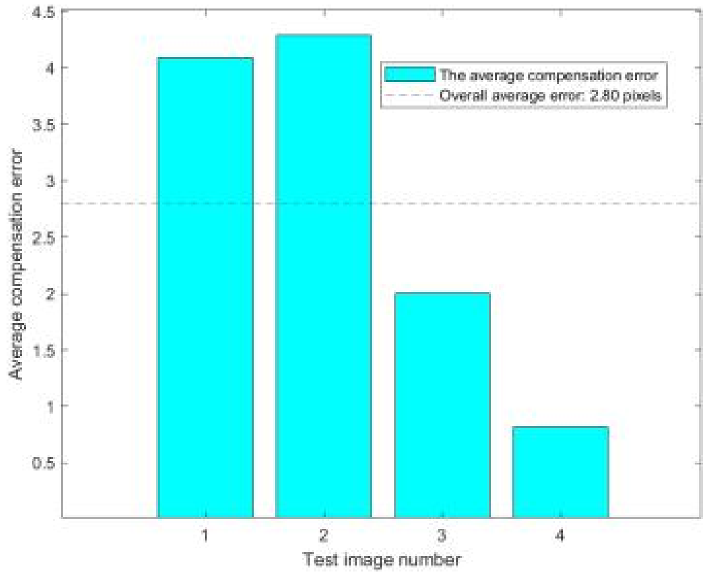

Figure 4. The average compensation error of each image based on mainstream calibration methods.

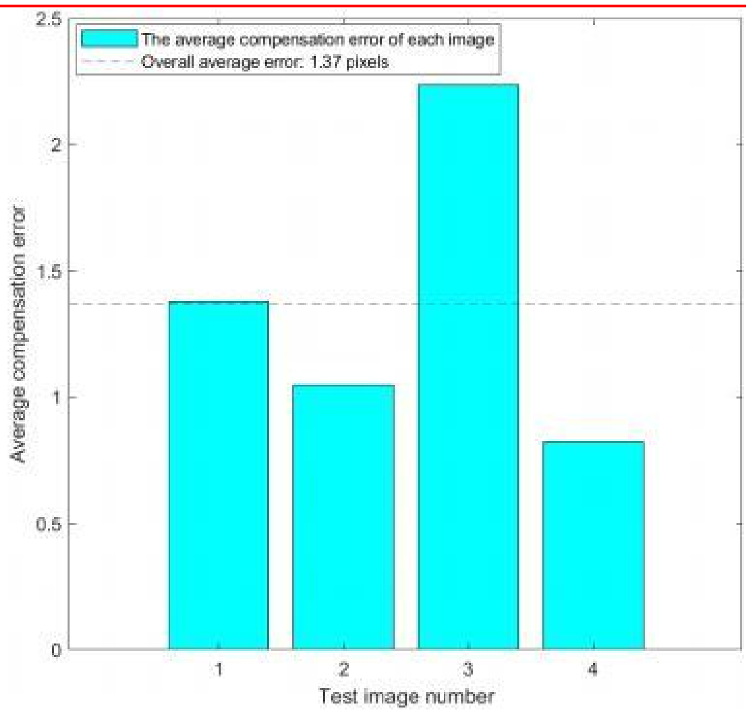

Figure 5. The average compensation error of each image based on the camera calibration method described in article.

4. CONCLUSION

This article proposes a method for asymmetric lens distortion compensation based on feature point projection transformation and linear reconstruction. By defining a minimum reference grid and traversing the detected feature point coordinate matrix, the weighted comprehensive error of line error, cross-ratio error, and parallel line error is calculated to find the optimal reference grid. The homography matrix is then used to perform linear reconstruction on the distorted image feature points. This method demonstrates higher accuracy and applicability, especially in scenarios involving complex lens distortions, such as asymmetric lens distortion.

Compared with traditional camera calibration methods, the proposed approach effectively reduces distortion compensation errors, particularly in applications involving long-focus and wide-angle lenses, significantly improving the accuracy and adaptability of camera calibration. Future research will focus on further optimizing the parameter fitting process and exploring the application of this method in real-time image processing.

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产品与样机成果证明

证明方： 威海激光通信先进技术研究院

被证明方： 龚凡崴同学

证明内容：

该同学于 2023 年 7 月 2 日开始至 2024 年 7 月 14 日在我司实习实践期间，参与设计和开发了点对点激光通信设备样机，情况属实，特此证明。

产品与样机相关信息：

1）**产品与样机功能：** 通过主控上位机与 FPGA 板卡以及各种外设(如 CCD 相机、电机、光模块等)之间的信息交互，实现设备之间点对点的远距离激光通信。

2）**创新性介绍：** 实现了激光通信设备之间的高精度对准，并能够进行低延迟、低误码的数据传输，并且能够通过上位机实时控制和检测各种外设的运行信息，提高了系统的稳定性。

3）**社会经济效益：** 设计和开发点对点激光通信设备能够提高通信的效率和可靠性，并且具有较强的抗干扰能力，能够为军事通信提供高保命性和高速率的通信链路。

4）**个人贡献说明：** 龚凡崴同学在本次实践中，基于千兆以太网进行了管理通道的数据传输与通信测试，设计并实现管理通道的测试模块，实现通信的速率、误码率、丢帧率、误帧率的统计。实现了主控上位机与 FPGA 之间的信息交互，进行了所有外设数据流的监控。同时完成了适配千兆光模块的通信模块设计与 FPGA 实现，实现了以太网数据的不定长帧到光模块通信所需的定长包的转换，使得光模块之间能进行高效的数据传输。对于该产品与样机的完成与完善做出了重要贡献。贡献排名：6/30

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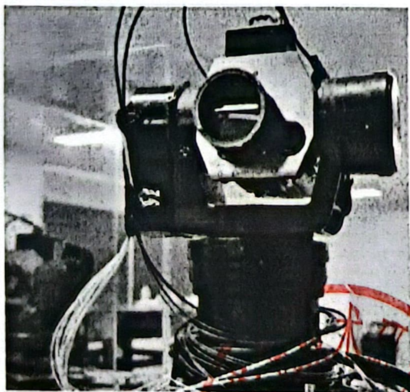

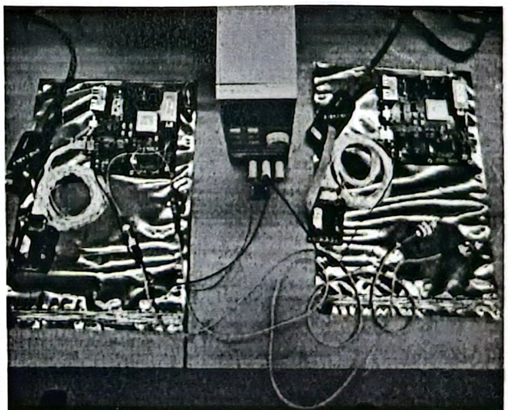

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