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激光焊接机器人三维焊缝跟踪运动规划算法设计

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目前，在机器人焊缝跟踪领域，许多方法都采用 Eye-in-hand 手眼结构。而金属薄板工件的焊缝形状往往包含许多复杂的三维结构，这常常会导致 Eye-in-hand 模式下线结构光传感器因机器人姿态问题丢失跟踪目标。因此，针对三维焊缝跟踪过程的采样姿态和焊接姿态规划问题，设计了一套机器人运动规划算法。首先，采用一种基于非均匀有理 B 样条的动态轨迹规划方法，生成焊缝轨迹并对其平滑优化，避免因工件局部的异形结构或纹理导致轨迹点在空间位置上突变，进而减小姿态规划结果的波动；而后，为了确保在焊接过程中传感器始终能够采样到焊缝并使焊接头保持合适的焊接姿态，采用一种基于预设轨迹的前馈姿态规划算法。在批量焊接过程中，通过 CAD 文件或对其中一个工件进行示教来提前给出焊接轨迹的预期路线，并通过计算机器人当前位置的参考球面和预设轨迹之间的相交关系，来预测每个轨迹点处的机器人末端 TCP 姿态。最后针对三维焊缝进行跟踪实验，实验结果表明，本方法能够实现对三维焊缝的跟踪焊接，并且在 20 mm/s 的机器人末端线速度下，三维工件的平均跟踪误差可以控制在 0.3 mm 以内，能够满足金属薄板三维焊缝的跟踪需要。

关键词：激光焊接；机器人；线结构光；运动规划

Design of Motion Planning Algorithm for 3D Seam Tracking of Laser Welding Robot

At present, in the field of robot seam tracking, many methods use the Eye-in-hand structure. However, the welding seams of metal sheet workpieces often contain complex three-dimensional structures, which can cause the camera to lose sight of the targets during welding due to robot pose issues. Therefore, a set of robot motion planning algorithms are designed to address the challenges of sampling attitude and welding attitude planning in the 3D welding seam tracking process. Firstly, a dynamic trajectory planning method based on Non-Uniform Rational B-Splines (NURBS) is employed to generate weld trajectories and optimize them for smoothness. This approach avoids sudden changes in trajectory points in spatial position due to local special-shaped structures or textures of the workpiece, reducing fluctuations in attitude planning results. Secondly, to ensure that the sensor can continuously sample the welding seam during the welding process and maintain the welding head in an appropriate attitude, a feedforward attitude planning algorithm based on the preset trajectory is adopted. In batch welding processes, the expected route of the welding trajectory is predetermined through CAD files or by teaching one of the workpieces. The Tool Center Point (TCP) pose is predicted at each trajectory point by calculating the intersection between the reference sphere of the robot's current position and the preset trajectory. Finally, tracking experiments are conducted on the 3D welding seam. The experimental results demonstrate that the proposed method enables effective tracking welding for three-dimensional welding seams of metal sheets. Under a linear speed of the robot end effector of 20 mm/s, the average tracking error for the three-dimensional workpiece is controlled within 0.3 mm, which meets the tracking requirements of metal sheet three-dimensional welding seams.

Key words: laser welding; industrial robot; line-structured light; motion planning