Advances in Engineering Software 78 (2014) 60–66

Contents lists available at ScienceDirect

Advances in Engineering Software

journal homepage: www.elsevier.com/locate/advengsoft

System identification and control of robot manipulator based on fuzzy adaptive differential evolution algorithm

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ARTICLE INFO

Article history:
Received 17 July 2014
Received in revised form 12 August 2014
Accepted 24 August 2014
Available online 19 September 2014

Keywords:
Robot manipulator
Adaptive differential evolution
Fuzzy logic
Parameter estimation
FADE algorithm
Parameter control

ABSTRACT

A requirement for new robotic manipulators is the ability to detect and manipulate objects in their environments. Robotic manipulators are highly nonlinear systems, and an accurate mathematical model is difficult to obtain using conventional techniques. Therefore, an efficient technique is required to deal with these types of complex and dynamic systems. Differential Evolution (DE) algorithm is a very powerful optimization technique and has become popular in many fields. Arguably, it is now one of the most predominant stochastic algorithms for real-parameter optimization. However, DE is very sensitive to its control parameters of the mutation operation (F) and crossover operation (CR) in such a way that their fine tuning greatly affect DE performance. Fuzzy Adaptive DE (FADE) algorithm is one of the well known adaptive DE variants that show superiority and reliability in solving different types of optimization problems. The objective of this article is to develop a new dynamic parameter identification framework to estimate the barycentric parameters of the CRS A456 robot manipulator based on FADE. The simulation results presented in this paper show the effectiveness of the FADE method over other conventional techniques, transcending the limits of the existing state-of-the-art algorithms in solving the problem of robot.

1. Introduction

There are many industrial applications where the robot manipulator is required to carry out precise task with high accuracy and repeatability. Recently, the application of robotic technology in clinical medicine has been a very active research area. For instance, in surgical operations the robot manipulator serves as an assistant to the doctor or as an extension of the doctor capabilities [1,2]. These kinds of advanced robot applications require an accurate model of the robotic system, which in turn, requires sufficiently accurate knowledge of the parameters of robot dynamics to be applied in advanced control system design, preoperative planning, process supervision, and simulation and training.

Dynamic models of robot arms used in model-based control schemes are designed in terms of various inertial and friction parameters that must be either measured directly or determined experimentally. However, direct measurements of such characteristics are rather impractical or even impossible in many cases. Inertial parameters of robot links cannot be measured without dismantling the robot arm, while highly nonlinear inherent phenomena at robot joints cannot be directly quantified. Therefore, models describing nonlinear effects such as friction should be addressed in conjunction with methods of determining parameters of the dynamic model of the arm based on experiments, in order to fully identify the dynamic model of the robot arm [3].

There are many traditional methods that have been used for dealing with dynamic robot parameter identification including Kalman filter [4] and least square method [5,6]. However, some model parameters such as link mass and link lengths cannot be easily measured using these methods especially with the effect of noise factor, or in other words their measurements relatively difficult [7]. Moreover, these traditional techniques are relatively effective for a class of specific issues. For example, the structural model is reliable but the data has limited accuracy. Furthermore, they depend on unrealistic assumptions that models must be

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http://dx.doi.org/10.1016/j.advengsoft.2014.08.009
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unimodal, continuous and derivable. These methods sometimes converge slowly, and sometimes at local optimum, or even not at all.

Recently, there have been intelligent proposed methods for estimation based on the use of universal approximations such as fuzzy logic and neural network methodologies. These methods seem to be very attractive because in the ideal case they allow the modeling of the dynamic effects even ‘bad’-modeled, for example, friction. In recent years, Evolutionary algorithms such as Genetic Algorithm (GA), Differential Evolution (DE) and Particle Swarm Optimization (PSO) have been studied extensively. They have been used to improve the dexterity of robot manipulators in many fields such as control, parameter identification, robot design and planning [8–10]. They have been known to be better suited for noisy, discontinuous functions because they require no knowledge or gradient information about the response surface. This ability of Evolutionary algorithms has encouraged researchers to use these methods in order to moderate the difficulties of noise and nonlinearity that often arise in dynamic models. GAs is better suited for noisy, discontinuous functions because there is no requirement for a derivative in the fitness function. Moreover, GAs accumulate information about the system during the search process, which makes them more desirable than the traditional numerical methods [11] through the use of real-coded GA to estimate friction and torque sensor model parameters. The simulation approach demonstrates the effectiveness of the GA. By identifying the parameters, the position tracking error and the velocity tracking of the joint is enhanced. The performance of GA has been also analyzed and evaluated in optimizing the precision of kinematic parameters of the robot manipulator by developing a forward calibration algorithm which is based on GAs. The main problem for this approach is to find a good mathematical correction function and in [12] a suggestion has been made to enhance the accuracy of the robot manipulator by using some new techniques such as ANN and Fuzzy Logic technique.

Differential Evolution (DE) Algorithm is a new evolutionary approach proposed by Storn and Price in 1996 [13,14] to minimize nonlinear and non-differentiable continuous space functions. Price and Storn presented this algorithm to optimize a variety of problems. Similar to GA, it has been applied to various fields successfully. So far, there has been no attempt to optimize the design parameters of manipulator by which performance variations will be minimal. In [15] a modification in differential evolution optimization technique is proposed to incorporate the effect of noise in the optimization process and obtain the optimal design of manipulator, which is insensitive to noise. In this optimization process, the kinematic and dynamic models of the manipulators are used. The results indicate that the DE converges quickly with fewer generations and function evaluations than GA. Hence, fast performance of DE indicates that this approach can be a viable optimization technique. However, the performance of DE is still sensitive to its control parameters such as mutation factor (*F*) and crossover rate (*CR*).

Recently, the development of adaptive DE has shown more reliable performance than DE with manual settings [16–18]. Fuzzy Adaptive Differential Evolution algorithm (FADE) is one of the well-known adaptive DE variants. It is implemented by applying a mechanism in which the crossover and the mutation control parameters (*F* and *CR*) are both adaptive using fuzzy logic-based controllers; the input signal for the fuzzy system has been calculated from the population mean square diversity. In this algorithm, Fuzzy system plays a key role in updating the control parameters of DE as well as increasing the convergence rate.

In this paper, the application of FADE algorithm is proposed to estimate the barycentric parameters of the CRS A456 robot manipulator. This algorithm is used to off-line estimate the optimal parameters of the inverse dynamic model of the CRS A465 robot arm, which are expected to be insensitive to noise.

This paper is organized as follow. The detailed description of the CRS A465 robot arm and its barycentric parameters are presented in Section 2. The complete steps and structure of FADE algorithm is described in Section 3. Results and discussion of applying FADE algorithm as an estimator of the CRS A465 robot arm barycentric parameters is presented in Section 4. Section 5 concludes the paper.

2. Dynamic model of the CRS A456 robot manipulator

The CRS A465 arm considered in this work is used as a slave robot in a research cell for orthopedic robot-assisted surgery (see Fig. 1).

In this application, the end effector of the arm carries the surgical tool – the “drilling/machining tool”. Due to the symmetry of the drilling tool, only five degrees of freedom is required. Therefore, only the first five joints of the arm are considered to be the subject for the modeling task in this work.

The equation of motion for the robot is developed using the *L–E* formulation. The *L–E* is non-recursive method that allows the development of the robot model using a set of equations derived from the energy model [19]. Based on this formulation the torque acting on any joint axis is:

$$\tau_i = \sum_{j=1}^{N} D_{ij}(q,\chi)\ddot{q} + \sum_{j=1}^{N}\sum_{k=1}^{N} H_{ijk}(q,\chi)\dot{q}_j\dot{q}_k + G_i(q,\chi) + \tau_{fi} \tag{1}$$

where τ_i is the torque acting on joint *i*, *i* = 1,2…*N*, *N* is the number of degrees of freedom, $q, \dot{q}, \ddot{q}$ are the position, velocity and acceleration of robot joints, respectively, χ is the model parameters, D_{ij} is the effective and coupling inertia, H_{ijk} is the centripetal and Coriolis effect, G_i is the Gravity loading, and τ_{fi} is the joint friction.

The details of the coefficients D_{ij} and H_{ijk} is given in [19] through examination of Eq. (1) shows that the equation of motion is linear in the robot physical parameters, that is the mass, center of gravity locations moments and products of inertia of each link see Fig. 2.

The terms of the equation of motion given in Eq. (1) are linear in the model parameters χ that are the mass, center of gravity locations moments and products of inertia of each link. Therefore it can be written in:

$$\tau = \Phi(q,\dot{q},\ddot{q})\chi \tag{2}$$

where $\boldsymbol{\tau}$ is the torque vector, $\Phi(q,\dot{q},\ddot{q})$ represents an $(N \times R)$ observation matrix, and the R- length vector χ, contains the effective inertial parameters of the manipulator grouped in the barycentric or base parameters. The identification “observation” matrix $\Phi(q,\dot{q},\ddot{q})$ depends on the joint angles, velocities, and accelerations. The barycentric parameters of a link are combinations of its inertial parameters and its descendants in the kinematic chain [21]. The categorization and grouping of the barycentric parameters is done symbolically or by applying a set of rules. Normally, special computer programs are developed for automatic generation of the symbolic model and the associated barycentric parameters. For the CRS A465 the set of the barycentric parameters χ are given [20].

In this study, in order to make a clear comparison among the estimation methods, the problem is simplified to consider only a single joint arm of the CRS A465 to estimate its parameters. The CRS 465 single joint arm has four parameters a_i, *i* = 1,…, 4 to be identified; they are the inertia, the viscous friction coefficient, the positive side Coulomb friction, and the negative side Coulomb friction, respectively. The system equation becomes:

$$\tau = a\chi \tag{3}$$

where τ is the torque, and χ is the barycentric parameters that have been reduced to four parameters, they are the angular acceleration