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Torque sensorless decentralized neuro-optimal control for modular and reconfigurable robots with uncertain environments[☆]

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ABSTRACT

A technical challenge of addressing the decentralized optimal control problem for modular and reconfigurable robots (MRRs) during environmental contacts is associated with optimal compensation of the uncertain contact force without using force/torque sensors. In this paper, a decentralized control approach is presented for torque sensorless MRRs in contact with uncertain environment via an adaptive dynamic programming (ADP)-based neuro-optimal compensation strategy. The dynamic model of the MRRs is formulated based on a novel joint torque estimation method, which is deployed for each joint model, and the joint dynamic information is utilized effectively to design the feedback controllers, thus making the decentralized optimal control problem of the environmental contacted MRR systems be formulated as an optimal compensation issue of model uncertainty. By using the ADP method, a local online policy iteration algorithm is employed to solve the Hamilton–Jacobi–Bellman (HJB) equation with a modified cost function, which is approximated by constructing a critic neural network, and then the approximate optimal control policy can be derived. The asymptotic stability of the closed-loop MRR system is proved by using the Lyapunov theory. At last, simulations and experiments are performed to verify the effectiveness of the proposed method.

1. Introduction

Modular and reconfigurable robots (MRRs) are comprised of the robot modules, which contain power electronics, computing systems, sensors and actuators. These modules are assembled to desirable configurations with standard electromechanical interfaces to satisfy the requirements of various tasks with complex working environments. Profiting from the advantages above, MRRs are often utilized in uncertain and dangerous environments, e.g. space exploration, disaster assistance, high/low-temperature operations et al. Besides, in the face of complex and uncertain environments, MRRs need appropriate control systems to provide stability and accuracy of motion control after reconfigurations.

Besides the property of reconfigurability, an ideal MRR system should be designed to possess the ability of physical interaction with the external environment, e.g., the dynamic contact and collision with time-varying environment constraint. To tackle the concerns of raising interaction stability, numerous researches have focused on developing robot-environment contact models [1,2], which are implemented for investigating the cases of position control [3,4] and force control [5,6]. Moreover, some other investigations are presented to address the problems of robust stabilization of robotic systems in contact with uncertain environment by using the robust integral of sign of error (RISE) feedback-based control method [7], and the robustly stable interaction control method [8]. However, the limitation of the existing contact model-based control methods and robust control methods are seriously relying on the exact knowledge of the robot and environment dynamics. Indeed, the MRRs are always designed to satisfy various task requirements under uncertain environments, which means the dynamic model of MRRs will be changed under different configurations, with the same reason, the robot-environment contact models are also hardly to be obtained. To avoid using the

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enclosed forms of robotic and environmental models, and seeking out accuracy control for MRRs, joint torque feedback techniques are attached attentions of both robotic researchers and industrial manufacturers. It is not just that joint torque feedback facilitates in suppressing the effect of the payloads in motion control of the MRRs, and it also considerably eases the necessity to model the robot-environment contact. Several researches reported direct torque sensing-based joint torque feedback techniques. In [9], the joint torque sensor measurements are implemented in force and stiffness control of the light-weight robots. [10] introduced a general passivity-based framework for controlling flexible joint robots using joint torque sensing. In [11,12], the torque sensor measurements are utilized to compensate the model uncertainties associated with link and payload masses of MRRs. However, using joint torque sensor measurements directly are known for many drawbacks, which may jeopardize the simplicity, reliability and mechanical ruggedness of the robots. For one thing, the strain gauges, which are the most important components of the torque sensors, are known with intensive sensitivity to peripheral temperature variations; for another, the sensor data is contaminated with too much noise and unstable states, which was caused by the narrow bandwidth of the torque information. Therefore, it is meaningful to devise a high-performance control method for uncertain environmental contacted MRRs that will eliminate the needs of robot-environment contact models and force/torque sensors.

To ensure the stability and accuracy of trajectory tracking of the robotic systems, and simultaneously taking into account the optimal realization of the composite of control performance and power consumption have attached widespread attention in the robotics community. As an effective tool to address the optimal control problems in nonlinear systems, the adaptive dynamic programming (ADP) methodology, which is proposed by Werbos [13] has been considered as one of the key directions for the researches on designing discrete-time [14–16], continuous-time [17–19] and data driven-based [20–22] intelligent systems. Several literatures have been carried out on analytical description of robot manipulator systems under the ADP-based optimal control. An adaptive critic-based optimal real-time redundancy resolution scheme is presented to address the motion control problem of a redundant manipulator [23]. By employing adaptive neural network algorithm, Tang et al. proposed a learning-based adaptive optimal control method to deal with the trajectory tracking problem of an n-link rigid robot manipulator [24]. Based on reinforcement learning (RL) theory, Li et al. investigated the optimal coordination control problem for multi-robots to handle an object with a common desired trajectory [25]. Based on the energy-balancing actor-critic (EBAC) algorithm, Nageshrao et al. presented an optimal passivity control method for a 2-DOF robot manipulator [26]. However, these methods are concentrated on centralized control, indeed, due to high computational costs and complexities, a centralized controller designed on the basis of an entire system may hardly be applicable for controlling MRRs.

In order to address the problems as mentioned above, decentralized control strategy, which utilizes only local states and dynamic information of each subsystem, is considered an efficient and effective approach. In the past few years, a number of attentions have been paid to the design of decentralized controllers for various complex nonlinear systems. Hua et al. [27] investigated a decentralized output feedback adaptive neural network tracking control for time-delay nonlinear systems with prescribed performance. In [28], an adaptive fuzzy decentralized output-feedback control method is proposed for switched nonlinear systems with unknown nonlinearities and dead zones. An adaptive neural decentralized controller is designed in [29] to address the problem of tracking control of MIMO uncertain stochastic nonlinear strong interconnected systems. Based on a self-tuned local feedback gain technique, Zhao et al. [30] investigated a decentralized fault tolerant control approach for a class of large-scale nonlinear systems. Moreover, some insightful investigations are reported by combining the decentralized control scheme with the ADP-based optimal control approach. Based on a robust ADP method, a decentralized optimal controller is designed for large-scale systems with unmatched uncertainties [31]. Liu et al. presented an online learning-based decentralized stabilization method [32], and subsequently improved by Wang et al. to deal with the decentralized optimal control problems of the classical nonlinear systems [33]. Zhao et al. presented an observer-critic structure-based ADP method to address the problem of decentralized tracking control of unknown nonlinear systems [34], on this basis, a policy iteration algorithm-based decentralized control method is investigated for large-scale nonlinear systems with unknown mismatched interconnections [35]. However, these decentralized control strategies are investigated from the premise that the dynamic information of the nonlinear systems are completely unknown, thus the application of these methods are limited to address the optimal control problems of specific classes of robotic systems without implementing optimal dynamic compensation. In fact, when we are designing decentralized controllers for robot manipulators, especially for MRR systems, the obtainable part of the dynamic model should be utilized effectively. Unfortunately, to the best of the authors' knowledge, there are few types of research that focus on investigating the decentralized optimal control approach, which simultaneously possesses the performance of model-based compensation control and ADP-based optimal control for MRRs, particularly, under the situation of uncertain environment contact.

In this paper, a torque sensorless decentralized neuro-optimal control method is presented for harmonic drive-based MRRs in contact with uncertain environment. First, the dynamic model of MRRs is formulated based on a novel joint torque estimation method that exploits the existing structural elasticity of robotic joint with harmonic drive transmission. Then, by effectively utilizing the obtained joint dynamic information, the decentralized optimal control problem of the whole robotic system is reformulated as an optimal compensation issue of model uncertainty. Second, according to the ADP approach, a local online policy iteration algorithm is employed to solve the HJB equation with a modified cost function, which is constructed by combining the performance index of both the position and velocity tracking error as well as the control torque of each joint module, moreover, a critic neural network is used to approximate the cost function, and then the optimal control policy can be derived directly. Based on the Lyapunov theory, the uniformly ultimately boundedness of the weight approximate error and the asymptotic stability of the closed-loop robotic system are proved. Finally, simulations and experiments are conducted to verify the effectiveness and advantage of the proposed method.

The main contributions of this paper can be summarized as follows:

- Unlike conventional methods that rely on robot-environment contact models or force/ torque sensing techniques, this paper addressed the optimal control problems of uncertain environmental contacted MRRs based on a novel joint torque estimation method that uses the motor-side and link-side position measurements of each joint module along with the harmonic drive model. Experiments are performed to confirm the effectiveness of the proposed torque estimation method.
- Different from the existing decentralized optimal control methods that leave the dynamic compensation out of consideration, in this paper, the obtainable joint dynamic information is utilized effectively to design the model compensation controller, thus making the decentralized optimal control problem of the