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激光与光电子学进展 先进成像

基于虚拟相机的位姿估计研究进展

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摘要 物体位姿估计在机器人、无人驾驶、航空航天、虚拟现实等领域有着广泛的应用。主要围绕主流测量系统及方法展开论述，对比分析各类测量系统和方法的差异、优势与缺陷，综述其研究现状、前沿动向和热点问题。相比之下，基于虚拟相机的位姿估计系统具有突出的系统集成度，同时兼顾高精度和低成本；基于深度学习的方法在场景和目标适应性方面表现突出，有望进一步广泛应用于工业场景。最后，从感知场景和对象出发，分析当前位姿估计技术面临的诸多严峻挑战，展望位姿估计技术的研究重点和方向。

关键词 仪器测量与计量；位姿估计；虚拟相机；深度学习

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Research Progresses of Pose Estimation Based on Virtual Cameras

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Abstract Pose estimation for objects is employed in rich artificial intelligence fields, such as robotics, unmanned driving, aerospace, and virtual reality. This paper mainly discusses the mainstream measurement systems and methods in term of research status, frontier trends, and hot issues, the differences, advantages and disadvantages of which are compared and analyzed in detailed. In general, virtual-camera-based pose estimation systems have outstanding system integration while providing with high accuracy and low cost. Deep-learning-based methods exhibit excellent performance in adaptability of scenes and objects, which are expected to be widely used in unstructured industrial scenarios. Finally, starting from the perception of scenes and objects, this paper analyzes many severe challenges faced by the current pose estimation technology, and looks forward to the research focus and direction of pose estimation technology.

Key words instrumentation measurement and metrology; pose estimation; virtual camera; deep learning

1 引　　言

智能感知是人工智能的关键技术之一，我国在《“十四五”智能制造发展规划》中明确将智能感知技术列为重点攻克任务[1]。其中，位姿估计是智能感知技术的重要组成部分，已广泛应用于无人驾驶、卫星在轨对接、机器人自主导引、工业机器人标定等领域，精准鲁棒高效的位姿估计是智能装备平稳运行的重要保障，受到国内外研究人员的广泛关注[2]。

近年来，位姿估计在基础硬件研发和方法理论研究方面成果丰硕，形成了较为完备的理论方法和技术系统，呈现系统精密化、集成化、智能化和方法多维化、精准化、鲁棒化的发展趋势，成为制造过程在线监测、智能装备自主控制和产品性能测试保证不可或缺的核心技术[3]。典型的位姿估计系统包括激光跟踪仪[4]、惯导测量系统[5]、视觉测量系统[6]等。本课题组提出了基于动态虚拟相机的位姿估计系统，该系统可柔性布置期望数量和位置的虚拟相机，具有高动态、低成本及密集集成优势，适应多遮挡、大噪声、受限空间的测量场景。另外，一系列与测量系统相匹配的位姿估计方法被提出，如基于点特征的位姿估计方法、基于绝对定向的位姿估计方法、基于深度学习的位姿估计方法[7]。面对复杂感知场景的不断拓宽以及感知目标的不断丰富，已有的测量系统仍然面临诸多问题。

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本文对主流测量系统及方法进行系统性综述，对比性能优势及缺陷，重点介绍了基于虚拟相机的位姿估计系统的原理、组成及应用，分析各类系统及方法的优势和缺点，提出当前位姿估计面临的主要问题及解决思路，展望位姿估计的发展趋势和重点研究方向。

2　位姿估计系统

2.1　传统位姿估计系统

根据位姿估计系统的物理感知方式和原理，传统位姿估计系统主要包括基于机械定位的位姿估计系统、基于激光跟踪仪的位姿估计系统、基于惯性单元的位姿估计系统、基于视觉的位姿估计系统等。

基于机械定位的位姿估计系统利用机械结构与多种传感器融合，结合机构运动学理论，辨识空间目标位姿信息[8]，主要包括串/并联式关节机构位姿估计系统和基于拉线位移传感器的位姿估计系统。串联式位姿估计系统通常为开环的链式结构，如作为典型的串联式位姿估计机构的柔性坐标测量臂[9-11]。相比之下，并联式位姿估计系统基于多轴并联支撑机构构成封闭测量链[12-13]，具有稳定性好、负载能力强、不易产生累积误差等优势。拉线位移传感器是当前应用较为广泛的柔性机械式测量模块。Ceccarelli 等[14-15]首次采用该传感器研发了 CaTraSys 系统，实现了人体运动多维度位姿估计。此外，相关学者针对机器人末端位姿估计，开展了一系列基于拉线式位移传感器的相关研究[16-17]。如被大家所熟知的 DynaCal 机器人校准系统，采用拉线位移传感器获取不同姿态的机器人位姿，辨识机器人运动学参数[18]。基于机械定位的六自由度测量系统具有测量精度高、抗噪能力强、系统工作稳定等优势，但测量方式为接触式测量，难以实现动态及对易变形对象的实时在线测量，应用场景有限。

激光跟踪仪是一种与全站仪[19]类似的典型测量系统，通过激光干涉测距原理获取微米级精度深度信息[20]；另外，依靠 phase-sensitive detector（PSD）位置检测器，可实现对动态目标的跟踪测量。图 1 为激光跟踪仪原理图。

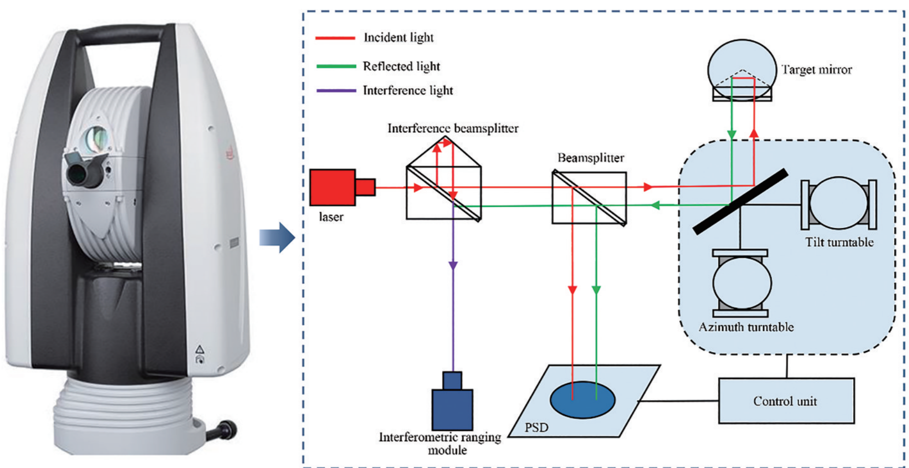

图 1　激光跟踪仪原理图[20]

Fig. 1　Schematic of a laser tracker[20]

实际应用场景中，激光跟踪仪通常配合多传感器协同作业，以满足复杂非结构化的测量现场需求。如面向大飞机的制造与装配，激光跟踪仪作为全局基准测量站，联动关节臂测量机（portable CMM arm）提取机身关键点及隐蔽点的三维坐标，配合 3D 扫描仪（laser scanner）对机身表面形貌进行三维成像[21-23]。尤其合作靶标与激光跟踪仪配合作业，可动态获取被测目标六自由度位姿，已引起德国徕卡、美国 FARO、美国 API 等精密测量公司的重点关注[24-27]。基于激光跟踪仪的六自由度位姿估计系统具有作业精度高、动态性能好、可实现非接触跟踪测量的特点，已广泛应用于对工业机器人[28-29]、盾构机[30]等智能制造装备的在线状态监测，但仍存在售价昂贵、系统标定复杂、需合作靶镜等挑战，难以广泛应用于高端制造领域，操作复杂和抗噪能力差仍是其最大缺陷。

基于惯性单元的空间位姿估计系统[31]是一种基于加速计等惯性感知单元的位姿估计系统，主要包括基于激光惯性单元的位姿估计系统、基于光纤惯性单元的位姿估计系统和基于 Micro-Electro-Mechanical System（MEMS）惯性单元的位姿估计系统。三类位姿估计系统的基本原理及组成如图 2 所示[32]。惯性测量系统的精度易受温度、零漂等动态误差的影响[33]。为此，以惯性单元为核心与多种感知模块结合的方案被提出，如 GPS[34-35]、磁力计[36]、视觉[37-38]、激光扫描仪[39]、超声[40]、RFID[41]等。以惯性单元数据为基础，融合多传感器感知信息，结合多维数据降维与配准、离群点随机一致性剔除等数据融合策略，充分发挥各测量单元的感知优势，基于惯性单元的空间位姿估计系统可实现高精度、高分辨、多维度测量，但系统初始化耗时，多测量模块联合标定复杂，存在误差累积等难题。

基于视觉的位姿估计系统以成像单元为核心，通

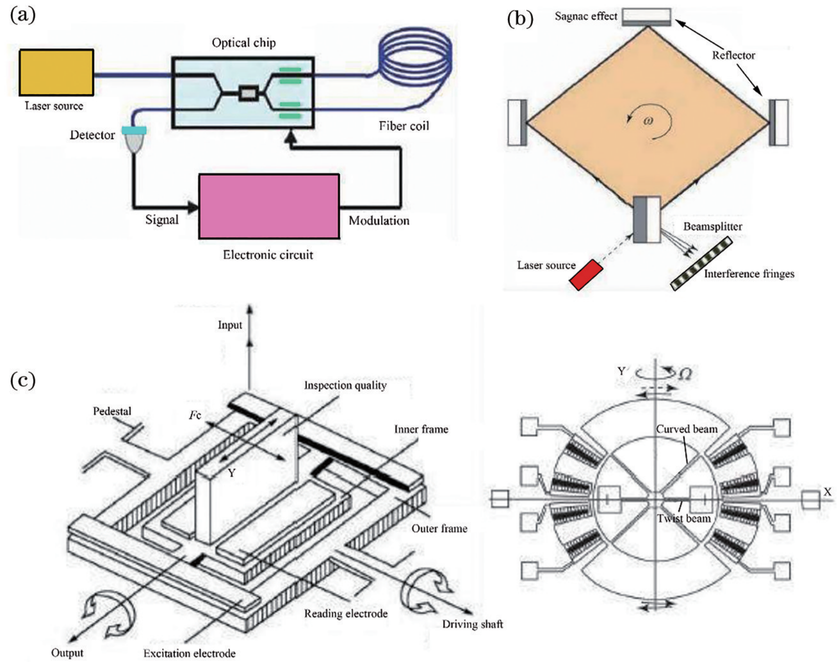

图2　主流基于惯性单元的位姿估计系统的基本原理图[32-33]。(a)基于激光惯性单元的位姿估计系统；(b)基于光纤惯性单元的位姿估计系统；(c)基于MEMS惯性单元的位姿估计系统

Fig. 2　Basic schematic diagram of mainstream inertial-unit-based pose estimation system[32-33]. (a) Pose estimation system based on laser inertial units; (b) pose estimation system based on fiber optic inertial units; (c) pose estimation system based on MEMS inertial units

过高分辨图像采集单元捕获目标，经过一系列图像处理过程获取高质量图像，根据物像映射、坐标变换及几何约束，提取目标形貌信息、位置信息及姿态信息[42]。根据测量系统的布置形式和信息提取原理，基于视觉的位姿估计系统主要分为单目系统[43-46]、双/多目系统[47-50]以及线阵相机系统[51-54]，相对激光跟踪仪等精密测量装备，具有价格低、系统简单、跟踪测量等优势。但是其深度及滚角信息提取能力差，标定及装调繁琐，难以适应于安装空间、移动空间受限的测量场景。

2.2　基于静态虚拟相机的位姿估计系统

近年来，单相机附加变视轴单元构建的虚拟相机系统受到广泛关注，可替代复杂空间布置的多目系统，能够获取自定义视角的目标信息，具有低成本、高效成像、紧凑配置等优势。Lee等[55]首次提出了基于棱镜的单目多维信息提取系统并引入虚拟点的概念，如图3(a)所示。基于上述工作，在相机与棱镜严格对准的条件下，Lim等[56]结合多面体棱镜，从双目虚拟相机

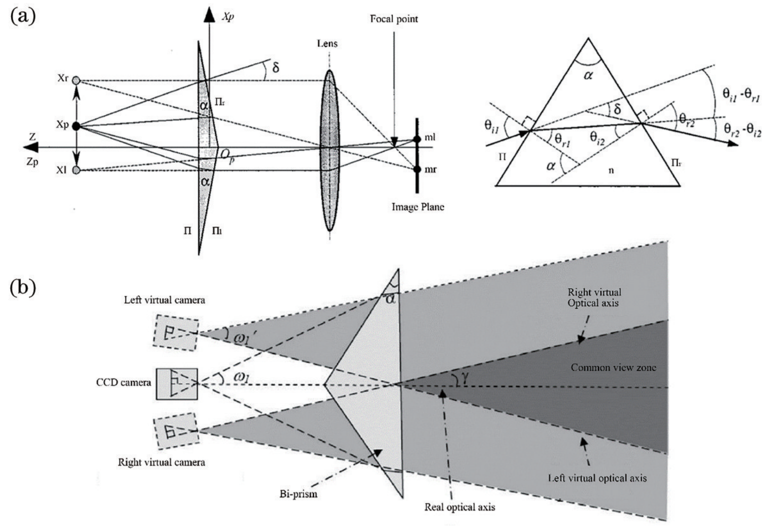

图3　基于二分棱镜的虚拟相机成像系统。(a)虚拟视点成像系统[55]；(b)虚拟相机成像系统[56]

Fig. 3　Virtual camera imaging system based on a bipartite prism. (a) Virtual viewpoint imaging system[55]; (b) virtual camera imaging system[56]

系统扩展到多目虚拟相机系统，进一步拓宽和发展了虚拟相机的概念，如图 3(b)所示。此后，针对虚拟相机成像，该团队开展了图像畸变矫正、虚拟极限约束、系统参数误差分析等一系列研究[57-60]。为了进一步拓宽虚拟相机模型的适应性，Cui 等[61]根据几何光学光束传播基本原理，建立了准确的任意平面折射成像模型。实际上，相机与棱镜难以实现严格意义上的对准。为此，该团队开展了相机-棱镜系统标定方法研究，提出了相机与棱镜间的相对位姿估计方法[62]，研究表明，经过严格的系统标定该方法可有效提升测量精度，可进一步应用于相关光学系统的标定。

为进一步适应肠胃道、油路管道等受限空间感知场景，提升感知系统的灵活性和集成性，Chen 等[63]创新性地将传统的棱镜改造为微型棱镜阵列，借助对称布置的微型棱镜阵列同时捕获双视角下的目标视差图。在此基础之上，Yang 等[64-65]进一步改进微型棱镜阵列的几何参数和形式，将微棱镜阵列嵌入单目相机形成的多视角虚拟相机，同步采集多视角图像序列，实现实时三维重建，如图 4 所示。然而，微型棱镜阵列感知系统仍存在加工制造困难、系统标定复杂及感知分辨率低等难题。

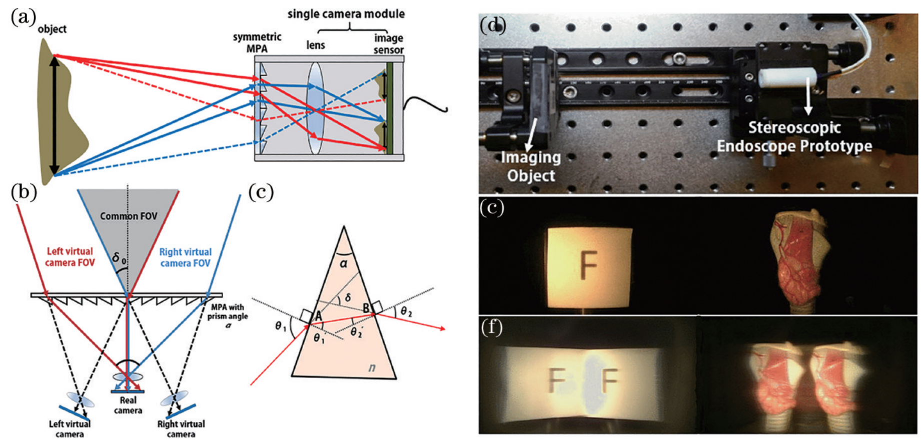

图 4　基于微型棱镜阵列的虚拟相机成像系统[64-65]。(a)系统原理图；(b)重建原理；(c)光束传播原理；(d)系统组成；(e)传统内窥镜成像；(f)虚拟相机成像

Fig. 4　Virtual camera imaging system based on a micro-prism array[64-65]. (a) System schematic; (b) reconstruction principle; (c) beam propagation principle; (d) system composition; (e) traditional endoscopic imaging; (f) virtual camera imaging

基于衍射光栅的虚拟相机位姿估计系统[66]采用衍射光栅与相机结合的方式进行多视角成像。基本原理是被测目标的成像光线经过衍射光栅形成多级衍射图像，结合衍射理论和小孔成像模型，建立各级图像之间的匹配关系，实现对感知目标的多维信息提取。Trivi 等[67]首先提出了基于衍射光栅的虚拟相机系统，该系统可同时捕获目标的正常图像和±1 阶衍射图像；通过不同视角的目标图像阵列，可重建目标的三维位姿。文献[68]结合针孔成像模型，修正了三维信息提取公式，研发了基于衍射视觉成像的数字图像三维测量系统，如图 5 所示。Xia 等[69]提出了一种新型光学显微系统，将衍射光栅成像与荧光显微成像结合，实现对微小尺度对象的三维形貌重建和变形估计，实验表明该方法可提供亚毫米级空间分辨能力。

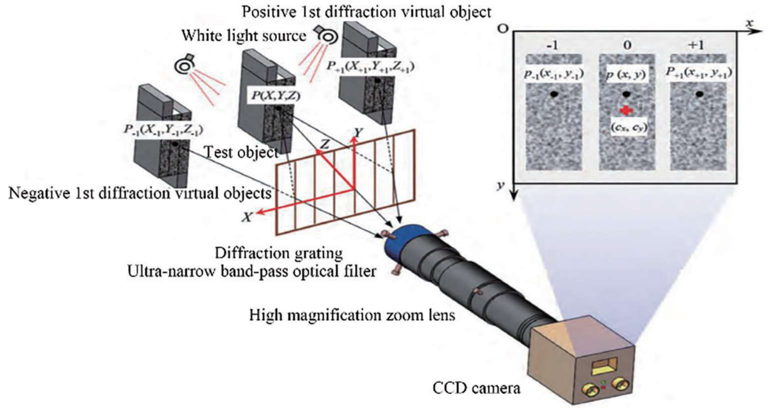

图 5　基于光栅衍射的虚拟相机成像系统[68]

Fig. 5　Virtual camera imaging system based on a grating diffraction[68]

2.3　基于动态虚拟相机的位姿估计系统

基于平面反射镜的虚拟相机成像系统最为常见，辅助光学反射镜系统主要包括单反射镜、双反射镜、三反射镜及四反射镜[70-72]，如图 6 所示。

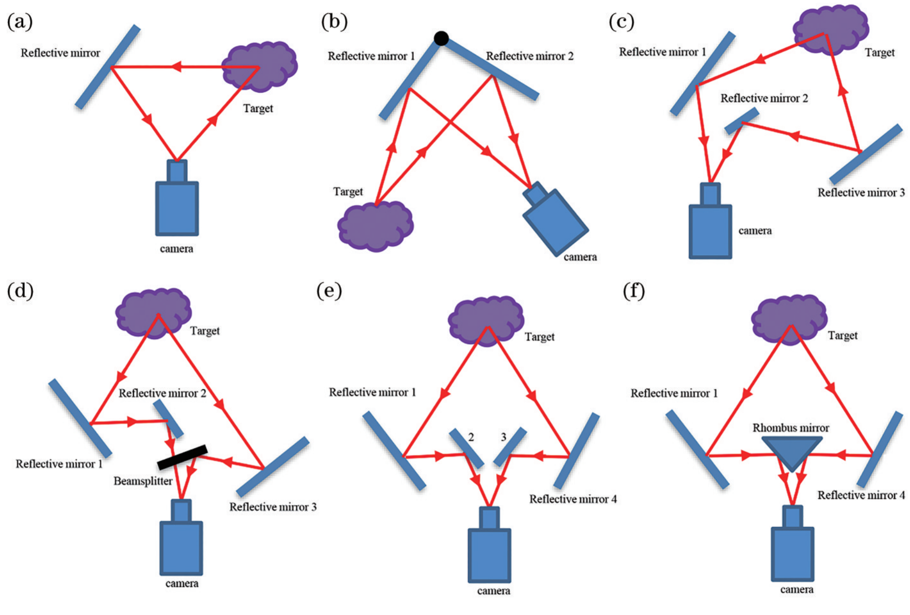

图 6 基于反射镜的可调虚拟相机成像系统[70-72]。(a)单反射镜;(b)双反射镜;(c)三反射镜;(d)三反射镜组合分束器;(e)四反射镜;(f)双反射镜组合棱形反射镜

Fig. 6 Mirror-based adjustable virtual camera imaging system[70-72]. (a) Single mirror; (b) double mirrors; (c) triple mirrors; (d) triple mirrors with a beam splitter; (e) four mirrors; (f) dual mirrors with a prismatic mirror

Sturm 等[73]采用反射镜构建可调虚拟相机系统,推导了两次平面镜反射成像的基本理论,实现了目标位姿的线性求解。Takahashi 等[74]将单个反射镜与相机结合,通过调整反射镜辅助相机连续采集不同视角图像,采用 5 幅以上图像后可同步标定相机的内外参数。另外,Li 等[75-76]和 Liu 等[77]也采用单反射镜配合相机不断变换姿态,迫使相机提取目标的不同视角图像,结合旋转平均理论,获得最优位姿信息。Takahashi 等[78]将双反射镜分别设置于相机两侧,该系统可对被测目标实现多视角全景成像,适应非视域目标的鲁棒精准位姿估计。

相比反射镜,基于棱镜折射的虚拟相机具有突出的指向精度。Jang 等[79]采用 MEMS 驱动光学透明平面镜精准调整相机视轴,通过捕捉对象在不同视点的全部活动像素产生视差图,但此系统仅具有亚毫米级基线距,感知信息精度、维度和范围有限。值得注意的是,基于旋转棱镜的视轴调整单元在指向精度、扫描范围及环境适应性方面具有更突出的优势,已引起国内外科研院所的深入研究。Rosell[80]率先将 Risley 棱镜应用于激光扫描。近年来,文献[81]采用 Risley 棱镜高速扫描激光束,根据调频干涉测量原理,实现大范围高分辨三维成像,如图 7 所示。

本课题组针对基于旋转棱镜的视轴调整技术开展

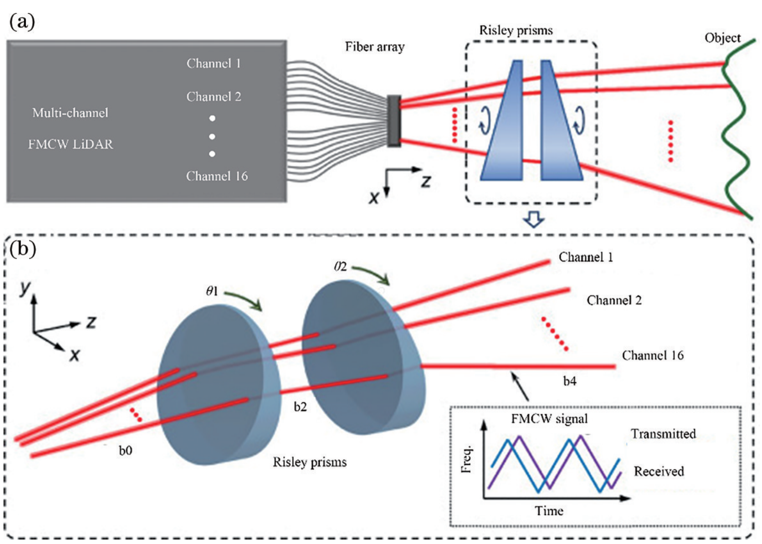

图 7 FMCW LiDAR 3D 成像示意图[81]。(a)系统布置;(b) Risley 棱镜的多光束扫描机制

Fig. 7 Schematic illustration of 3D imaging using FMCW LiDAR[81]. (a) System layout; (b) multi-beam scanning mechanism using Risley prisms

了一系列研究，率先提出动态虚拟相机三维成像方法[82]、基于双视场成像的多尺度目标监测与跟踪方法[83]、基于成像反馈的柔性精密跟踪方法[84]，建立了完备的旋转双棱镜正逆向解理论体系[85]。尤其，本课题组将旋转棱镜与单相机同轴布置，该系统可动态按需产生虚拟相机阵列，充分利用多视角先验信息，结合旋转平均及物方残差优化理论，实现了高精度鲁棒六自由度位姿信息提取，如图 8 所示[86]。

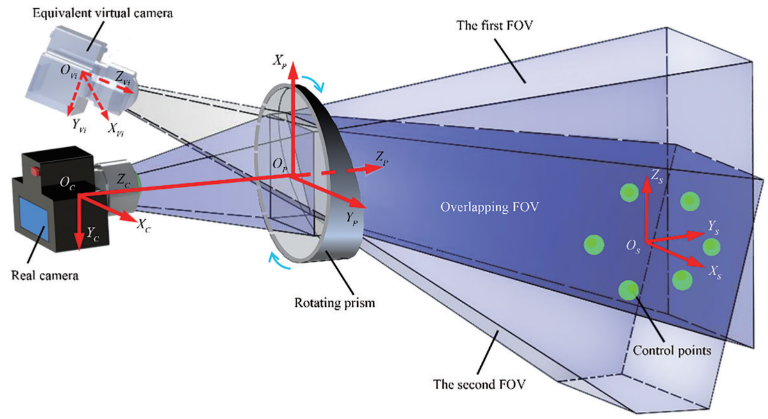

图 8 基于动态虚拟相机的位姿估计系统[86]

Fig. 8 Pose estimation system based on dynamic virtual cameras[86]

3 位姿估计方法

3.1 基于二维信息的位姿估计方法

基于二维信息的位姿估计方法通过目标形貌、颜色、关键点等二维特征恢复目标当前位姿状态[87]，根据位姿估计原理，主要包括基于目标特征的位姿估计方法和基于模板匹配的位姿估计方法。

基于目标特征的位姿估计方法是目前应用最广泛的位姿估计方法[88]。尤其，针对 n 点透视问题(Perspective-n-Point，PnP 问题)，常用解算方法包括基于 3 个特征点的 P3P 方法[89]和基于 4 个特征点的 P4P 方法[90]，图 9 为基于点特征的目标位姿估计方法的基本原理。在实际测量场景中，低于 5 个特征点的测量结果易受到环境噪声的影响。因此，文献[91]将大量冗余控制点融入解算模型，以提升解算模型面对复杂场景的鲁棒性，这无疑将增加解算过程的复杂度，难以满足实时解算要求。为避免复杂计算，一系列复杂度为 $O(n)$ 的高效非迭代算法被提出[92-93]，但测量精度表现一般。然而，工业测量现场往往对测量精度具有较高的要求。为此，一系列基于迭代法[94-95]和代价函数[96-99]的方法被提出，但是它们的测量精度、鲁棒性、稳定性依赖于控制点数量，难以适应弱纹理、无纹理及高反光目标。线特征相比于点特征具有更明显的几何特点，不易受光照变化、冲击震动等噪声的影响，可克服弱纹理目标特征难以提取的难题[100]。相似地，基于线特征的位姿估计问题被统称为 PnL(Perspective-n-Line)问题，常用解法包括 P3L 解算方法和 P4L 解算方法[42]。Taylor 等[101]首次提出了针对线特征的迭代解算方法，该方法可有效提升测量结果精度。此外，文献[102-103]也在精度和抗噪能力提升方面开展了深入研究。

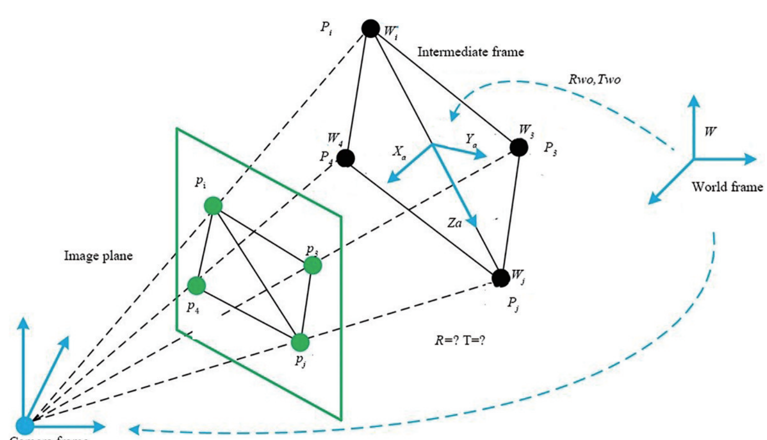

图 9 基于点特征的目标位姿估计基本原理[90]

Fig. 9 Basic principle of target pose estimation based on point feature[90]

基于模板匹配的位姿估计方法[104]对待测目标的图像与模板库进行对比，以最相似模板的位姿参数为目标位姿参数，常用于强曝光、弱特征的工业检测场景，如图10所示。

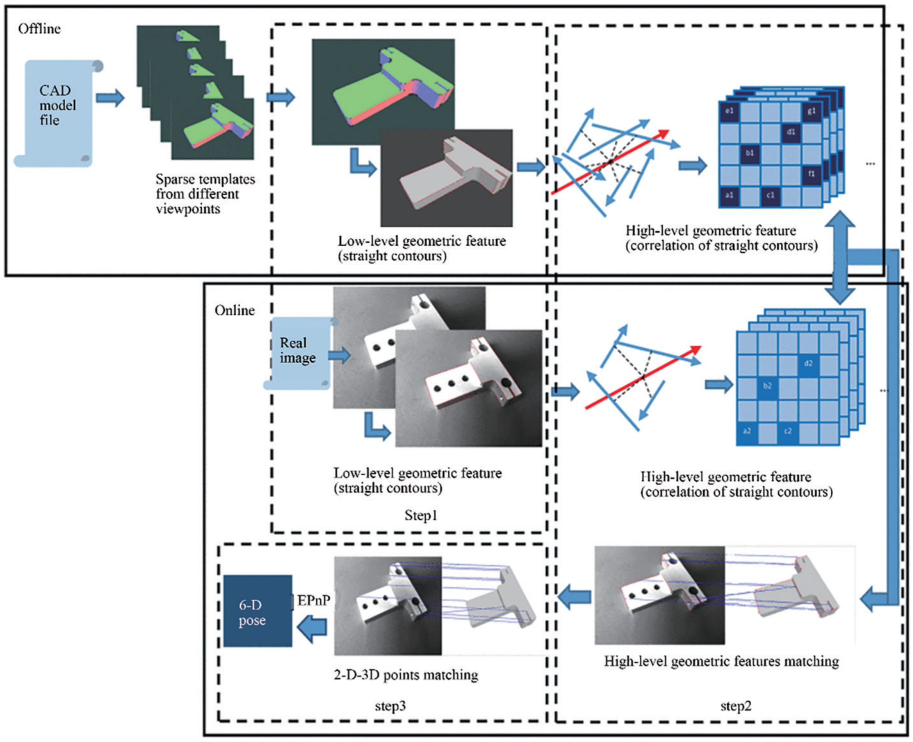

图10　基于CAD模板匹配的位姿估计[104]

Fig. 10　Pose estimation based on CAD template matching[104]

文献[105]针对飞机不同位姿建立模板库，采用generalized point feedback iteration (GPFI)算法进行目标与模板的匹配，以最优模板的位姿为输出结果，但是该算法面对复杂背景的应用场景时适应能力较差。Hinterstoisser等[106]针对复杂背景下的目标位姿估计，融合物体表面法向量和深度特征，提出LINEMOD强鲁棒模板特征匹配方法，该方法可实现稳定位姿估计，但配准精度较差。另外，Muñoz等[107]和Lin等[108]针对匹配精度和测量精度的改善，开展了一系列相关研究。然而，外点数据剔除及超大量数据匹配仍是高效精准位姿估计的主要挑战。为此，文献[109-110]开展了在数据降维采样、离群点随机一致性剔除及欠约束模板匹配等方面的研究。

3.2　基于三维信息的位姿估计方法

随着深度相机[111]、3D扫描仪[112]、激光雷达[113]等精密测量系统的不断发展，基于3D信息获取目标位姿的方法已广泛应用于机器人自主导航、虚拟现实等人工智能领域[114-115]，主要包括基于特征配准的位姿估计方法和基于绝对定向的位姿估计方法。

基于特征配准的位姿估计方法通过两组点云集合的特征描述确定点云间的对应关系。Rusu等[116-117]针对目标的全局三维信息融合视角信息，提出鲁棒性较高的点特征直方图描述算子(FPFH)。Li等[118]在此基础上融合先验几何信息，增加冗余特征点，提升了测量精度和效率。另外，do Monte等[119]对基于目标颜色信息、特征空间分布的点云匹配方法开展了重点研究。但基于全局特征的匹配方法在面对遮挡、杂乱、噪声场景时适应能力较差。针对该问题，通常以局部特征描述替代全局特征描述，如Yu等[120]采用rbBRIEF描述算子表征目标的局部特征，通过剔除外点获得精准的匹配关系。

基于绝对定向的位姿估计方法通常采用一系列经典的匹配算法，建立待测特征集合间的映射关系[121]，随后以匹配点三维信息为基础，恢复两映射集合的坐标转换关系，即解决绝对定向问题。针对绝对定向问题，国内外学者已展开了广泛的研究[122]。基于奇异值分解(SVD)的求解算法是较为经典的绝对定向解算方法，已在地质测绘、遥感探测等领域广泛应用[123]。此外，文献[124-125]将四元数引入绝对定向问题，可适应大角度、大尺度变换的姿态估计。事实上，点云集合间的映射通常难以直接获得。针对对应关系未知的点云配准，以Besl等[126]及Chen等[127]提出的ICP算法最为经典，但该算法易陷入局部最优。因此，一系列基于ICP的改进算法被提出[128-131]。

3.3　基于深度学习的位姿估计方法

近年来，随着深度学习算法的不断发展，基于神经网络的六自由度位姿估计方法受到国内外学者的重点研究[132]。基于位姿估计的基本框架包括直接回归法

和间接回归法。

直接回归法以端到端的形式构建目标图像与位姿的映射关系。Yin 等[133]将图神经引入位姿估计，充分利用目标形貌信息和几何约束信息，该方法具有较强的辨识能力和像素级位姿估计能力，如图 11 所示。文献[134]重点研究了基于彩色图像的位姿估计方法，为实现高帧频、大范围测量提供有力支撑。Chen 等[135]重点解决了复杂遮挡场景下的位姿估计，构建了基于图像信息与点云信息融合的密集点云配准关系，采用损失函数引导点云与模型配准。左国玉等[136]开展了低质量渲染、小样本数据等受限条件下的位姿估计方法研究。值得关注的是，对称目标旋转半周后的姿态与初始姿态相同，以上方法均难以解决该奇异问题。Manhardt 等[137]从对称特点表征、损失函数改造等方面开展了深入研究，克服了对称目标的位姿不确定性难题。

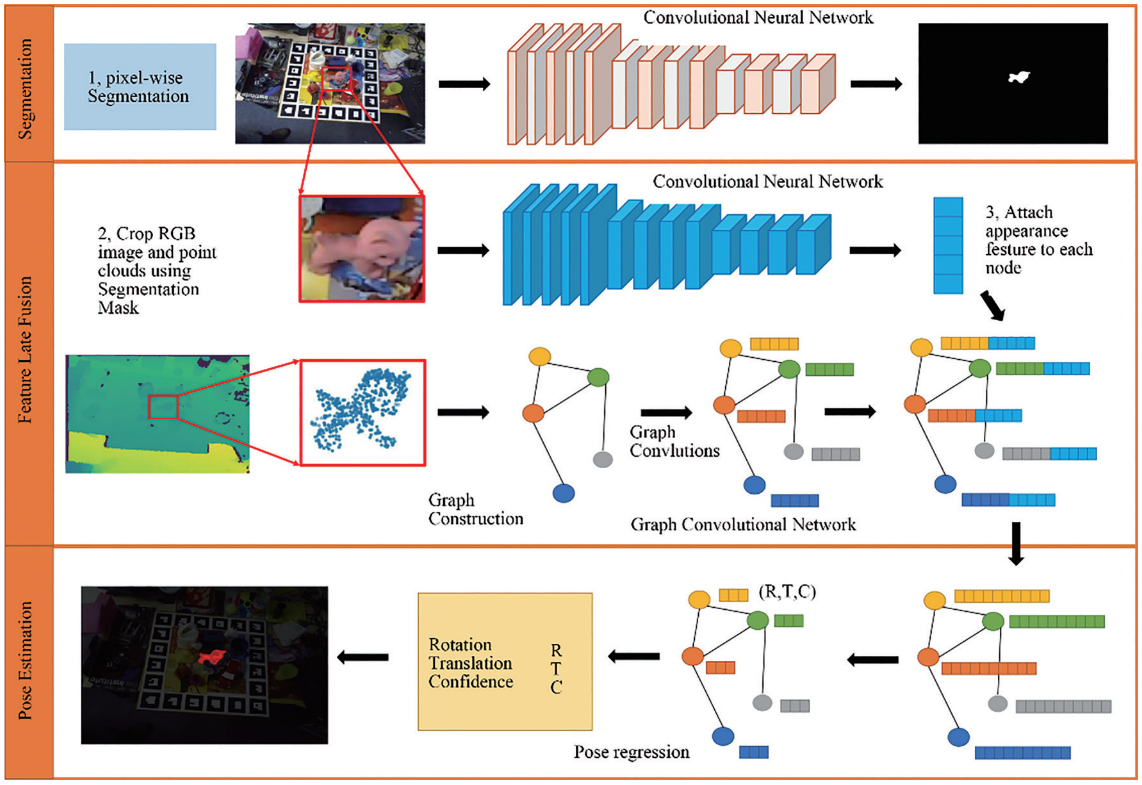

图 11 基于图神经网络的位姿估计方法基本原理[133]

Fig. 11 Basic principle of pose estimation method based on graph neural network[133]

间接回归法采用神经网络确定空间三维关键点与二维像点映射，采用 PnP 方法提取位姿。Tekin 等[138]基于 BB8[139]提取 9 个关键点，采用经典的 EPnP 方法恢复位姿信息，但面对遮挡场景时 BB8 方法难以胜任。Peng 等[140]针对遮挡或截断目标的位姿估计问题，结合基于随机一致性的投票策略选取关键点，构建了基于关键像点的 PVNet 网络，运用 PnP 算法恢复六自由度位姿信息。另外，文献[141]和文献[142]分别采用离散重组和自动编码预测的思想，结合经典的 PnP 算法实现目标位姿估计，可克服遮挡目标和对称目标的鲁棒估计难题。

4 性能对比分析

4.1 测量系统对比分析

如表 1 所示，分别从测量精度、效率、范围、成本、是否接触、有无合作靶标、环境适应性、动态测量可行性等方面，比较了典型位姿估计系统的测量性能指标。

基于机械定位的位姿估计系统在测量精度及环境适应性方面具有一定优势，但是仪器测量效率较低，难以适应对动态、易变形对象的位姿估计。基于激光跟踪仪的位姿估计系统具有非接触、高精度、大范围优势，可适应对动态目标的位姿提取，但价格昂贵，成本极高，需合作靶标协同作业，严重阻碍其在工业场景中的广泛应用。基于惯性单元的位姿估计系统具有成本低、非接触、环境适应性较好的优点，但测量精度低，存在零偏现象，难以实现对静态目标的绝对测量。基于视觉的位姿估计系统兼顾测量精度和成本，可实现动态跟踪测量，但是应用对象和场合有限，易受光照变化、冲击振动等环境噪声的影响。基于静态虚拟相机的位姿估计系统具有非接触、低成本、高系统集成等优势，可实现对合作及非合作目标的实时位姿估计，但是感知尺度、维度和分辨率有限，成像视点单一固定。基于动态虚拟相机的位姿估计系统可兼顾非接触、高精度、大范围测量能力，满足对动态目标的位姿提取要

表 1　主流位姿估计系统性能指标对比

Table 1　Performance comparison of mainstream pose estimation systems

Name	Accuracy	Efficiency	Target	Range	Touching	Adaptability	Dynamic measurement	Cost
Coordinate measuring arm	Angle：1″~2″ Position：5-10 μm+3. 3 μm/m	+	N	≤5 m	Y	+++	N	++
Laser tracker	Angle：1″~2″ Position：10-20 μm+6 μm/m	+++	Y	≤80 m	N	++	Y	+++
Total station	Angle：0. 5″~1″ Position：0. 6 mm±1 mm/m	++	Y	≥100 m	N	+++	N	++
IMU	Angle：0. 3° Position：2 cm	++	N		N	++	Y	++
Monocular+ rangefinder	Angle：1° Position：3 mm	++	N	≤30 m	N	++	Y	+
Binocular	Angle：0. 2° Position：0. 1 mm+1. 2 mm/m	++	N/Y	≤10 m	N	+	Y	+
Biprism-based system	Position：≤2. 36%	+++	N/Y	≤50 mm	N	++	Y	+
Mirror-based system	Angle：≤1° Position：≤12 mm	++	N/Y	≥60 mm	N	++	Y	+
Rotating-prism-based system	Angle：≤0. 4° Position：≤0. 4 mm	++	N/Y	≥80 mm	N	+++	Y	+

求，但是难以实现实时的对非合作目标的位姿估计。总体来说，基于虚拟相机的位姿估计系统在兼顾测量精度和维度的同时，具有较突出的系统集成性和低成本特点，尤其适应于多遮挡、大噪声、受限空间的测量场景，但感知系统标定较复杂。

4.2　测量方法对比分析

针对测量精度、耗时、鲁棒性、在线性能及应用范围，比较了主流位姿估计方法的性能，如表 2 所示。

表 2　主流位姿估计方法对比

Table 2　Comparison of mainstream pose estimation methods

Category	Method	Accuracy	Time consuming	Robustness	Online performance	Scope of application
Pose estimation based on 2D information	Target feature	+++	+	+	++	+++
	Template matching	+++	++	+++	+	+
Pose estimation based on 3D information	Feature matching	++	++	+	+	+++
	Absolute orientation	+++	+/++	+	+	++
Pose estimation based on deep learning	Direct regression	+	+++	++	+++	+
	Indirect regression	++	+++	++	+++	+

在精度方面，基于二维信息的位姿估计和基于绝对定向的位姿估计方法具有较高的测量精度，主要受控制点数量和场景噪声的影响。基于深度学习的位姿估计方法除受以上因素影响外，还依赖于模型对目标的分类精度及匹配精度，即样本数量及差异分辨率决定着测量精度，然而获取大量丰富的训练数据集较困难，导致其测量精度较低。

在耗时和在线性能方面，基于深度学习的方法需耗费大量时间训练模型，因此该方法耗时最高，但在线性能较突出。基于模板匹配的位姿估计方法因需大量时间构建不同位姿目标的图像模板，且在线阶段也需较长时间完成匹配，因此在耗时和在线性能方面均不理想。相比之下，基于目标特征的位姿估计方法无需额外的离线操作时间，仅在线阶段需一定特征匹配时间，具有耗时低、在线可行性强等优势。然而，三维信息的匹配和搜索相比二维信息更加复杂，基于三维信息的位姿估计方法在耗时和在线性能方面表现一般。

在鲁棒性方面，基于模板匹配的位姿估计方法通过建立模板库与目标精准匹配，不受光照变化、弱纹理、高反光等复杂因素的影响，但应用对象固定单一。基于深度学习的位姿估计方法充分考虑测量场景信息和目标信息（如颜色、形状、深度），能够构建较精准的位姿映射网络，相比其他方法，具有更突出的鲁棒性，尤其适应复杂背景和遮挡场景。

在应用范围方面，基于目标特征的位姿估计方法和基于三维信息的位姿估计方法在精度、耗时、鲁棒

性、在线性等方面具有较均衡的性能，此外硬件系统简单、灵活、低廉，目前应用范围最广泛。基于模板匹配的位姿估计方法需事先构建模板库，应用对象较为固定，主要应用于结构化感知场景，如金属零件的检测。基于深度学习的位姿估计可适应杂乱、遮挡环境及高反光、弱纹理、对称目标，但训练网络极为耗时是最大弊端，此外测量精度不高，硬件性能要求较高，目前实际应用不多，处于深入探索和研发阶段。

5 问题和展望

近年来，位姿估计研究已取得巨大进展，但随着感知场景和感知目标的不断丰富和拓展，仍面临诸多严峻挑战[143-144]。在感知场景方面，照明状态呈现明暗阴影、强光辐射等光照时变特点；背景状态呈现杂乱无序、多遮挡重叠等复杂背景特点；空间状态呈现非通透、多狭长、蜿蜒曲折等空间受限特点。如何适应复杂非结构化场景，实现密集紧凑、高鲁棒、强适应性测量是面临的重要挑战之一。在感知对象方面，表面特征呈现高反光、弱纹理甚至无纹理等特点；种类差异呈现颜色相同、材料相近、外形相似等特点；几何特性呈现体积尺寸大、作业精度高、运动速度快等特点。如何适应弱特征、多种类、相似性感知目标，实现大范围、高精度、高效动态测量是面临的重要挑战之二。

综上可知，当前测量系统及方法往往仅适应单一特定应用场景。相比之下，基于虚拟相机的位姿估计在系统集成、测量范围、动态性及成本等方面具有一定优势，但需复杂严格的系统标定过程，深度信息提取精度较低。进一步优化系统标定方法，改善感知信息质量，融合多模态感知信号，研发密集紧凑、精准鲁棒的位姿估计系统是重要的发展方向。此外，基于深度学习的位姿估计方法在鲁棒性、在线性方面表现突出，有望突破复杂应用场景存在的技术瓶颈，但耗时的网络训练过程及较低的估计精度仍是最大弊端。因此，结合基于二维及三维信息的位姿估计方法提升位姿感知精度，通过网络轻量化设计降低模型构建耗时，将是重点研究方向之一。

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