Inverse Kinematic of Biped Robot Based Simulated Annealing

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ABSTRACT

Biped robot has become more general purpose in our live as general behavioral patterns. It can walk very similar to human walking pattern. Therefore, many robots have been researched and developed in recent years. Through this paper a planner biped robot is modeled for specific task. This paper tries to explore the potential of using Simulated Annealing (SA) methodologies in the Inverse Kinematic Problem (IKP),utility and effectiveness of this method for the solve IKP of biped robot is presented. It presents a new objective function to find the optimal posture of biped robot by employing some constrain in the objective function to meet best posture. A comparison between the proposed method and the classical method using Genetic Algorithm (GA) are made through the Matlab 2009a software to show the efficiency of the new method. Experimental results demonstrate that better performance can be achieved with this method.

Keywords: Biped Robot, Inverse Kinematic, Simulated Annealing

حل المشكلة العكسية للانسان الالي ذوالقدمين باستعمال طريقة التلدين المقلد

الخلاصة

الإنسان الآلي ذو القدمين اصبح أكثراً عموميةً في حياتنا بشكل مباشر كأنماط سلوكية عامّة.حيث يتمكن من تقليد مسير لانسان بشكل كبير لذلك عدة انواع درست و طورت. هذا البحث نحاول ايجاد مخطط لهذا الانسان الالي لاداء مهمة معينة حيث يتم استعمال طريقة التلدين المقلد لمنهجياتِ المشكلةِ الحركيّةِ المعكوسةِ ، وبيان جودة هذه الطريقة. دالة موضوعية جديدة تم اقتراحها لإيجاد الموقفِ المثاليِ للإنسان الآلي ذو القدمينِ باستخدام بعض القيود ضمن الدالة لتحقيق افضل موقف. تمت مقارنة الطريقة المقترحة مع الطريقة التقليدية خلال ماتلاب 2009 a لاظهار كفاءةِ الطريقةِ الجديدةِ. بينت النتائج كفاءة الطريقة المقترحة.

INTRODUCTION

The word “Robot” first appeared in 1920 describing the perfect worker. It was only possible to actually develop a mechanical man after the invention of integrated circuits. The compact and electrically advanced IC’s were able to give some sense of supervised intelligence to mechanical parts. The beginning of research on biped robots began with the development of the lower limb of a robot.

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Since then the biped robots have come a long way; in present time the biped robot can perform various actions such as walking, running [1].

The development of legged locomotion systems has recently received an increased attention due to their higher mobility than conventional wheeled vehicles. Legs are adapted to environments allowing the machine to stride over obstacles. The biped robots are an important branch of the legged robots, which are based on human oriented facilities. They are awaited to imitate human behaviors and locomotion abilities, e.g. getting up and down stairs and ladders, passing uneven and rough grounds. Some of these demands, which are not achievable by the wheeled robots, emphasize more on the use of the biped robots. These new demands together with the new concepts in the biped robots field demand applying new and well adapted motion control approaches. As much as these methods are inspired by human walking algorithms, the expectations of the biped robot would be satisfied more [2].

A biped robot can be considered with an upper main body, linking two arms, a neck and a head, or as a combination of multiple manipulators, which are themselves linked together through waist and neck joints to emulate a human’s functions. Because of its human-like, bipedal movement, the kinematic structure of a humanoid robot has no fixed root node and has a large number of degree-of-freedoms (DOF). Since the robot servo system requires the reference inputs to be in joint coordinates and a task is generally stated in the Cartesian coordinate system, controlling the position of the end point a leg of a biped robot requires the understanding of the inverse kinematic joint solution of a biped robot [3].

This paper focuses on applications of soft computing for the inverse kinematic of planner biped robot like simulating the task of walking by specifying the position its feet in task space coordinates, that result stable walking which is as “close” as possible to human walking.

INVERSE KINEMATIC PROBLEM

A rigid multibody system consists of a set of rigid objects, called links, joined together by joints. Well-known applications of rigid multibodies include biped robots which are complex mechanisms composed by serial kinematic chains with some degree of redundancy. The most interesting movement tasks for this kind of systems, such as walking, are defined in the task space. This space is different from the joint space where motor commands must be issued. Hence, movement planning requires appropriate coordinate transformations from task to joint space before motor commands can be calculated.

The transformation from kinematic plans in task space coordinates to joint coordinates is the classic; a problem that originates from the fact that inverse transformation is often ill-posed. Therefore, to control the movement of a rigid multibody, it is common to use IKP [4]. The problem of inverse kinematics is not linear, as rotations are involved. This means that analytical solutions are only available in limited situations. In all other cases, alternative methods will have to be employed. The most-used alternative is numerical solutions. Analytical solutions are the best option to use when available, as they are the fastest and most reliable inverse kinematics solvers. The problem of analytically solving inverse kinematics is that it does not scale to more complex bone sets and is therefore only an option for simple situations. The numerical solution that can be utilized to solve the inverse kinematics problem is through the use of existing optimization algorithms. The problem is formulated as an optimization problem and the optimization itself is considered to be a black box that returns the resulting transformation of the manipulator [5].

Traditional derivative based optimization methods are fast and accurate for many types of optimization problems. These methods are designed to solve continuous and differentiable minimization problems, as they use derivatives to determine the direction of descent. However, using derivatives is often ineffective with discontinuous, nondifferentiable or stochastic objective functions. For nonsmooth problem, soft computing are effective alternatives Genetic algorithms are stochastic search algorithm inspired by the principle of natural selection and natural genetics.

Simulated Annealing (SA) is motivated by an analogy to annealing in solids. The algorithm simulates the cooling process by gradually lowering the temperature of the system until it converges to a steady [6].

GENETIC ALGORITHM

GA is a stochastic search optimization technique based on the mechanisms of natural selection. Recently, GA has been recognized as an effective and efficient technique to solve optimization problems.GA starts with an initial population containing a number of chromosomes where each one represents a solution of the problem which performance is evaluated by a fitness function. Basically, GA consists of three main stages: Selection, Crossover and Mutation. The application of these three basic operations allows the creation of new individuals which may be better than their parents. This algorithm is repeated for many generations and finally stops when reaching individuals that represent the optimum solution to the problem [7]**.**

Optimization of IKP firstly needs design the optimization goal, and then encode the parameters to be searched. Genetic operator is running until the stop condition is satisfied. To obtain the optimal performance, the following implementations of the genetic algorithm are used [8].

A. Representation of Parameters

The real coding technique is used to represent a solution to a given problem. In real coding implementation, each chromosome is encoded as a vector of real numbers. According to IKP, joint angles are required to be computed in this research.

B.Crossover

Arithmetic crossover takes two parents and performs an interpolation along the line formed by the two parents. It is constructed by borrowing the concept of linear combination of vectors from the area of convex sets theory. When applying affine and linear crossovers to a particular problem, the absolute values of multipliers should be restricted to be below an upper bound according to the domain constraint in order to force genetic search within a reasonable area. Crossover uses the linear crossover with probability 0.85.

C.Mutation

Mutation adopts dynamic mutation, also called nonuniform mutation; it is designed for fine-tuning capabilities aimed at achieving high precision. Non-uniform mutation changes one of the parameters of the parent based on a non-uniform probability distribution. This Gaussian distribution starts wide, and narrows to a point distribution as the current generation approaches the maximum generation.

SIMULATED ANNEALING MECHANICS

Simulated annealing is a random search technique which to use an analogy between the way in which a metal cools and freezes into a minimum energy crystalline structure and the search for a minimum in a more general system; it forms the basis of an optimization technique nonlinear problems. The technique has been widely applied to a variety of problems. The main advantages and robustness over other search methods are its flexibility and its ability to approach global optimality [9]. The flow chart of a basic SA method is illustrated in Figure (1), and it can be described by the following steps [10]:

1. Define an objective for an optimization of the tested problems.
2. Define parameters of the algorithm; i.e. a starting temperature, a freezing temperature, a reducing rate and iteration.
3. Random a starting point with 'k' variables related to size of the tested problems. Then calculate the responses by replacing variables (*X1, X2, ... Xk*) with random values as a starting point (*s*).
4. Create an anneal schedule from a starting temperature and a reducing rate; i.e. the starting temperature is 2^{o}C, the reducing rate is 0.9 then the next anneal temperature is equal to 1.8^{o}C.
5. Set a counter for iteration in each anneal temperature.
6. Calculate the neighbor responses (*sn*) from the anneal schedule by replacing a variable (*Xi*) of the tested problem.

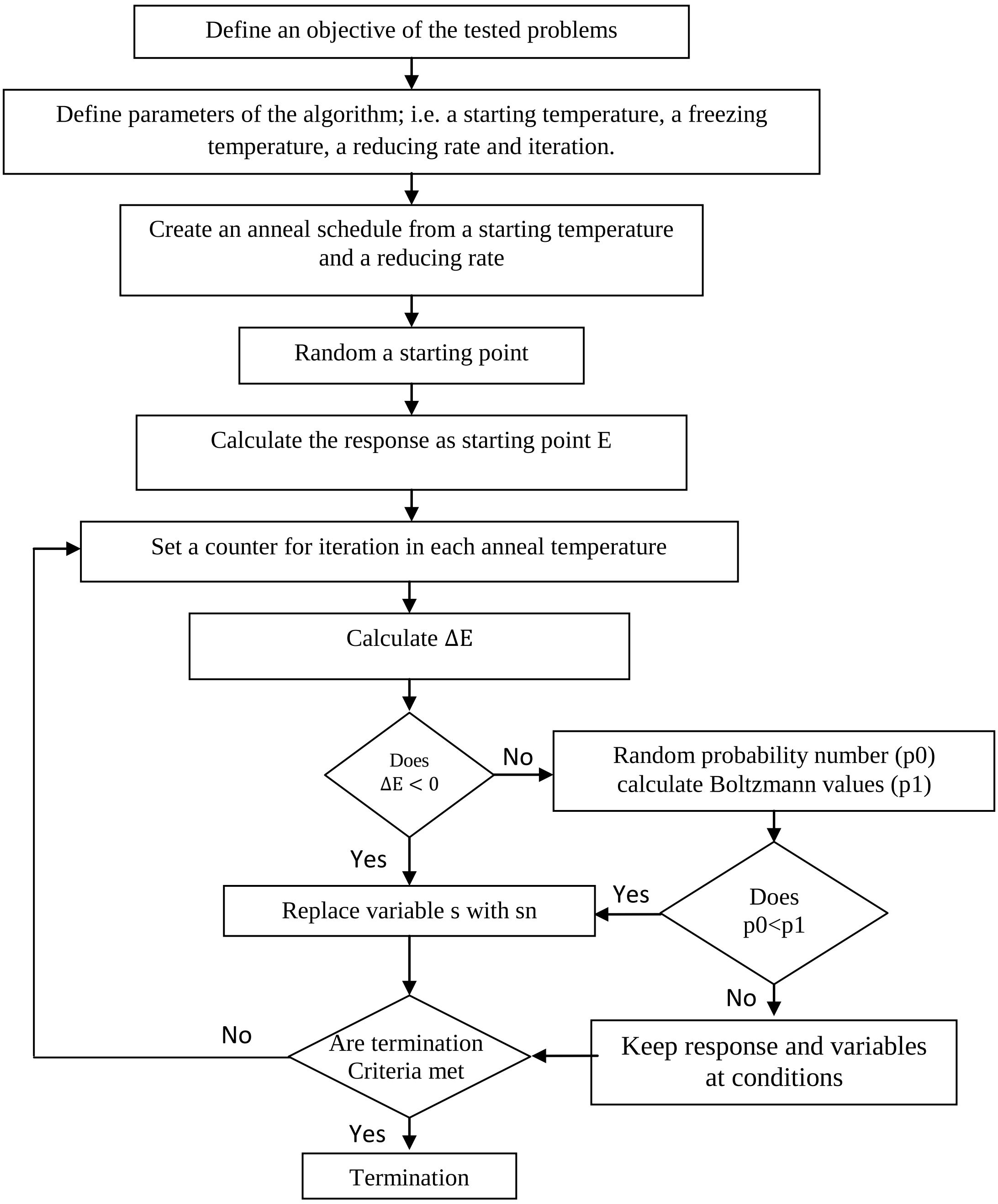

Figure (1) Flow Chart of Simulated Annealing Algorithm [10].

7. Compare the calculated responses in step 3 and 6 then calculate a value of ΔE by *sn* - *s*. If ΔE is less than 0, replacing variables at condition *s* with *sn*.
8. On the other hand, if the calculated value of ΔE is greater than 0, random the probability number (*p1*) to compare with Boltzman value (*P0*) where Boltzman (*p0*) = *exp* (ΔE /*T*)

9. If the probability number (*p0*) is less than Boltzman value (*p1*), replacing variables at condition *s* with *sn*.
10. Do step 6-9 until an iteration criterion is reached.
11. Calculate next anneal temperature as describe in step 4.
12. Do step 5-11 until the anneal temperature is less than the freezing temperature. Then a termination criterion has been reached.

It can be seen that the SA algorithm can simulate the procedure of gradually cooling a metal until the energy of the system achieves the global minimum. The candidate is updated through the random perturbation, and the improvement of its fitness is calculated. If $sn \leq s$, the moving change results in a lower or equivalent energy of the system, and the new solution is accepted. Otherwise, the displacement is only accepted with a probability *p1*

$$p1 = e^{-\frac{sn-s}{T}} \qquad \dots (1)$$

The temperature is updated by:

$$T(k+1) = \lambda T(k),\ 0 < \lambda < 1 \qquad \dots (2)$$

Where k is the number of generations. T is temperature ,As a matter of fact, the cooling schedule can be adjusted by modifying parameter λ. The SA method is terminated when the final temperature is sufficiently low, which makes it reach the global optimal solution with a high probability. The probability dependent acceptance policy for the new solutions helps the SA algorithm in the solution exploitation. [12].

WALKING STRATEGY

The most crucial step in applying soft computing is to choose the objective functions that are used to evaluate fitness of each individual. Optimizing the objective function while satisfying the constraints, forces the robot to become stable and perform a desired walk. a set of equality and inequality constraints will be established in this section. Some constraints help us to force the biped robot to walk.

1) The joint constraints: $qi_{\min} \leq qi \leq qi_{\max}$
2) The level constraint guarantees the biped to maintain its erected posture during the locomotion;
3) The swing foot has to remain above the ground level at all times $ye \geq 0$ [2].

KINEMATICS OF BIPED ROBOT MODEL

For the kinematics analysis of the biped robot, the coordinate system is shown in Figure (2). This proposed model is composed of 4 degree of freedom (DOF) .The D-H Notation adapted in this paper is widely used in the transformation of coordinate systems of linkages and robot mechanisms. The planner biped has four links, yielding a configuration space with coordinates:
$q = (q1, q2, q3, q4)$ Where, as illustrated in Figure (2), q1 is the angle of the stance foot, q2 is the angle of the stance knee, q3 is the angle of the hip and q4 is the angle of the non-stance (or swing) knee [12]. where a1=a2=a3=a4=25 cm .It can be used to represent the transformation matrix between links. The D-H

Notation can be shown in Table 1, and, from it, the matrix of final position of foot can be computed;

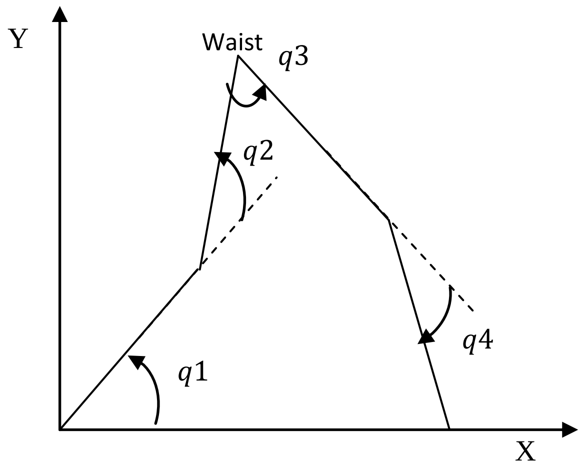

Figure (2) planner biped robot model [12].

Table (1) D-H Parameters of Biped robot.

Frame (joint)	q_i(rad)	d_i(cm)	a_i(cm)	α_i(rad)
1	q_1	0	a1	0
2	q_2	0	a2	0
3	$q_3 + \pi$	0	a3	0
4	$-q_4$	0	a4	0

The final form of matrix *A* is:

$$A_i = \mathrm{Rotat}_{z,q_i} * \mathrm{Translation}_{z,d_i} * \mathrm{Rotat}_{x,\alpha_i} * \mathrm{Translation}_{x,a_i}$$

$$= \begin{bmatrix} \cos(q_i) & -\sin(q_i) & 0 & 0 \\ \sin(q_i) & \cos(q_i) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} * \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} * \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos(\alpha_i) & \sin(\alpha_i) & 0 \\ 0 & \sin(\alpha_i) & \cos(\alpha_i) & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} * \begin{bmatrix} 1 & 0 & 0 & a_i \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$=\begin{bmatrix} \cos q_i & -\cos\alpha_i \sin q_i & \sin\alpha_i \sin q_i & a_i \cos\alpha_i \\ \sin q_i & \cos\alpha_i \cos q & -\sin\alpha_i \cos q_i & -a_i \sin\alpha_i \\ 0 & \sin\alpha_i & \cos\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad \ldots (3)$$

It has the following transformation matrices

$$A_1 = \begin{bmatrix} c_1 & -s_1 & 0 & a_1 c_1 \\ s_1 & c_1 & 0 & a_1 s_1 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, A_2 = \begin{bmatrix} c_2 & -s_2 & 0 & a_2 c_2 \\ s_2 & c_2 & 0 & a_2 s_2 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix},$$

$$A_3 = \begin{bmatrix} -c_3 & s_3 & 0 & -a_3 c_3 \\ -s_3 & -c_3 & 0 & -a_3 s_3 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, A_4 = \begin{bmatrix} c_4 & s_4 & 0 & a_4 c_4 \\ -s_4 & c_4 & 0 & -a_4 s_4 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Where 'c' is cosine of theta and 's' is sin of theta
The final transformation matrix is
$A=A_1*A_2*A_3*A_4$. The forward kinematic of human arm is represented by

$$A = A_1 * A_2 * A_3 * A_4 = \begin{bmatrix} nx & ox & ax & px \\ ny & oy & ay & py \\ nz & oz & az & pz \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad \ldots (4)$$

Where

px= a1*c1 + a2*c1*c2 - a2*s1*s2 - a4*c4*(c3*(c1*c2 - s1*s2) - s3*(c1*s2 + c2*s1)) - a4*s4*(c3*(c1*s2 + c2*s1) + s3*(c1*c2 - s1*s2)) - a3*c3*(c1*c2 - s1*s2)+ a3*s3*(c1*s2 + c2*s1) … (5)

py= a1*s1 + a2*c1*s2 + a2*c2*s1 - a4*c4*(c3*(c1*s2 + c2*s1) + s3*(c1*c2 - s1*s2)) + a4*s4*(c3*(c1*c2 - s1*s2) - s3*(c1*s2 + c2*s1)) - a3*c3*(c1*s2 + c2*s1) - a3*s3*(c1*c2 - s1*s2) … (6)

pz=0 … (7)

The transfer matrix *A* is composed of both the two rotation matrix and the two translation one. The position that we try to find, is the last coordinate of the tip of the foot. Therefore, it is acquired by multiplying the entire matrix A [13].

Using a forward kinematics we can calculate the position of the tip of the foot when there is presented all values of the angle of each joint. Whereas in the opposite case, that is, when we know the position of the tip of the foot and don't know all values of the angle of each joint, can't we use the inverse determinant of the matrix *A*. The inverse matrix *A* can't be used because the matrix *A* is composed of the non-linear factor. So, for the solving this problem, it is adapted with the theory of the optimization methods [13].

PROPOSED METHOD FOR IKP.

In our work, a planner bipedal robot is considered see Figure (2). The motivation for considering this specific model is that it is simple enough to make the discussion of ideas related to human-inspired control more concise, while being complex enough to display interesting behavior.

Since the soft computing depends only on the objective function to guide the search, it must be defined before the soft computing is initialized. The IKP can be considered as an optimization problem of the objective function stated as follows:

$$fitness(q) = \begin{bmatrix} \left|px^d - px(q)\right| \\ \left|py^d - py(q)\right| \end{bmatrix} \qquad \dots (8)$$

To provide stable walking for biped robot , the fitness function should be has the constrain as shown in the following function.

$$propsed\ fitness(q) = \begin{bmatrix} \left|px^d - px(q)\right| \\ \left|py^d - py(q)\right| \\ 1/py_w \\ \left|px^d - px_w\right| \end{bmatrix} \qquad \dots (9)$$

Where px^d , py^d represents desired position of the feet.
$px(q)$, $py(q)$ represents actual position of the feet.
px_w, py_w Represents actual position of the waist.

RESULT AND DISCUSSION

In order to validate the proposed objective function in this paper, the desired position of the end point is set

$$p = \begin{bmatrix} px^d \\ 0 \\ 0 \end{bmatrix} \qquad \dots (10)$$

Where px^d is changed from 12.5 cm to 37.5 cm. Apply the objective function (Eq.8) using genetic algorithm to find the joint angles of biped robot $(\mathrm{q1}, \mathrm{q2}, \mathrm{q3}, \mathrm{q4})$, The parameters of GA which are used to find the constants $(\mathrm{q1}, \mathrm{q2}, \mathrm{q3}, \mathrm{q4})$ are chosen:
Number of generations=50, No. of variables =4, Chromosome length per variable=20, Number of population =20, Probability of crossover = 0.8, Probability of mutation = 0 .01.

Apply these angles in the equations (5-6) to find actual position, compare the obtained result with the proposed method. Figure. 3 shows the trajectory of all methods.

The objective function equation (8) which represent classical objective function for optimization algorithm try to find the minimum error regardless the posture of the robot .The proposed method try to find the optimal posture with minimizes the error .This make the posture of the proposed method has optimal posture compared with the classical method. With the new objective the GA and SA methods are comparing to show the effective of the SA.

From the simulation results Table (2), it can be noticed that, the classical objective provides minimum error but posture of robot isn't stable and inefficient walking. With the new objective the performance of walking becomes better; to show the powerful of SA with respect to GA the new objective is running with these methods. As shown in figure.3 the SA has a good search method by comparing with GA especially in Figure (3. a, c, e).

Table (2) Norm of error between desired and actual position (meter).

Classical objective	New objective with GA	New objective with SA
0.0250	0.0203	0.0002
0.0016	0.0202	0.0027
0.0261	0.0182	0.0035
0.0217	0.0065	0.0012
0.0003	0.0247	0.0115
0.0016	0.0130	0.0042

CONCLUSIONS

In general, numerical methods are important alternative in the solution of IKP, whose mathematical model appears to be extremely complex. In this paper, IKP has been transformed into an optimization problem with a good objective function to meet optimal posture of biped robot. The IKP based on classical objective function, GA and SA using suitable objective function has been performed. From the simulation result can be concluded that, employing some constrain in the objective function can be improve the performance of the system as shown in the result also the SA has a good search method by comparing with GA .

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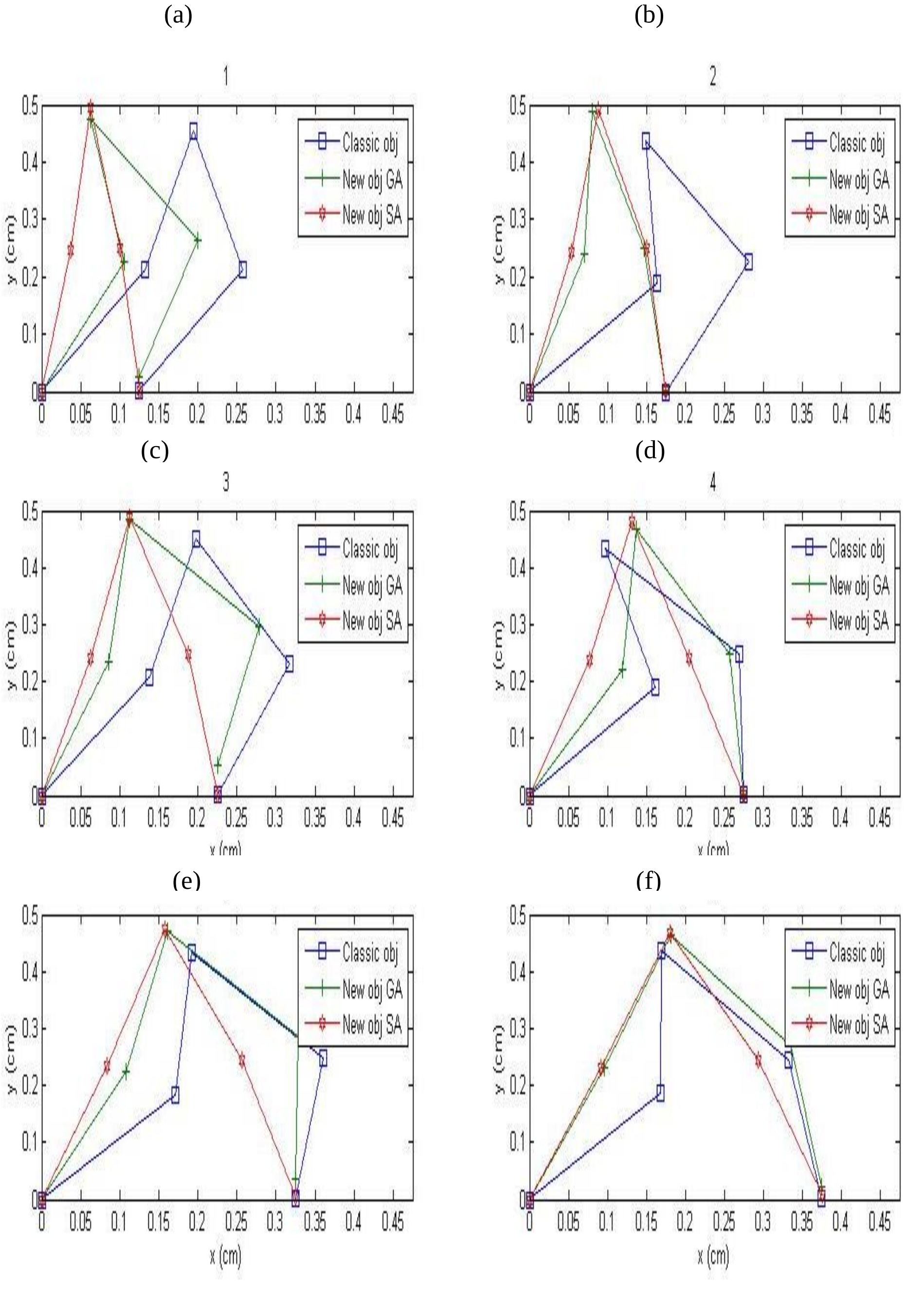

Figure (3) Trajectory of Biped Robot with different methods.