

博士学位论文

六足机器人复杂地面特性感知及足地接触
自主规划研究

RESEARCH ON COMPLEX TERRAIN
PERCEPTION AND AUTONOMOUS
FOOT-TERRAIN CONTACT PLANNING
FOR HEXAPOD ROBOTS

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摘 要

足式机器人单独控制腿与环境交互,并通过选择离散落足点行走的能力使其在室外复杂地形上具有天然的通过性优势。六足机器人因其稳定性好、负载能力强、地形适应性强的特点,被认为是复杂环境中足式移动的最佳选择之一。然而,户外环境中机器人不仅需要躲避树桩、陡峭岩石等几何障碍物,还需应对淤泥、沙坑等非几何障碍物。感知地面力学特征是辨别非几何障碍物的有效方式,触觉感知结果最为精准但无法实现远程预测;相反,视觉预测方法以有监督和自监督为主,依赖专家前期的参与,难以适应动态环境。此外,复杂地形条件会对机器人运动施加几何与接触约束,同时随着腿数量的增多,步态耦合落足点的决策量指数级增长,这使得六足机器人难以在有限时间内寻找到可通行的接触序列。另外,在砂石混合等混杂力学特性地形环境中,远程规划的落足点难以保证稳定支撑,需要机器人主动与环境交互寻找可靠支撑区域。本文针对这些问题,开展了六足机器人复杂地面特性感知及足地接触规划研究以提高机器人在复杂环境中的运动能力。

为实现不同地形环境下的地面力学特征自主识别,以法向/切向足地作用力学模型为基础,设计了基于模型-数据的无监督学习框架,实现了具有认知冲突解决能力的增量式在线视-触觉融合感知。在视觉感知方面,采用对比学习和超像素分割技术建立了无监督的环境地形分割模型。在触觉感知方面,提出了基于统一足地接触模型的地面力学特征表征参数,设计了足-地接触轨迹便于收集接触过程中接触力和相应位移用于特征辨识。采用了增强型自组织神经网络对所提取特征进行聚类,并构建了相应的特征认知层。最后,设计了一个基于尖峰神经网络的关联层实现触觉和视觉认知聚类簇之间的映射,有助于机器人建立知识的遗忘机制,实现认知冲突的处理。

为保证机器人通过复杂的地形环境,提出了一种考虑多约束可达性的足式机器人接触序列并行规划方法,规划器能够保证在有限时间内找到可行的接触序列,同时规划结果需要满足环境和机器人本体的各项约束。首先,建立了一种新的蒙特卡罗搜索树(Monte Carlo Tree Search, MCTS)节点评分机制,该机制可以传播被困节点的信息,从而加快搜索过程;利用蒙特卡罗树并行特性,算法可以在有限时间内探索更多的接触状态,解决六足机器人接触规划这一组合爆炸问题。为保证搜索结果的物理可行性,分别建立了足式机器人的运动稳定

性、地形接触、运动学、关节力矩和碰撞约束条件，并构建完善的机器人接触状态可达条件，用于快速筛选 MCTS 算法中扩展环节中的可行子节点。最后，在不同挑战性地形环境下开展了通过性仿真与对比实验，验证了算法的有效性。

为解决远程感知、约束规划方案无法适应的混杂力学特性地形场景，提出了一种足-地交互轨迹规划方法，实时为机器人寻找到复杂地形环境中的可靠区域。采用了动态基元法构建机器人足端与地形的交互轨迹模型，利用专家经验构建了足地交互轨迹规划基础策略；在其基础上利用强化学习构建交互轨迹策略的残差项，设计了残差修正策略，以提高交互轨迹在不同地形环境下的泛化能力。为了保证机器人能够在交互过程中获得更为准确的环境表征，提出了一种迭代交互策略，将每次交互过程后编码的结果作为下一次交互的输入，进而提高机器人在复杂地形下寻找到可靠接触区域的成功率。

最后，为了验证所提出算法在硬件平台上的应用效果，搭建了六足机器人软硬件框架。基于此，开展了地面力学特征感知和预测实验，验证了所提出算法实时、逐步地构建环境的力学特征预测模型的能力；开展了包括平面离散地形、壕沟地形，三维阶梯地形、上下障碍物地形、三维崎岖地形等多种地形环境下通过性实验，验证了算法在通过性和在处理不同约束条件的优越性和所提出的足地交互算法在寻找不同地形环境下可靠接触区域的能力；最后，开展了综合导航实验，展示了所提出的不同方法在多地形环境下的综合应用价值。

关键词：六足机器人；足地交互；运动规划；接触规划

Abstract

Legged robots possess a natural advantage in traversing complex outdoor terrains due to their ability to independently control their legs, interact with the environment, and select discrete footholds. Among these, hexapod robots are particularly suited for mobility in complex environments owing to their superior stability, load capacity, and terrain adaptability. However, navigating outdoor environments requires robots to address both geometric obstacles (e.g., tree stumps, steep rocks) and non-geometric obstacles (e.g., silt, sand pits). While tactile perception offers accurate mechanical parameters of terrains, it lacks remote prediction capabilities. Conversely, visual prediction methods, often reliant on supervised or self-supervised learning, depend heavily on the involvement of experts and struggle to adapt to dynamic environments. Furthermore, complex terrains impose geometric and contact constraints on robot motion, and the exponential increase in gait-coupled foothold decisions with increasing legs makes it challenging for hexapod robots to identify viable contact sequences within limited timeframes. In heterogeneous terrains like sand-gravel mixtures, remotely planned footholds often fail to ensure stable support, necessitating active environmental interaction to locate reliable support areas. To address these challenges, this study investigates the perception of complex terrain characteristics and foot-terrain contact planning for hexapod robots to enhance their mobility in complex environments.

To enable autonomous physical characteristics perception of terrains across diverse environments, an unsupervised learning framework based on the normal/tangential foot-terrain contact model is proposed. This framework incorporates incremental online visual-tactile fusion perception with cognitive conflict resolution capabilities. In terms of visual perception, an unsupervised terrain segmentation method is developed using contrastive learning and superpixel segmentation technique. For tactile perception, mechanical parameters of terrains are designed based on a unified foot-terrain contact model, and a foot-terrain contact trajectory is designed to capture contact forces and displacements for feature identification. An enhanced incremental self-organizing neural network is employed to cluster the extracted features, creating the corresponding cognitive layer. Finally, a spike neural network-based associative layer is designed to map tactile and visual cogni-

tive clusters, enabling the robot to establish a forgetting mechanism and resolve cognitive conflicts.

To ensure successful navigation through complex terrains, a parallel planning method for contact sequences, considering multi-constrained reachability, is proposed. This planner generates feasible contact sequences within limited timeframes while satisfying environmental and robot-specific constraints. A novel Monte Carlo Tree Search (MCTS) node scoring mechanism is introduced to propagate information from trapped nodes, accelerating the search process. Leveraging the parallel nature of MCTS, the algorithm explores more contact states within constrained time, addressing the combinatorial explosion in hexapod robot contact planning. Motion stability, terrain, kinematics, joint torque, and collision constraints are integrated to construct a comprehensive reachability condition, enabling rapid screening of feasible sub-nodes during MCTS expansion. Simulation and comparative experiments in challenging terrains are performed to validate the algorithm's effectiveness.

For terrains with mixed mechanical characteristics, where remote perception and planning fall short, a trajectory planning method for foot-terrain interaction is proposed. This method enables real-time identification of reliable support areas in complex terrains. The dynamic motion primitive method models foot-terrain interaction trajectories, with expert-defined trajectories used to learn basic interaction strategies. Reinforcement learning is employed to construct residual modification terms, enhancing the generalization of the trajectory-planning strategy across diverse terrains. An iterative interaction strategy is also introduced, using encoded results from each interaction as input for subsequent interactions, improving the success rate of locating reliable contact areas.

Finally, a hexapod robot hardware and software framework are developed to validate the proposed algorithms. Experiments on terrain perception and feature prediction are performed to demonstrate the algorithm's ability to construct real-time, step-by-step predictive models of environmental mechanical features. Traversing experiments in various terrains, including discrete planes, trenches, 3D steps, and rugged wooden surfaces, are conducted to verify the algorithm's superiority in handling constraints and locating reliable contact areas. A comprehensive navigation experiment showcases the integrated application of the proposed methods across multiple terrain environments.

Keywords: Hexapod robot, foot-terrain interaction, motion planning, contact planning