Inverse Kinematics Study for Intelligent Agriculture Robot Development via Differential Evolution Algorithm

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***Abstract*—Robots with intelligent moving and manipulating ability are able to improve productivity of agriculture work. We prototyped a mobile robot equipped with reductant manipulator (7-DOF). Here, for controlling the manipulator precisely, we investigate the inverse kinematics (IK) issue of the manipulator. A novel IK solving method by adopting an improved differential evolution algorithm has been validated. Also, random change crossover is employed to restrict the tendency of falling into local optimization when we use the algorithm. In parallel, considering the position and posture errors, boundary processing has been redesigned for avoiding joint limits. Thereafter, we obtain the global optimal IK solutions. Simulation tests have been carried out using the numerical model of the redundant arm. By testing accuracy and stability of the arm, we verify the feasibility and efficiency of the proposed approach.**

Keywords-intelligent agriculture robot; redundant arm; inverse kinematics; differential evolution algorithm

I. INTRODUCTION

Robotics and intelligent algorithms have become more popular and promising than ever which are able to improve automation level in multiple fields including agriculture. Previously, we developed a smart agriculture robot system which consists of a self-propelled vehicle and a redundant operation arm. The vehicle integrated a motion and a visual recognition system for remotely path control and dexterous operating. The arm can also be matched with various end-effectors for satisfying diverse requirements. Thanks to the advanced visual recognition technology and maneuvering flexibility of the redundant arm, the robot can be adapted to many agricultural tasks, such as cotton topping, pesticide spraying. In this paper, we focus on solving the IK (Inverse Kinematics) issue of redundant arm. Generally, for a redundant arm, multiple or namely non-unique postures can be acquired for a desired end-effector position, leading to infinite solutions of IK issues.

Geometric, algebraic method and intelligent algorithms have been widely used for solving IK problem. Each method has inherit merits and disadvantages as well. Geometric method solves IK problem based on analyzing the structure of arms aforehand, and then acquries analytical IK solutions by combining the spatial geometry and IK equations. Kofinas [1] proposed a method that divided the Aldebaran NAO humanoid robot into five independent parts (head, two arms, two legs) followed by obtaining the analytical IK solutions.

Figure 1. " A self-developed robot for mutiple agricultural tasks.

Mu [2] transformed the IK problem to parameter optimization by splitting a spatial hyper-redundant arm into three sections: wrist, elbow, shoulder. Faria [3] introduced two parameters to cope with the self-motion manifolds, and presented an analytic method to uniquely solve IK issue of 7 degrees-of-freedom arms (7-DOF) while avoiding joint limits and singularities. Zaplana [4] reduced a redundant arm to a non-redundant arm by denoting redundant joint and parameterizing the joint variables, and therefore analytical solutions can be presented for a given pose. Sinha [5] presented a method that can compute multiple IK solutions using two-parameter search by exploiting geometry of the structure of a redundant manipulator. While, the geometric method often requires complicated structure pre-analyses and matrix transformation limiting its application to the arms with specific structures.

Algebraic method mainly includes Jacobian matrix pseudo-inverse method, augmented Jacobian, gradient projection and weighted minimum norm method. Wan [5] added an elastic field function to the origin weighted least-norm method for sustaining the constraints of joint angular velocity limits, and proposed an improved clamping weighted least-norm method. Dong [6] proposed an iterative inverse kinematics solution algorithm which utilized a nonlinear working space density function as the objective function. Ananthanarayanan [7] used analytical solutions to enhance the speed of numerical solving, presented a novel, computationally efficient method. Martin [8] proposed a method to solve the inverse kinematics problem of hyper-redundant and soft arms through the cyclic coordinate descent (CCD) approach. Although precision of algebraic method is relative high, the corresponding calculation quantity is normally large which impairs solving efficiency.

With the development of hardware, novel approach based on smart algorithms have been employed to solve the inverse kinematics. Toshani [9] leveraged neural network algorithm and quadratic programming to satisfy constraints and train neural networks. Dong [10] adopted genetic algorithm to solve IK of a 7-DOF arm for trajectory planning. Dereli [11] used firefly algorithm to solve IK of a 7-DOF arm. Hassan [12] focused on formulating IK as a quadratic programming optimization problem and solved by different kinds of recurrent neural networks. Kouabon [13] proposed a learning framework for solving IK, adopted a growing neural gas network (GNG) for workspace clustering, and a neighborhood function (NF) was introduced in configuration space clustering. Tringali [14] proposed the globally optimal IK method that allows for the optimization of different integral cost functions. Theoretically, smart algorithms benefit from the advantage of computer science and engineering, and therefore have enhanced calculating efficiency and precision.

In this work, we present a novel IK solving method which leverages an improved differential evolution algorithm. To avoid differential evolution algorithm falling into local optimum procedure, adjustments have been applied to the crossover operation. Joint limit, position and posture error have been together included during the solution evaluation. Testing result validate the feasibility and efficiency of the proposed approach.

II. KINEMATICS

The redundant arm we adopted has seven degree of freedom as shown in Fig.2. Prior to solving the kinematics issues, we investigated its structure and established kinematics model using Denavit-Hartenberg (D-H) method. D-H parameters of the arm are shown in Table I.

TABLE I. D-H PARAMETER OF THE REDUNDANT ARM

i	*θ/rad*	*α/rad*	*d/mm*	*a/mm*	*Range/rad*
1	θ_1	-π/2	340	0	±17π/18
2	θ_2	π/2	0	0	±2π/3
3	θ_3	- π/2	400	0	±17π/18
4	θ_4	π/2	0	0	±2π/3
5	θ_5	- π/2	400	0	±17π/18
6	θ_6	π/2	0	0	±2π/3
7	θ_7	0	126	0	±35π/36

Herein, θ, α, d, a are the parameters describing movement and rotation of the redundant arm. The position and posture of the end-effector are defined by the motion of all joints, each of which has a corresponding motion range.

Motion between two adjacent links ${}^{i-1}\boldsymbol{T}_i$ can be calculated by the parameters $c\theta$ ($\cos(\theta)$) and $s\theta$ ($\sin(\theta)$) as Eq.1. Thereafter, the position and posture of the end-effector ${}^{7}\boldsymbol{T}_0$ can be acquired by Eq.2,

$$ {}^{i\text{-}1}\boldsymbol{T}_i = \begin{bmatrix} c\theta_i & -s\theta_i c\alpha_i & s\theta_i s\alpha_i & a_i c\theta_i \\ s\theta_i & c\theta_i c\alpha_i & -c\theta_i s\alpha_i & a_i s\theta_i \\ 0 & s\alpha_i & c\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{1} $$

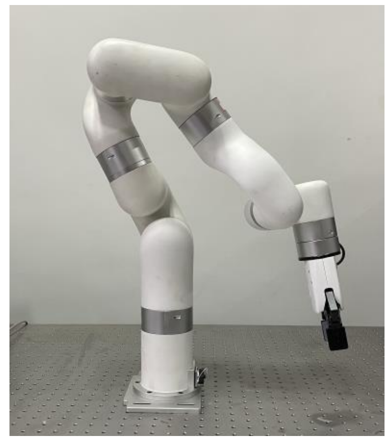

Figure 2. Image of a redundant operating arm (7-DOF).

$$ \begin{aligned} {}^0\boldsymbol{T}_7 &= {}^0\boldsymbol{T}_1\,{}^1\boldsymbol{T}_2\,{}^2\boldsymbol{T}_3\,{}^3\boldsymbol{T}_4\,{}^4\boldsymbol{T}_5\,{}^5\boldsymbol{T}_6\,{}^6\boldsymbol{T}_7 \\ &= \begin{bmatrix} r_{11} & r_{12} & r_{13} & p_x \\ r_{21} & r_{22} & r_{23} & p_y \\ r_{31} & r_{32} & r_{33} & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} \boldsymbol{n} & \boldsymbol{o} & \boldsymbol{a} & \boldsymbol{p} \\ 0 & 0 & 0 & 1 \end{bmatrix} \end{aligned} \tag{2} $$

Herein, $\boldsymbol{n}$, $\boldsymbol{o}$, $\boldsymbol{a}$ are the vectors describing posture of the end-effector; $\boldsymbol{p} = [x, y, z]$ indicates position. To simplify the expression of posture, we adopted the Z-Y-Z Euler angles α, β, γ as shown in Eq.3 to describe the posture. In this scenario, the position and posture can be expressed as $(x, y, z, \alpha, \beta, \gamma)$.

$$ \begin{aligned} \beta &= A\tan 2(\sqrt{r_{31}^2 + r_{32}^2}, r_{33}); \\ \alpha &= A\tan 2(\frac{r_{23}}{s\beta}, \frac{r_{13}}{s\beta}); \\ \gamma &= A\tan 2(\frac{r_{32}}{s\beta}, \frac{-r_{31}}{s\beta}) \end{aligned} \tag{3} $$

After acquiring the position and posture, forward kinematics (FK) analysis was finalized. Obviously, the FK is a single mapping process which means one group joint angles solo corresponds to a specific position and posture.

For a 7-DOF redundant arm, position and posture are determined by seven joints. In contrast, seven joint angles should be figured out for desired position and posture by IK analysis. Therefore, IK study is actually a process solving transcendental equation.

III. DIFFERENTIAL EVOLUTION ALGORITHM

Differential evolution (DE) algorithm is a bionic algorithm that optimizes calculation issues by iteratively computing with a given IK solution quality. DE algorithm has been widely adopted by research in chemistry, electronics, signal processing, mechanical design and related fields for its strong global convergence ability and robustness. Multiple individuals are generated randomly and calculated iteratively until obtaining the optimal individual that fulfils all requirements. The calculating procedure includes population initialization, mutation, crossover, and selection.

A. Population Initialization

A population contains multiple individuals, each of which is actually a solution for an optimization issue. The dimension of individuals should be consistent to the problem. For solving a problem with m dimensions, provided that we initialize a population including N individuals with m dimensions, the mathematical relationship follows Eq.4.

$$p = rand(0,1) \times (p_{\max} - p_{\min}) + p_{\min} \tag{4}$$

Herein, p is an element of an individual, $p_{\max}$ and $p_{\min}$ define the range of p. In this scenario, p indicates a joint angle; $p_{\max}$ and $p_{\min}$ are numbered by the joint motion range.

B. Mutation

Mutation enriches the diversity of the population which is helpful to greatly increase the probability and searching speed during optimization. The DE/best/1/bin mutation is adopted to generate novel individuals, and the operation is based on calculation between different individuals as shown in Eq.5.

$$P = F(P_1 - P_2) + P_{best} \tag{5}$$

Herein, F is the mutation factor ranging from 0 to 2; P_{best} is the optimal individual of the present population.

C. Crossover

For furtherly increasing the population diversity, DE exchanges some elements of individuals through probability that controlled by crossover factor CR. The crossover step is presented as following equation:

$$P = \begin{cases} V, & if\ \ CR > rand(0,1) \\ U, & if\ \ CR < rand(0,1) \end{cases} \tag{6}$$

Normally, CR is constant resulting in a non-random crossover. For improving the effect of crossover, randomly changed crossover operation has been introduced to CR:

$$CR = \frac{3}{4} \times (0.5 + rand(0,1)) \tag{7}$$

D. Boundary Processing

Following the above operations, some individuals may jump beyond joint limit. Considering the joint limit avoidance, we employed a boundary processing as below. For these elements out of range, we reassigned them as the median of joint range to keep the value away from boundary value.

$$p = \begin{cases} (p_{\min} + p_{\max})/2 & if\ \ p < p_{\min}\ \ or\ \ p > p_{\max} \\ p & else \end{cases} \tag{8}$$

E. Selection

Individuals are substituted into the fitness function during Selection. We set the fitness as the sum of position and posture error. Correspondingly, the fitness function is set as follows:

$$f = k_p \cdot \sqrt{\Delta x^2 + \Delta y^2 + \Delta z^2} + k_r \cdot \sqrt{\Delta\alpha^2 + \Delta\beta^2 + \Delta\gamma^2} \tag{9}$$

Herein, k_{p}, k_{r} are weight factors for maintaining the convergence balance between positon and posture.

Therefore, for an IK problem, the solution that can minimize errors should be the optimal one. The algorithm selects the best solution of each iteration, and the global optimal solution is comparatively selected among these solutions following Eq.10:

$$P = \begin{cases} Q & if\ \ fitness(Q) < fitness(P) \\ P & else \end{cases} \tag{10}$$

The proposed algorithm solves IK problem using differential evolution algorithm which optimizes feasible selections following the error minimization principle. Furthermore, to avoid joint limit and the local optimum tendency, we added the randomly change crossover operation and redesigned boundary processing. By this approach, the global optimal IK solution could be readily acquired using D-H parameters.

IV. EXPERIMENTS AND DISCUSSION

To evaluate the efficiency and stability of the presented method, we performed numerical experiments to quantify the calculating precision and error fluctuation. The result demonstrated the proposed method is capable of solving IK of redundant arm. For a desired end point (334, 471, 539, π/2, π/4, π/6), by setting the literation at 200, F=0.5, we established an numerical experiment platform on Windows 10 and employed the Intel Core i7-8700K@3.7GHz for computation. Single-point solving test and repetitive test were carried out using this platform.

A. Single-Point Solving Test

First of all, we substituted the target position and posture (334, 471, 539, π/2, π/4, π/6) into the equations, and set the number of iterations to be 200. Then, we acquired a joint angle group (-0.1463, 2.0494, 1.9414, 1.9062, 0.4786, 0.4610, -1.6490). the fitness value was 6.65×10^{-6}. Also, we substituted this solution into forward kinematics, and the position and posture of these joint angles were found to be (334.0000, 471.0000, 539.0000, 1.5708, 0.7854, 0.5236). Obviously, the results are close to the target point. The convergence curve of the calculation is presented in Fig.3. It can be found that the convergence trend is quite clear and the algorithm is converged at the 80th iteration step. A whole computation for a single point cost 0.93 s. It can be concluded that the IK issue of the redundant arm have been solved with high precision and efficiency.

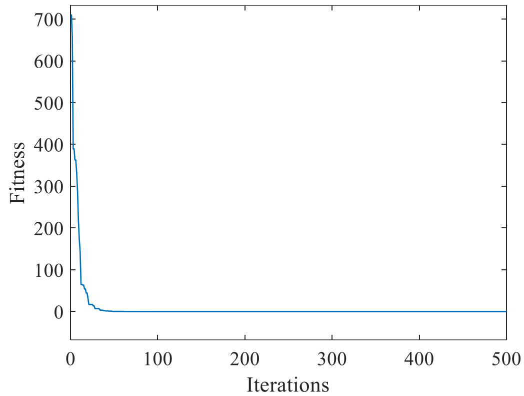

Figure 3. The convergence curve of the fitness.

B. Repetitive Test

Since the differential evolution algorithm is a method optimizing problem based on random search, quality of calculation cannot be predicted. Therefore, we evaluated the fitness of 30 IK computations for identical targeted position and posture. Similarly, we substituted (334, 471, 539, π/2, π/4, π/6) into the algorithm, programmed a loop for 30 calculations, and recorded all fitness results as shown in Fig.4. By the data plot, we can find that the fitness maintained stable, and the average value was 1.27×10^{-6}. Thus, it can be concluded that the proposed method is also capable of providing reasonable precision and stability for large-scale calculation or repeating tasks.

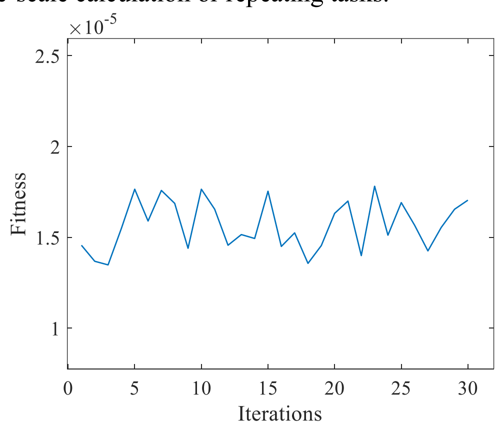

Figure 4. The fitness curve of repeated positioning.

V. Conclusions

In this work, we proposed a novel method adopting differential evolution algorithm to solve IK issues of a 7-DOF redundant arm. Random change crossover factor and specially designed boundary processing for avoiding joint limits have been introduced. Errors of position and posture were studied together for evaluating solution quality. D-H parameters were the solo necessaries for calculating. We performed single-point and repetitive solving simulation tests to quantify the precision and efficiency. Furthermore, the methodological scalability is adjustable for redundant manipulators with higher DOF.

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References

[1] Kofinas N, Orfanoudakis E, Lagoudakis M G. Complete analytical forward and inverse kinematics for the NAO humanoid robot[J]. Journal of Intelligent & Robotic Systems, 2015, 77(2): 251-264.

[2] Mu Z, Yuan H, Xu W, et al. A segmented geometry method for kinematics and configuration planning of spatial hyper-redundant arms[J]. IEEE Transactions on Systems, Man, and Cybernetics: Systems, 2018.

[3] Faria C, Ferreira F, Erlhagen W, et al. Position-based kinematics for 7-DoF serial arms with global configuration control, joint limit and singularity avoidance[J]. Mechanism and Machine Theory, 2018, 121: 317-334.

[4] Zaplana I, Basanez L. A novel closed-form solution for the inverse kinematics of redundant arms through workspace analysis[J]. Mechanism and machine theory, 2018, 121: 829-843.

[5] Sinha A, Chakraborty N. Geometric Search-Based Inverse Kinematics of 7-DoF Redundant Manipulator with Multiple Joint Offsets[C]//2019 International Conference on Robotics and Automation (ICRA). IEEE, 2019: 5592-5598.

[6] Wan J, Wu H T, Ma R. A study on avoiding joint limits for inverse kinematics of redundant arms using improved clamping weighted least-norm method[J]. Journal of Mechanical Science and Technology, 2018, 32(3): 1367-1378.

[7] Dong H, Du Z, Chirikjian G S. Workspace density and inverse kinematics for planar serial revolute arms[J]. Mechanism and Machine Theory, 2013, 70: 508-522.

[8] Ananthanarayanan H, Ordóñez R. Real-time Inverse Kinematics of (2n+ 1) DOF hyper-redundant manipulator arm via a combined numerical and analytical approach[J]. Mechanism and Machine Theory, 2015, 91: 209-226.

[9] Martin A, Barrientos A, del Cerro J. The natural-CCD algorithm, a novel method to solve the inverse kinematics of hyper-redundant and soft robots[J]. Soft robotics, 2018, 5(3): 242-257.

[10] Toshani H , Farrokhi M . Real-time inverse kinematics of redundant arms using neural networks and quadratic programming: A Lyapunov-based approach[J]. Robotics & Autonomous Systems, 2014, 62(6):766-781.

[11] Dong H , Wu W , Yao L , et al. A novel algorithm combined with single mapping workspace and Genetic Algorithm for solving inverse kinematic problem of redundant arms[J]. 2019.

[12] Dereli S, Köker R. Calculation of the inverse kinematics solution of the 7-DOF redundant robot arm by the firefly algorithm and statistical analysis of the results in terms of speed and accuracy[J]. Inverse Problems in Science and Engineering, 2020, 28(5): 601-613.

[13] Hassan A A, El-Habrouk M, Deghedie S. Inverse Kinematics of Redundant Manipulators Formulated as Quadratic Programming Optimization Problem Solved Using Recurrent Neural Networks: A Review[J]. Robotica, 2020, 38(8): 1495-1512.

[14] Kouabon A G J, Melingui A, Ahanda J J B M, et al. A Learning Framework to inverse kinematics of high DOF redundant manipulators[J]. Mechanism and Machine Theory, 2020, 153: 103978.

[15] Tringali A, Cocuzza S. Globally optimal inverse kinematics method for a redundant robot manipulator with linear and nonlinear constraints[J]. Robotics, 2020, 9(3): 61.