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Real-time inverse kinematics of redundant manipulators using neural networks and quadratic programming: A Lyapunov-based approach

Hamid Toshani, Mohammad Farrokhi *

Iran University of Science and Technology, Narmak, Farjam St., Tehran 16846, Islamic Republic of Iran

HIGHLIGHTS

- An adaptive method to solve inverse kinematics of redundant manipulators.
- Neural networks are used to obtain joint angles in the Cartesian coordinates.
- Quadratic programming is used to satisfy constraints and train neural networks.
- Fuzzy logic is used for better initialization of the weights of neural networks.
- Inverse kinematics is performed in the position level of joints.

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ABSTRACT

In this paper, an online adaptive strategy based on the Lyapunov stability theory is presented to solve the inverse kinematics of redundant manipulators. In the proposed approach, Radial Basis Function (RBF) Neural Networks (NNs) are employed to obtain the joint angles of the robot using the Cartesian coordinate of the end-effector. Quadratic Programming (QP) method is incorporated in the training algorithm of the NNs to satisfy the constraints of the problem such as the joint angle limits and obstacles in the workspace of the robot. For better initialization of the NNs' weights, fuzzy logic is employed. In this way, smaller errors for the initial position of the end-effector and feasibility of the joint angles can be obtained. The convergence of the NNs' weights and satisfaction of the constraints are guaranteed by employing an adaptive scheme that is based on the Lyapunov stability analysis and Kuhn–Tucker conditions, which is part of the QP to update the NNs' weights. In addition, obstacle avoidance is also considered in the proposed method. The simulations are carried out on the seven degrees-of-freedom PA-10 robot manipulator. The results show the effectiveness of the proposed approach in obtaining successful configurations of the robot while the solutions of the inverse kinematics are feasible. Moreover, a comparison with the recently reported methods in the literature shows advantages of the proposed method.

1. Introduction

The problem of inverse kinematics is known as a mapping from the Cartesian space to the joint space. This problem is considered as one of the most important issues in the field of robot manipulators such as design, motion planning and control. Various approaches have been developed by researchers to solve this problem, which, in general, depends on the structural and workspace of the robot.

Typically, the main task of the robot manipulators is to track a desired trajectory in the Cartesian space with minimum error. However, in practice, joints of the robot have physical limitations. Moreover, in many applications, the workspace of the robot contains obstacles. In order to overcome these problems, redundant manipulators are employed in practice. These robots have more Degrees of Freedom (DOF) than required for specifying the position and orientation of the end-effector. The redundancy enables the robot to achieve a suitable configuration among various solutions. Hence, typically, there exist an infinite number of solutions for the problem of inverse kinematics of redundant manipulators.

Various approaches have been presented by researchers in the literature to resolve the redundancy problem of redundant manipulators. The Jacobian's pseudo inverse-based techniques are widely used to deal with the redundancy resolution problem. These methods consider the inverse kinematics as a first order mapping and typically obtain a general solution that corresponds

* Corresponding author. Tel.: +98 9123939087; fax: +98 2173225777.
E-mail addresses: h_toshany@yahoo.com (H. Toshani), farrokhi@iust.ac.ir (M. Farrokhi).

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to the minimum-norm and homogeneous solutions that is pertaining to the redundancy ability of the robot. Perdereau et al. have proposed an adaptive matrix that uses the Jacobian matrix and its transpose to update the joint angles of the robot [1]. In order to avoid obstacles, they have presented a concept called "pseudo distance", which is described by the means of a quadratic surface. The proposed method is able to handle complicated obstacles. However, it has a low convergence rate.

The Jacobian's pseudo-inverse based approaches resolve the redundancy in two different ways: (1) the gradient projection method and (2) the task space augmentation. Wang et al. have used the first approach to avoid joint physical limits of a seven Degree-of-Freedom (DOF) robot [2]. They have designed a closed-loop structure using the Cartesian error of the end-effector to improve movements of the joints. To avoid obstacles, Benzaoui et al. have considered a task-space augmentation method to describe the self-motion of the robot [3]. These methods have a simple structure, but they suffer from some drawbacks such as instability around the singular regions and the lack of repeatability. Utilization of the pseudo inverse in the acceleration level is proposed by Antonelli et al. [4]. They have defined a concept called "virtual time" to reform the movement of the robot. This approach guides the end-effector to the desired point slowly. Hence, it may have limited performance in the applications where fast movements are required. Since the computation of the Jacobian's pseudo-inverse methods is time consuming, a novel method based on the augmentation of the Jacobian matrix is presented by Tchon et al. [5] to approximate the Jacobian's pseudo inverse. The main problem of this method is the complexity of its equations and lack of analytical solutions. Zergeroglu et al. have used Jacobian's pseudo-inverse method to control the redundant robot manipulators. For this purpose, an error dynamic model is defined in the Cartesian space and is incorporated into the torque equation of the robot. Using the Lyapunov method, they have proved that the method is convergent [6]. In a similar manner, Singh and Sukavanam proposed an adaptive control scheme based on a feed-forward NN, in which the NN estimates the dynamics of the robot. Moreover, the external disturbances and uncertainties of the model have been considered and an adaptive compensator with stability analysis is designed to control a 3-DOF robot manipulator [7].

In order to handle the robot around the singular regions, damped least squares methods are employed by some researchers. Phuoc et al. have used Gaussian functions for damping factor and optimizing parameters of these functions using a genetic algorithm [8]. The proposed approach is able to smooth movements of the joints when crossing singular regions. However, it is suitable for offline applications. In a similar manner, Caccavale et al. have used this method in the acceleration level [9]. In order to ensure the stability of the method, certain boundaries are considered in a conservative manner on the velocity and acceleration of the end-effector. In general, Jacobian's inverse-based approaches have several drawbacks such as lack of repeatability, necessity to adjust several parameters, lack of a straightforward method to ensure stability, and the existence of integration drift.

Aristidou et al. have presented an iterative approach based on the geometrical information of the robot that is composed of the forward and backward stages [10]. The solution is obtained after a few iterations by combining these two stages. The proposed method has a low computational time and yields accurate solutions. However, it is not suitable for robots with complicated structures and does not guarantee convergence of the algorithm. Yahya et al. have used a geometrical approach, in which only the first angle is distinguished from the rest [11]. The proposed method drives suitable equations and solves them using iterative algorithms.

Artificial neural networks (or Neural Networks (NNs) for short) are widely used to solve optimization problems such as the inverse kinematics of redundant manipulators. Several aspects such as learning, versatility, generalization, and parallel distributions have distinguished them from other methods. NNs are trained in two different ways: offline and online. The offline methods are suitable for repetitive applications while online methods are suitable for real-time applications and dynamic environments. Chiddarwar et al. have employed Multi-Layer Perceptron (MLP) and Radial-Basis Function (RBF) NNs for solving the inverse kinematics of a six DOF robot manipulator [12]. In order to train these networks offline, the position and orientation of the end-effector and incremental values of them are applied as inputs to the NNs. Similarly, Hasan et al. have considered the singularity problem in the network training [13]. To this end, they have gathered data from singular regions and incorporated them into the training data. Angulo and Torras have decomposed the real robot into some virtual robots in order to simplify the learning of the inverse kinematics [14]. For this purpose, Parameterized Self-Organized Map (PSOM) NN is used to learn the forward kinematics of the virtual robots. Training of the NNs is performed offline, which makes it suitable only for static environments.

Kumar et al. have used the SOM NN to solve the inverse kinematics of a seven DOF manipulator [15]. In order to obtain different solutions, an algorithm called sub-clustering is incorporated into the SOM network to divide the joint space into several regions. In this method, it has been assumed that the position and orientation of the robot are separable, which is not true for several applications. Duguleana et al. have incorporated a learning reinforcement technique into the MLP NN to avoid obstacles in the workspace of redundant manipulators [16]. When there is a danger of collision, the learning strategy retrains the network to reform the movement of the robot. The main problem is that the computation time is significantly high with respect to approaches such as Jacobian's pseudo-inverse methods and projection-based NNs. Zhang et al. have used dual NNs to solve the inverse kinematics of a seven DOF robot manipulator under the joint physical limits and obstacles in the workspace of the robot [17,18]. In this method, first, the Jacobian's inverse technique is converted into a Quadratic Programming (QP) problem. Then, a decision vector is defined. Finally, a single layer network with linear activation functions is constructed. The solution is found by establishing proper conditions for convergence of the algorithm. The presented approach depends on the robot structure and has a high computational time. A combination of NNs and fuzzy logic is proposed by Assal et al. to solve the inverse kinematics of a seven DOF robot manipulator [19]. According to this method, a first-order Sugeno fuzzy model is used to handle the joint physical limits. Then, a Widrow–Hoff NN is employed to solve the inverse kinematics. The performance of the proposed approach is compared with the gradient projection method and the results are studied qualitatively and quantitatively. An inverse-forward adaptive strategy is presented by Kumar et al. to solve the redundancy problem of a seven DOF robot manipulator [20]. In the proposed method, a RBF NN is used online to train the forward kinematics while obstacles are presented in the workspace of the robot. This method suffers from high dimensions and does not guarantee convergence of the algorithm.

In this paper, a numerical online approach that is composed of NNs, fuzzy logic, and a QP method is presented to solve the inverse kinematics of 7 DOF redundant manipulators. The proposed method overcomes the aforementioned drawbacks of the existing methods. In this method, an adaptive approach based on the Lyapunov theory and Kuhn–Tucker conditions is proposed that has the following advantages:

- it solves the inverse kinematics problem in real-time; hence, it is suitable for dynamic environments;
- no explicit information of the robot is required;
- the stability of the algorithm is guaranteed;