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A comprehensive research on the use of swarm algorithms in the inverse kinematics solution

Sürü algoritmalarının ters kinematik çözümde kullanımı üzerine kapsamlı bir araştırma

***Yazar(lar) (Author(s))**: Serkan DERELİ[1], Raşit KÖKER[2], İsmail ÖYLEK[3], Mükremin AY[4]*

ORCID[1]: 0000-0002-1856-6083

ORCID[2]: 0000-0002-3811-2310

ORCID[3]: 0000-0002-2647-076X

ORCID[4]: 0000-0002-8568-264X

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A Comprehensive Research on the use of Swarm Algorithms in the Inverse Kinematics Solution

Araştırma Makalesi / Research Article

Serkan DERELİ[1*], Raşit KÖKER[2], İsmail ÖYLEK[3], Mükremin AY[4]

[1,3]Sakarya Meslek Yüksek Okulu, Bilgisayar Teknolojileri Bölümü, Sakarya Üniversitesi, Türkiye
[2]Teknoloji Fakültesi, Elektrik-Elektronik Müh. Bölümü, Sakarya Üniversitesi, Türkiye
[4]Sakarya Meslek Yüksek Okulu, Mekatronik Bölümü, Sakarya Üniversitesi, Türkiye

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ABSTRACT

A comprehensive study was presented on swarm algorithms used in the inverse kinematic solution which is the basis of robot control in this paper. Because it is a complex and difficult problem group, the inverse kinematic solution is an important problem especially in robot arms with a lot of joints. So, swarm optimization techniques which were inspired by the animals in the nature, are often used by researchers, because these techniques find the best solution in a particular solution space. Artificial bee colony, firefly algorithm and particle swarm algorithm are the swarm techniques mentioned in this study. Since, these algorithms are frequently used in inverse kinematic solution in the literature.

Keywords: Robotic, inverse kinematics, swarm algorithms.

ÖZ

Bu çalışmada, robot kontrolünün temelinde bulunan ters kinematik çözümün bulunması için kullanılan sürü algoritmalarının kapsamlı bir araştırması sunulmuştur. Ters kinematik çözüm karmaşık ve zor problem grupları arasında olduğundan önemli bir problemdir. Özellikle bu durum robot kolunun çok fazla sayıda eklemi bulunduğunda çok daha zorlaşmaktadır. Bu nedenle doğadaki hayvanların davranışlarından esinlenilen sürü optimizasyonu teknikleri araştırmacılar tarafından sık sık kullanılmaktadır. Çünkü bu teknikler parçacık çözüm uzayındaki en iyi değeri elde etmektedirler. Yapay arı kolonisi, ateş böceği algoritması ve parçacık sürü algoritması bu çalışmada bahsi geçen tekniklerdir ve literatürde sıklıkla tercih edilmişlerdir.

Anahtar Kelimeler: Robotik, ters kinematik, sürü algoritmaları.

1. INTRODUCTION

Nature has contributed incredibly to the development of modern technology. Because today, the most advanced technologies of human beings are based on inspiration from nature. Swarm algorithms which were inspired by animals such as birds [1], fish, bees [2], fireflies [3] and ants [4], are one of the best examples. Despite the fact that the individuals of the swarms do not have a complicated structure, swarm intelligence emerges thanks to this cooperation of the individuals [5]. These algorithms are widely used to solve the most difficult problems [6] such as route determination, scheduling and inverse kinematics in almost all areas [6].

A new industrial revolution which its name is the fourth industrial revolution is being spoken today. Because the basis of this revolution is industrial robots the most important features of which are accuracy, speed and efficiency, the inverse kinematics that is the determination of the angle of the joints from the position of the end effector of a robot is important [8]. In addition, effective control of robots in the industrial revolution will gain importance. Therefore, the inverse kinematic issue has become even more important.

Swarm algorithms have been widely used by researchers in many areas such as science, engineering [9], robotics [10], commerce and control [11]. These optimization techniques have been used frequently in the inverse kinematic solution and effective results have been obtained. The solution of this problem is the most fundamental problem in robotics and it can take a long time especially in complex robots [12]. They obtained the inverse kinematic solution of a six-jointed puma robot using the artificial bee colony algorithm. They obtained the results in terms of position error and solution time, and compared these results with the PSO algorithm. It has been seen that the bee algorithm used in the study provides much better results both in terms of position error and working time [13]. Pham and his friends have altered the food search behavior of the bees in order to obtain more effective solutions and have introduced a new approach. They have realized the inverse kinematic solution with multi-layer neural network and used the bee colony algorithm to train the artificial neural network [14]. Rokbani and his friends have computed the inverse kinematic solution of a three-jointed robot arm using a relatively recent heuristic approach based on the communication methods of fireflies. The results of the study were obtained in terms of position error and solution time. [15]. Durmus and his friends have solved this problem using both particle swarm optimization and harmony search algorithm algorithms and have compared their results and they carried out the tests using six jointed puma type robots. The results are discussed as the position error and the average solution time of the

*Sorumlu Yazar (Corresponding Author)
e-posta : dereli@sakarya.edu.tr

algorithms and ultimately the PSO seems to produce much better values than the HSA [16]. Ayyıldız and Çetinkaya have used four heuristic techniques two of whom are swarm algorithm to obtain inverse kinematic solutions of a 4-jointed robot which is a self-designed robot manipulator and they compared the results obtained with these four algorithms. They observed the results of the algorithms with two different scenarios. One of these scenarios is to find a hundred different points randomly determined in the working space, and the other is to estimate a predetermined trajectory. They compared the four optimization techniques in terms of runtime and position error. [17]. Huang and his friends have calculated the inverse kinematic solution of a much more complex seven-jointed robot arm with the PSO technique. they separately evaluated the position errors occurring in the x, y and z axes and specifically stated in the study. They have set a separate performance index as a fitness function and have preferred to go through it as a result [18].

2. KINEMATIC ANALYSIS OF A SAMPLE ROBOT ARM

In this study, different robot arms were used in all the researches cited. However, in order to demonstrate how kinematic analyzes are done, the robotic arm shown in Figure 1. Kinematic analysis calculations are very important to determine the movements of robots in working spaces. The robot arm which has seven articulated and redundant features, to be taken as an example in this study appears in Figure 1 [19].

The method recommended by Denavit-Hartenberg is used for position and orientation information of the end effector of a robot manipulator in the working space. In this method, the relation between links is expressed by homogeneous transformation matrices which are obtained with the aid of DH parameters [20, 21].

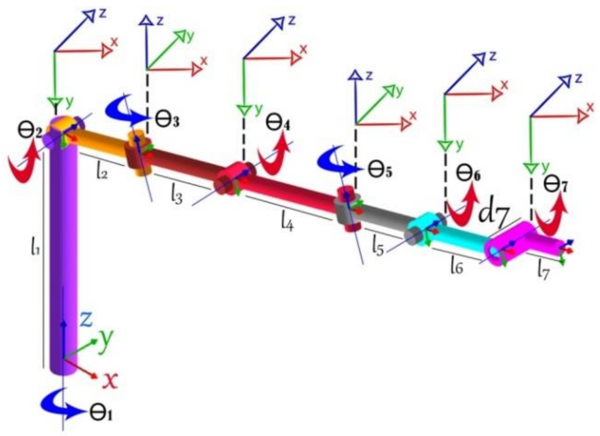

Figure 1. The structure of 7-degree of freedom (DOF) robot arm

Table 1. DH Parameter of the 7-DOF Robot Arm

i	ai(m)	αi(o)	di(m)	Θi(o)
1	0	-90	L1=0,5	-180<Θ1<180
2	L2=0,2	90	0	-90<Θ2<30
3	L3=0,25	-90	0	-90<Θ3<120
4	L4=0,3	90	0	-90<Θ4<90
5	L5=0,2	-90	0	-90<Θ5<90
6	L6=0,2	0	0	-90<Θ6<90
7	L7=0,1	0	D7=0,05	-30<Θ7<90

The position equations (Px, Py and Pz) of the robot arm according to the DH parameters in Table 1 are as follows:

$$\begin{aligned} Px =&(c1c2c3c4-s1s3c4-c1s2s4)(c5c6l7c7-\\ &c5s6l7s7- s5d7+c5l6c6+l5c5)+(-c1c2s3-s1c3)\\ &(s5c6l7c7s5s6l7s7+c5d7+s5c6l6+l5s5)+\\ &(c1c2c3s4-s1s3s4+ c1c4s2)(-s6l7c7-c6l7s7-\\ &l6s6) +c1c2(c3c4l4+l3c3)-s1(s3c4l4+l3s3)-\\ &c1s2l4s4+ c1c2l2 \end{aligned} \tag{1}$$

$$\begin{aligned} Py =& (s1c2c3c4+c1s3c4-s1s2s4)(c5c6l7c7-\\ &c5s6l7s7-s5d7+c5c6l6+l5c5)+(-s1c2s3+c1c3)\\ &(s5c6l7c7-s5s6l7s7+c5d7+s5c6l6+l5s5)+\\ &(s1c2c3s4+c1s3s4+s1s2c4)(-s6l7c7-c6l7s7-\\ &l6s6)+s1c2(c3c4l4+l3c3)+c1(s3c4l4+l3s3)-\\ &s1s2l4s4+s1c2l2 \end{aligned} \tag{2}$$

$$\begin{aligned} Pz =& (-s2c3c4-c2s4)(c5c6l7c7-c5s6l7s7-s5d7+\\ &c5c6l6+l5c5)+(s2s3)(s5c6l7c7-s5s6l7s7+\\ &c5d7+s5c6l6+l5s5)+(-s2c3s4+c2c4)(-s6l7c7-\\ &c6l7s7-l6s6)-s2(c3c4l4+l3c3)-c2l4s4-l2s2+l1 \end{aligned} \tag{3}$$

3. POSITION ERROR AND FITNESS FUNCTION

Optimization is accomplished by creating a fitness function in the process of obtaining optimum value by using swarm algorithms. This function is recalculated at each iteration and compared to the previous best value. Thus, optimum value is obtained at the end of the cycle and optimization is achieved [22].

In inverse kinematics applications, the fitness function is based on position error. In Figure 2, P1 is the actual position and P2 is the position calculated by the fitness function. The position error formula shown in Figure 2 can be obtained as in Eq. 4. The main purpose in the position error is to get the minimum value. As a result, using these algorithms, the most optimal seven joint angles of the robot arm in fig. 1 must be found.

$$Position\ Error = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2} \quad (4)$$

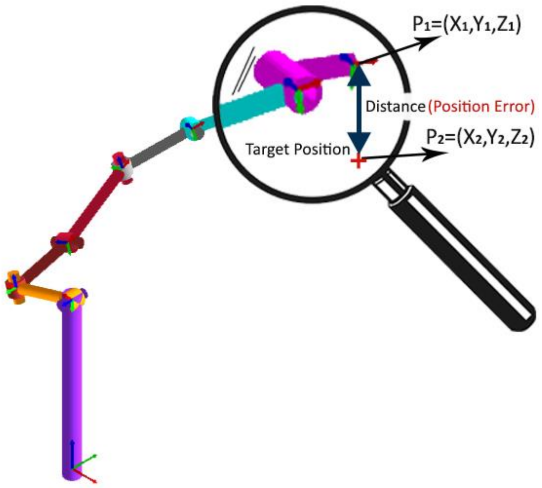

Figure 2. Representing the position error

4. USAGE OF SWARM ALGORITHMS

4.1. Particle Swarm Optimization

This optimization technique which was first used by Kennedy and Eberhart [1] is based on the movement of the birds. Its easy applicability and its powerful control parameters are important advantages of this algorithm [23]. In this algorithm, the particles travel at a certain speed (eq. 5) and reach a new position (eq. 6).

$$v_{id} = v_{id} + c_1.r_1.(p_{best} - x_{id}) + c_2.r_2.(g_{best} - x_{id}) \quad (5)$$

$$x_{id} = x_{id} + v_{id} \quad (6)$$

The inverse kinematic solution follows the following steps:

1. The number of particles (p) and iterations (n) is determined.
2. Seven joint angles are determined randomly for each particle.
3. The difference between the position obtained by randomly determined joint angles and the actual position is calculated according to equation 4. (only first particle)
4. The difference obtained according to step 3 is stored in memory as both local (pbest) and global best value (gbest).
5. The iteration (n) loop is started.
   - 5.1 The particle (p) loop is started.
     - 5.1.1. The position error for each particle is calculated (pbest).
     - 5.1.2. If the computed position error is less than the local best value (pbest), the new value is obtained.
   - 5.2 The particle loop ends.
   - 5.3 The local best value (pbest) is compared to the global value (gbest), and if it is smaller, it becomes the new global value (gbest).
   - 5.4 The joint angle values of the particles are updated according to the speed (eq. 5) and position equation (eq. 6).
6. The iteration loop ends.
7. The global best value (gbest) holds the optimum position error.

4.2. Artificial Bee Colony

The ABC algorithm which was first used by Karaboğa in 2005 [24], was developed by inspiring food search exploits of honey bees. This swarm algorithm consists of three types of bees: a worker, onlooker and a scout. Worker bees store nectar from randomly generated food sources. Onlooker bees are distributed to the food sources according to the dances of the workers' bees and they continue to carry the nectar to the hive. If there is no more nectar to carry to the hive, the onlooker bees turn into scout bees and they randomly look for a food source [25].

$$x_{i,j} = x_j^{min} + rand(0,1)(x_j^{max} - x_j^{min}) \quad (7)$$

$$v_{i,j} = x_{i,j} + \varphi_{i,j}(x_{i,j} - x_{k,j}) \quad (8)$$

$$P_i = fit_i / \sum_{j=1}^{N} fit_i \quad (9)$$

The inverse kinematic solution follows the following steps:

1. The number of bee population (p) and iterations (n) is determined.
2. Seven joint angles are randomly determined for each member of the population (Eq. 7).
3. The population loop is initiated (employed bees).
   - 3.1. The position error of each member in the population is calculated.
   - 3.2. The lowest value of the position error is stored in the memory as the global best value.
4. The population loop is finished.
5. The iteration (n) loop is started.
   - 5.1. The population (p) loop is initiated (onlooker bees).
     1. Neighboring food sources are searched by onlooker bees (A randomly selected joint angle is changed according to Eq. 8.).

2. The position error is calculated according to the new situation.
3. If the new position error is less than the old value, it is chosen as the best value. Otherwise, the possibility of abandonment of the food source is increased.

5.2. The population loop is finished.
5.3. If the probability of abandonment of the food source of each member of the population is exceeded, the scouts are sent to a random food source.
5.4. The local best value is compared to the global best value.

6. The iteration loop is finished.

4.3. Firefly Algorithm

This swarm optimization technique is an algorithm that is based on the natural behavior of fireflies in tropical climate regions. These fireflies use their lights to give fear to the enemy and to attract other fireflies [26]. Firefly whose light is brighter than the others, are the closest to solving. This algorithm was first used by Yang in 2008 [27].

$$I = I_0 e^{-\gamma r^2} \tag{10}$$

$$\beta = \beta_0 e^{-\gamma r^2} \tag{11}$$

$$r_{ij} = \|x_i - x_j\| = \sqrt{\sum_{k=1}^{d} (x_i - x_j)^2} \tag{12}$$

$$x_i = x_i + \beta_0 e^{-\gamma r^2}(x_j - x_i) + \alpha \varepsilon_i \tag{13}$$

The inverse kinematic solution follows the following steps:

1. The number of particle (p) and iterations (n) is determined.
2. Seven random joint angles are created for each particle.
3. The position error of the particles is calculated and the local best value (Pbest) is found.
4. The iteration (n) loop is started.
   a. The particle (p) loop is started. (first loop-i)
      i. The particle (p) loop is started. (second loop-j)
      ii. Pbest[j] is less than Pbest[i]?
         1. The distances of the joints to each other are found (Eq. 12)
         2. The coefficients in Eq. 10 and Eq. 11 are calculate
         3. The seven joint angles belonging to the i. particle are approximated to the j. particle (Eq. 13).
         4. The new position error value of the particle is calculated.
      iii. All Pbest values are compared and the best Pbest value is found.
   b. All Pbest values are sorted from small to large.
5. The smallest value is stored as Gbest.
6. The iteration (n) loop is finished.

5. COMPARISON OF THE OBTAINED RESULTS

The data obtained regarding the studies examined in this study are presented in Table 2 in detail.

Table 2. Comparison of the techniques studied in the literature

Paper	Robot Arm	Used Technique	Comparative Technique	
[13]	6-DOF	Bee	PSO	
		6.31e-13	3.32e-08	Error
		0.0286 s	0.0361 s	Time
[15]	3-DOF	10 Firefly	60 Firefly	
		1.27e-17	1.78e-18	Error
		1.21e-03 s	7.15e-3 s	Time
[16]	6-DOF	PSO	HSA	
		3.32e-08	2.31e-04	Error
		0.0361 s	0.376 s	Time
[17]	4-DOF	PSO	GA	
		7.70e-06	3.96e-04	Error
		0.0196 s	0.1753 s	Time
[18]	7-DOF	PSO	-	
		2.24e-2	-	Error

The inverse kinematic calculations, researchers focused on the position error of the end element and obtaining time of the coordinates of the correct point. PSO algorithm has been widely used in inverse kinematic calculations because it has powerful search features and is an easy to apply technique. Although the PSO algorithm is widely used, the bee and firefly algorithms produce much better results than the PSO technique.

6. CONCLUSION

Swarm algorithms such as particle swarm optimization, artificial bee colony and firefly algorithm are very effective in inverse kinematics calculations as well as in many applications. Researchers which used swarm algorithms have first turned their problems into a fitness function. In this study the use of these algorithms is described in their step-by-step manner. In the narration, a robot arm that he has seven joint was sampled. Kinematic analysis of this robot arm was performed and the fitness function was established by using the equations which emerged as the result of these analyzes. Thus, the study carries the characteristics of a horizon for researchers who will use these algorithms in their studies.

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