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# 动态虚拟相机六自由度位姿估计方法研究


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# Research on Six Degrees of Freedom Pose Estimation Method Using Dynamic Virtual Cameras


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# 摘要

多维信息感知技术是人工智能的重要测控手段之一，我国已在《“十四五”智能制造发展规划》中将其列为重点突破方向。六自由度位姿估计作为重要的智能感知技术是保障智能装备平稳运行的关键，已广泛应用于机器人技术、无人驾驶、航空航天等领域。然而，面对感知场景的日益丰富和发展，感知环境呈现光照时变、遮挡频繁、背景杂乱、空间受限等复杂特点；感知对象呈现材质相似、形状相近、工作精度高、运动速度快、无合作信息等特点。研究高精度、强鲁棒、高效动态测量方法，开发大范围、密集紧凑、强适应性测量系统，是六自由度位姿测量技术发展的必由之路。本文基于旋转棱镜视轴调整方式指向精度高、动态特性好，具有克服遮挡、抑制振动、结构紧凑等优势，提出动态虚拟相机六自由度位姿估计方法，为发展灵活紧凑的高精度位姿测量技术提供新途径。本文以动态虚拟相机成像模型为主线，开展了以下研究内容：

(1)构建动态虚拟相机位姿估计数学模型。采用旋转棱镜动态调整静态相机视轴，建立了基于旋转棱镜的动态虚拟相机位姿估计模型，定义并推导了坐标系间的转换关系。就静态目标而言，该模型形成动态变换视角的虚拟相机，实现静态单一传感器多视点目标观测；就动态目标而言，该模型形成空间连续变换位姿的动态虚拟相机，适应复杂运动轨迹的动态目标跟踪成像；研究了虚拟相机成像光束传播过程，提出了动态虚拟相机标定方法；研究了目标的识别与提取方法，实现了合作目标特征点的亚像素定位及非合作目标的识别与提取；分析了虚拟相机系统的测量范围、指向精度、参数匹配及成像优势。实验结果表明：该系统可以有效扩大成像视场，抑制由焦距扩大引起的视场缩减，能够一定程度上克服目标遮挡，具有灵活、紧凑、多视点成像优势。

(2)提出基于合作目标的鲁棒位姿估计方法。针对感知场景高噪声难题，基于旋转平均理论及光线矢量追迹，充分利用合作目标先验信息，提出了合作目标鲁棒位姿估计方法。针对无标定条件下位姿估计难题，采用控制点对目标特征点进行线性描述，确定了无标定虚拟相机焦距及畸变系数，提出了无标定相机合作目标位姿估计方法。与主流合作目标位姿估计方法进行了仿真对比分析，本文方法在测量精度、抗噪能力及稳定性方面具有一定优势。开展了合作目标位姿测量验证实验，实现了标定/无标定相机位姿估计，无标定相机位姿估计精度水平已接近常用已标定相机方法。相比双目视觉测量方法，在测量精度、稳定性及系统

集成度方面具有优势，尤其随着测量范围的扩大优势更明显。

(3)提出基于非合作目标的位姿估计方法。针对感知空间受限难题，构建了动态虚拟多站非合作目标位姿估计模型，结合 K-means 理论和坐标轴对齐，提出了快速绝对定向最小闭式解算方法。针对深度精度低的难题，构建了空间分布式动态测量网非合作目标位姿估计模型，基于最小二乘法和对偶四元数理论，提出了多光束交汇定位点云重建方法及加权对偶四元数绝对定向方法。与主流绝对定向算法进行了对比仿真分析，本文方法在测量精度、抗噪能力及解算效率方面具有一定优势。开展了非合作目标位姿测量验证实验，本文方法相比双目视觉方法，旋转测量精度接近且结构更紧凑，能够扩大成像景深，一定程度克服目标遮挡；相比单目、单目分布及相机-棱镜无分布方法，位姿精度及稳定性提升明显，尤其深度方向的提取精度明显改善。

(4)提出基于主辅相机的动态目标位姿估计方法。针对大范围广域监测和局部高分辨成像难以兼顾的难题，采用短焦大视场相机引导长焦高分辨相机指向兴趣目标，构建了主辅相机协同监测模型，提出了基于当量运动平面的主辅相机标定方法。针对高动态被测目标位姿估计问题，旋转双棱镜动态调整静态相机视轴，形成动态虚拟相机以适应动态目标的跟踪成像，基于成像反馈原理制定粗精级联视轴调整策略，以最小化物方残差为代价函数，形成了基于旋转双棱镜的加速正交迭代位姿估计方法。针对跟踪范围、跟踪效率、测量精度及实时性，对基于旋转棱镜视轴调整的跟踪方法进行了仿真对比分析，本文跟踪策略具有实时性优势；相比传统正交迭代位姿估计算法，本文方法具有更高测量精度和更低耗时优势。开展了目标跟踪及位姿跟踪测量验证实验，实现了跨视域协同监测、丢失目标跟踪恢复及动态目标位姿跟踪估计。

(5)开展机器人抓取及位姿状态估计应用。制定了目标抓取及位姿状态估计应用方案，搭建了机器人抓取及位姿状态估计平台，包括硬件组成、软件系统和控制方案，实现了应用系统参数标定。开展了机器人抓取应用，实现了场景重建、目标识别、位姿估计及目标抓取，对不同形状、颜色及材质的目标均具有良好的适应能力，目标提取、位姿估计及目标抓取的成功率均高于 82%。开展了六自由度位姿状态估计应用，制定了六自由度位姿状态表征指标，实现了机器人抓取、放置及搬运过程的位姿状态估计。

**关键词**：视觉测量，旋转棱镜，动态虚拟相机，六自由度位姿估计，合作目标，非合作目标，动态目标

# ABSTRACT

Multidimensional information perception technology plays an important role in the measurement and control methods in the field of artificial intelligence. China has listed it as a key breakthrough direction in the "14th Five-Year Plan" for the development of intelligent manufacturing. Six-degree-of-freedom pose estimation, as an important intelligent perception technology, is the key to ensuring the smooth operation of intelligent equipment. It has been widely used in flouring fields such as robotics, unmanned driving, and aerospace exploration. Accompanied by a continuous widening of perception scenes, the perception environment presents complex characteristics such as time-varying light, frequent occlusion, background clutter, and restricted space. The perception objects present similar materials, similar shapes, high accuracy, fast motion, and no cooperative information. Emerging trends for six-degree-of-freedom pose extraction are the development of large-range, dense, and compact sensing devices and accurate, robust, and efficient reconstruction methods. This paper proposed a six-degree-of-freedom pose estimation method using a dynamic virtual camera. A rotating-prism-integrated camera is employed to precisely and continuously adjust boresight and capture high-resolution multi-view images, which have high pointing accuracy, good dynamic characteristics, overcoming occlusion, suppressing vibration, and compact structure. It provides a new way to develop a flexible, compact, and high-precision pose measurement technology. The main research contents of this paper are as follows.

(1) The mathematical model of dynamic virtual camera pose estimation is established. A dynamic virtual camera imaging model is established using a rotating prism to dynamically adjust the boresight of a fixed camera. The conversion relationship between coordinate systems is defined and derived. As for static targets, the model forms virtual cameras with dynamic transform view angles to realize static multi-view target observation using a single sensor. As for dynamic targets, the model forms dynamic virtual cameras with continuously transformed poses in space, which adapts to target tracking and imaging with complex trajectories. The beam propagation process of the virtual camera imaging is studied to facilitate the construction of flexible pose solution models. In addition, the virtual camera

calibration method is proposed to determine the internal and external parameters of the system. The method of target recognition and extraction is studied to realize sub-pixel localization of feature points on a cooperative target and recognition and extraction of a non-cooperative target. To demonstrate the superiority of the imaging system, the relevant factors that may influence measurement range, pointing accuracy, parameter matching, and imaging advantages are investigated. The experimental results show that the system has the advantages of flexible, compact, multi-view imaging and enlarging field-of-view, which can suppress field-of-view reduction caused by focal length extension and overcome target occlusion to a certain extent.

(2) Robust pose estimation methods based on cooperative targets are proposed. In terms of the problem of high noise in the perceptual scene, a robust pose method for cooperative targets is proposed based on the rotational averaging theory and ray vector tracing, which can make full use of the prior information of the cooperative target to suppress the influence of large random noise. To improve the adaptability of the pose measurement method, the pose estimation method is proposed using a non-calibrated camera. The feature points on the cooperative target are described linearly using four control points, which can determine the focal length and distortion coefficient of the non-calibrated virtual cameras. Simulation for comparison analysis of mainstream visual pose estimation methods is carried out, and the method presented in this paper has an excellent performance in measurement accuracy, anti-noise ability, and stability. The experiments show that the architecture enables the target pose estimation under the condition of the calibrated camera even an uncalibrated one. The accuracy level of the uncalibrated camera method in this paper is close to that of the common calibrated camera method. Compared with the binocular vision measurement method, it has advantages in measurement accuracy, stability, and system integration, especially with the expansion of measurement range.

(3) The pose estimation methods for non-cooperative targets are proposed. To overcome the challenge of target pose measurement in confined space, a pose estimation model of noncooperative targets is constructed using a dynamic virtual multi-station with desired quantity and distribution. In particular, efficient absolute orientation without singular value decomposition (SVD) is proposed by combining K-means theory and coordinate alignment. In terms of poor depth accuracy, a pose estimation model of noncooperative targets using a spatial virtual measurement network is established, including stereo recovery using dense beam localization and

accurate absolute orientation based on dual quaternions with adaptive weight factors. The simulation analysis is carried out to compare with the mainstream absolute orientation algorithm, whose results show that the proposed method processes some advantages in measuring accuracy, anti-noise ability, and solving efficiency. The experiment to verify non-cooperative target pose measurement is carried out, which can enlarge the imaging depth of field and overcome target occlusion to a certain extent. Compared with the binocular vision method, the rotation measurement accuracy is close while the structure is more compact. Compared with the monocular, monocular with off-axis motion, and camera embedded in a rotating prism without off-axis motion methods, the pose accuracy and stability are improved significantly, especially in the depth direction.

(4) A dynamic target pose estimation method is proposed based on cooperative camera surveillance. To solve the problem of the difficult compromise between large-scale monitoring and local high-resolution imaging, a short-focus large field-of-view camera is used to guide the long-focus high-resolution camera to point at the region of interest. A master-slave camera cooperative monitoring model with a calibration method is established based on the equivalent motion plane. As for the problem of the dynamic target pose estimation, the boresight of the static camera is dynamically adjusted by the rotating double prisms, which form dynamic virtual cameras to adapt to the tracking imaging of dynamic targets. A coarse-fine coupling boresight adjustment strategy is put forward by combining imaging feedback and iterative refinement. In addition, a rotating-prism-based pose estimation method with accelerated orthogonal iterations is constructed by minimizing the object-square residuals. Simulation analysis and real experiments of tracking and pose measurement are conducted to verify the feasibility of the proposed method. In terms of tracking range, tracking efficiency, measuring accuracy, and time consumption, the rotating-prism-based boresight adjustment methods are simulated and compared. The proposed tracking strategy has obvious real-time advantages at the same tracking accuracy level. Compared with the traditional orthogonal iterative pose estimation algorithm, the proposed method has higher accuracy and solution efficiency. The verification experiments for target tracking and pose tracking measurement are carried out. The experimental results show that the architecture allows cross-scale cooperative monitoring, tracking recovery under the condition of dynamic target loss, and pose

tracking estimation for a dynamic target.

(5) The applications of robot gripping and pose status estimation are carried out. The application scheme of target grab and pose state estimation was designed. A robot grasping and pose estimation platform was built including hardware composition, software system, and control scheme. In addition, the parameters of the application system were calibrated. The robot grasping application for the interest target was carried out including scene reconstruction, object recognization, pose estimation, and target grasping. The success rates of target extraction, pose estimation and target grasping are all higher than 82%. It has good adaptability to targets of different shapes, colors, and materials. The characterization index of the six degrees of freedom pose state is proposed to evaluate the level of the pose state. The application of six-degree-of-freedom pose state estimation was carried out to realize the pose state estimation of the robot grasping, placing, and handling process.

**Key Words:** Visual measurement, Rotating prism, Dynamic virtual camera, Six degrees of freedom pose estimation, Cooperative target, Noncooperative target, Dynamic target