國 立 成 功 大 學

機械工程學系

碩士論文

新型多策略鯨魚演算法於終端對位撓性裝置之最佳化設計

Optimal Design of a Remote Center Compliance Device Using a Novel Multi-Strategy Whale Optimization Algorithm

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中華民國一一四年七月

摘要

在自動化的軸孔裝配任務中，因機械手臂的定位誤差或工件公差都有可能會導致裝配失敗，造成工件甚至是機械手臂的損壞。終端對位撓性裝置(Remote center compliance device, RCC device)為一種被動式誤差補償機構，可安裝於機械手臂末端，依靠撓性結構的變形補償誤差，無需依賴回授系統或高精度控制技術。過去的 RCC 裝置設計多以彈性剪切柱(Elastomer shear pad, ESP)作為撓性部件，其設計方式大多仰賴經驗法則，缺乏系統性的設計方法，因此本研究的目的為建立一套最佳化設計方法，基於鯨魚演算法結合數種常見且有效的策略，開發出新型多策略鯨魚演算法，可強化探索與開發能力。並在最佳化流程中加入代理模型，減少有限元素分析計算的時間與次數，以最小化裝配力作為目標函數，平移與旋轉特性作為限制式。根據演算法比較結果顯示，在 9 種測試條件組合中，本研究提出的新型多策略鯨魚演算法均能在最佳與平均目標函數值中有最佳的表現。另外，相較於無代理模型計算 1000 次與 3000 次的結果，加入代理模型後目標函數值分別可降低 23.4%與 12.4%，計算時間則分別節省下 47.9%與 82.7%。本研究將最佳設計結果以 3D 列印製作並進行實驗驗證，包含最大補償範圍實驗、裝配力實驗與剛性實驗，根據實驗結果可知：本研究 RCC 裝置可以補償的偏移量與偏轉角度誤差組合有 61 組，相較市售裝置的 48 組提升了 27.1%的補償範圍。本研究的 RCC 裝置在偏移量為±2 mm 的實驗中，相較市售 RCC 裝置的平均裝配合力可分別降低 71.1%與 71.5%。在偏轉角度為±2º 的實驗中，市售 RCC 裝置僅能在偏轉 2º 時完成裝配，而本研究的 RCC 裝置在偏轉±2º 的條件下皆能完成裝配。實驗結果顯示本研究的 RCC 裝置可在有效降低裝配力的情況下，保持一定的剛性與穩定性，並可在軸孔裝配中提供最大偏移量±6mm 與最大偏轉角度±4º 條件下的誤差補償。

關鍵字：終端對位撓性裝置、軸孔裝配、鯨魚演算法、代理模型、結構最佳化

ABSTRACT

Optimal Design of a Remote Center Compliance Device Using a Novel Multi-Strategy Whale Optimization Algorithm

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SUMMARY

In automated peg-in-hole assembly tasks, positioning errors of robotic arms and part tolerances may lead to assembly failure, potentially damaging both the workpiece and the robot. The remote center compliance (RCC) device is a passive error compensation mechanism mounted at the end of a robotic arm. It compensates for misalignments through the deformation of a compliant structure, eliminating the need for feedback systems or high-precision control. Traditional RCC devices typically adopt elastomer shear pads (ESP) as compliant components, with most designs relying on empirical rules and lacking systematic methods. This study proposes an optimization-based design method using a novel multi-strategy whale optimization algorithm (NMSWOA), integrating several strategies to enhance both exploration and exploitation. A surrogate model is also incorporated to reduce the computational time of finite element analysis. The objective is to minimize assembly force while ensuring required translational and rotational characteristics. Results show that NMSWOA outperforms other variants in all 9 test conditions in terms of best and average objective values. Additionally, compared to optimization without surrogate model, the proposed approach achieves a 23.4% and 12.4% reduction in objective function and a 47.9% and 82.7% saving in computational time under 1000 and 3000 evaluations, respectively. A prototype from the optimized design was fabricated via 3D printing and validated through compensation range, assembly force, and stiffness tests. The proposed RCC device compensate 61 combinations of positioning and angular errors, outperforming a commercial RCC device with 48 combinations—an improvement of 27.1%. In ±2 mm offset tests, it reduces average assembly force by 71.1% and 71.5% compared to the commercial device. In ±2º angular deviation tests, the commercial device completed only under +2º, whereas the proposed design succeeded under both directions. These results confirm that the proposed RCC device can effectively reduce assembly force while maintaining stiffness and stability, compensating for ±6 mm and ±4º errors in assemblies.

Keywords: remote center compliance device, peg-in-hole assembly, whale optimization algorithm, surrogate model, structural optimization