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Research of Modified Ternary Search Algorithm and Its Applications

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Abstract: Based on dividing the given interval into three parts, a ternary search is an algorithm in computing science for finding the minimum or maximum of a unimodal function. In this paper, the interval scaling factor is introduced to optimize the original ternary search algorithm. During searching the solution to the extremum value in a function that is either strictly increasing and then strictly decreasing or vice versa, the optimized ternary search algorithm can significantly reduce the iterations and achieve the purpose of saving computing time. The solution to the shortest distance between any two points on the cylinder surface is carried out to test its performance. Compared with the original ternary search algorithm and genetic algorithm, the results demonstrate that the optimized ternary search algorithm is superior to them.

Keywords: Optimized ternary search algorithm; The shortest distance between two points; Time cost; Genetic algorithm;

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1 Introduction

The research of the shortest distance between two points on the geometry surface has a long history . By the end of the last century, some scholars had studied the shortest path of any two points on the surface of the cuboid. In 1996, Gardener, M. unfolded the cuboid and calculate the shortest distance of the ants crawling on the cuboid surface[5]. In 1999, Wolfe, D. and Rodgers, T. discussed this problem and the different ants' paths when the cuboid unfolded in different ways [18]. For some geometries whose sides are flat surface(eg. prism and pyramid), the shortest distance between two points on their surface can be solved by unfolding them.

However, for some geometries whose sides are curved surface (eg. cone and cylinder), the above method is not useful, because the points will be changed when we unfold them. In fact, the equations of distance between two points on these geometry surfaces are difficult to solve. Generally, these equations are nonlinear. Nowadays, the solution to nonlinear equation has always been a difficult problem in mathematics[8]. With the development of computer technology, some traditional algorithms (eg. Newton's method, binary search and secant method) can be adopted to approximate the optimal solutions [17]. In these methods, numerical tests show that Newton's method is one of the methods of faster convergence[25].

Newton's method finds better approximations to the roots of a real-valued function. It requires that the derivative be calculated directly. However, in practice, we can only obtain the discontinuous function. Furthermore, an analytical expression for the derivative may not be easily obtainable and could be expensive to evaluate. The process of searching extreme is actually complicated by Newton's method [23]. In real application, ternary search algorithm is more

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straightforward to approximate extreme of unimodal function in set interval [1, 2]. So it is better than Newton's method at this point.

Some heuristic algorithms(eg. a genetic algorithm [10], a particle swarm optimization [12] and a simulated annealing algorithm [20] etc.) can solve the nonlinear equations. In computer science and operations research, a genetic algorithm simulates the biological species in the best choice, the survival of the fittest, and approach to the solution in tolerance scope by means of approximation. It is a metaheuristic inspired by the process of natural selection that belongs to the larger class of evolutionary algorithms. Meantime, genetic algorithm is commonly used to generate high-quality solutions to optimization and search problems. Some scholars have proposed many methods to improve genetic algorithm in nonlinear equation. For example, several classical algorithms are introduced to overcome the shortage of initial point selection for it [13]. By adding the heterogeneous strategy, Yan, L.W. and Chen, S.H. speed up genetic algorithm process of convergence and increase the probability of converging global optimal solution [21].

Particle swarm optimization and simulated annealing algorithm are also an effective way to find the answer to nonlinear equation. Particle swarm optimization is a computational method that optimizes a problem by iteratively trying to improve a candidate solution with regard to a given measure of quality. It solves a problem by having a population of candidate solutions, here dubbed particles, and moving these particles around in the search-space according to simple mathematical formulae over the particle's position and velocity. It is also evaluate the quality of the solution by the fitness, but it is more simple than the genetic algorithm rules without crossover and mutation. Jaberipour,M., etc. propose a new particle swarm optimization algorithm to solve systems of nonlinear equations[9]. Based on the thermodynamic annealing mechanism and simulating annealing process, the simulated annealing algorithm is put forward by Metropolis. When given an initial temperature, the optimal solution of the nonlinear function can be approximated by slowly decreasing the temperature parameter[3]. Jr., H.A. and Petraglia, A. use fuzzy adaptive simulated annealing to solve a solution for arbitrarily nonlinear systems of dangerous equations through stochastic global optimization [11]. However, due to the arbitrariness of the initial selection, it is not easy to make the search process into the most promising search area, so that the efficiency of simulation annealing is not high. Wu, L.L. etc. introduced the evolutionary strategy, optimized the simulated annealing algorithm, and effectively overcame the initial point of sensitivity and low efficiency[19]. Moreover, there are other heuristic algorithms like hybrid artificial bee colony algorithm [24], foraging algorithm [7] and some new technique for solving a system of nonlinear equations[6, 14, 15, 22].

Combined with these researches, heuristic algorithms actually can solve such problems. But in dealing with binary, ternary and other less unknown multiple functions and practical problems, the traditional algorithms (eg. a ternary search, Newton's method, binary search and secant method) are direct and simple. Nevertheless, heuristic algorithms need for operators to have a good professional mathematical knowledge. Hence, it's not easy to promote them due to some limitations. What's more, many practical problems are transformed to solve systems of nonlinear equations, such as application in physics, chemistry, economics, computational mechanics, aircraft control and so on . Because of these above researches and viewpoints, in this paper, we put forward the improved algorithm based on the existing ternary search algorithm, and applies it to some fields.

The rest of this paper is organized as follows: the way of optimizing the ternary search algorithm in section 2; the shortest distance on cylinder and cone surface in the analytical solution in section 3; the usage of ternary search algorithm for its value solution and the data for numerical simulation in section 4; the brief introduction of its application in surgery in section 5; and conclusion in the last section.

2 Optimized ternary search algorithm.

2.1 The ternary search algorithm and its optimization

A ternary search algorithm (TSA) is a technique in computer science for finding the extreme value of unimodal functions. It is dividing the given interval into three parts and comparing the function value of each dividing point. After iteration step by step, the interval including extreme value is narrowed gradually until the given precision is satisfied. Here, we discuss the minimum process by TSA.

Let $f(x)$ is a convex function, $x_0 \in [a,b]$. $\forall x \in [a,b]$, when $x \neq x_0$, $f(x_0) < f(x)$. Let x_1, x_2 are the trisecting points in [a,b], they satisfy the following equation (Eq.1).

$$\begin{cases} x_1 = a + (b-a)/3 \\ x_2 = b - (b-a)/3 \end{cases} \tag{1}$$

Based on the criterion (Eq.2), the interval of extreme value can be cut down (Figure 1).

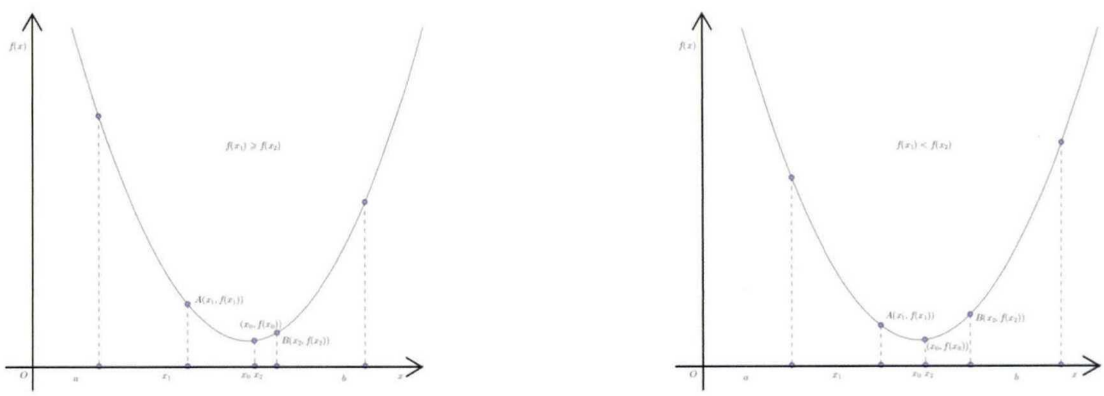

Figure 1: An iteration of TSA

$$x_0 \in \begin{cases} [x_1, b], & f(x_1) \geq f(x_2) \\ [a, x_2], & f(x_1) < f(x_2) \end{cases} \tag{2}$$

Then, let $a = x_1$ or $b = x_2$, repeat the above step, until the accuracy can be admitted.

In the process of each iteration of TSA, as long as the interval including the extreme point can be as small as possible, the iterations can be reduced, thus speeding up the convergence. Based on it, we put forward the optimized TSA (O-TSA) as follows.

$$\begin{cases} x_1 = (a+b)/2 \\ x_2 = (x_1 + \gamma(b - x_1)) \end{cases} \tag{3}$$

Here,γ is a constant, the latter steps are the same of TSA. In order to express them more clearly, the pseudo-codes of TSA and O-TSA are shown in the Algorithm 1..

2.2 Verify the convergence rate of O-TSA

In order to verify the performance of O-TSA, we randomly choose $f_1(x) = -x^2 + 1$ and $f_2(x) = -4\sin(x) - 6\cos(\frac{x}{2})$ to do a set of numerical experiments. Let the accuracy be $\varepsilon = 10^{-50}$,

Algorithm 1 TSA & O-TSA

Input: interval: $[a, b]$; objective function: $f(x)$; accuracy: ε; constant: γ .
Output: $minf(x_0), x_0 \in [a, b]$
while a - $b > \varepsilon$ **do**
  TSA: x_1=$a + (b - a)/3$; x_2=$b - (b - a)/3$
  O-TSA: x_1=$(a + b)/2$; x_2=x_1+$\gamma(b - x_1)$
  if $f(x_1) < f(x_2)$; b=x_2;
  else if $f(x_1) > f(x_2)$; a=x_1;
  else a=x_1; b=x_2;
end while
Return x_0 ; $f(x_0)$

the initial interval [-1,3]. We use TSA in the same PC with Python. The result shows that $f_1(x)$ and $f_2(x)$ meet the accuracy requirement after iterations of 289 and 145 respectively. And then, to O-TSA, the iterations are obtained by γ choosing $\frac{1}{2^1}, \frac{1}{2^2}, \frac{1}{2^3}, \cdots, \frac{1}{2^{30}}$ in the same accuracy and initial conditions respectively. The results are shown in Table 1 and Figure 2.

Table 1: The iterations of $f_1(x)$ & $f_2(x)$

Function \ γ	$\frac{1}{2^1}$	$\frac{1}{2^2}$	$\frac{1}{2^3}$	$\cdots$	$\frac{1}{2^{30}}$
$f_1(x)$	272	207	186	$\cdots$	169
$f_2(x)$	120	78	64	$\cdots$	18

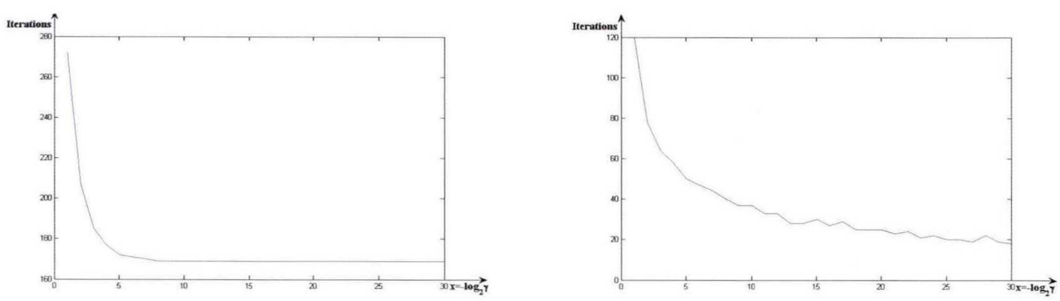

Figure 2: The iterations of different values of γ ($f_1(x)$(left),$f_2(x)$(right))

From table 1 and Figure 2, we can know that the iterations will be reduced when the γ lessen. Under the same condition, the reduction of iterations means the decrease of the calculation time. In the test, when the γ approaches a certain value, the iterations tend to be a constant. It's obvious that a certain iterations will be required to satisfy the accuracy even if each iteration can narrow the interval we expected. Due to the differences of the functions and the uncertainty of the initial interval and accuracy requirement, some values of γ might be perfect during the iteration.

3 Find the shortest distance between two points on the cylinder

3.1 Two points on the same bottom or side

These two cases are the simplest. Two points on the same bottom can directly compute the distance (Figure 3). If points are on the same side, we only need to expand the cylinder and compute (Figure 4). After the coordinates of C and D are known, applying the Pythagorean Theorem, we can get the distance between A and B .

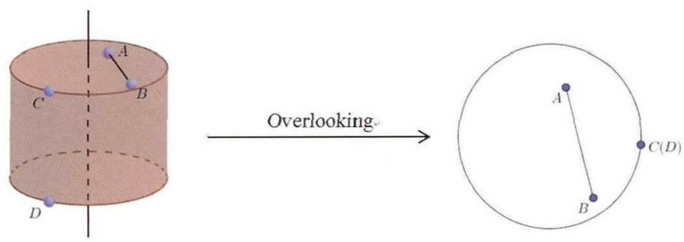

Figure 3: A,B on the same bottom

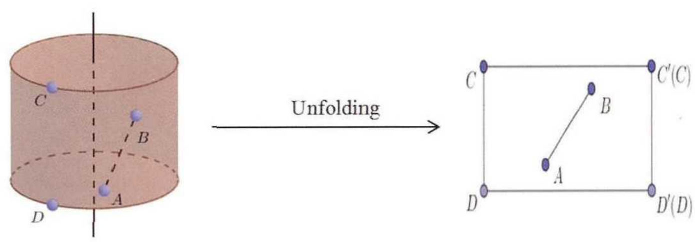

Figure 4: A,B on the same side

3.2 One point on the bottom and the other on the side

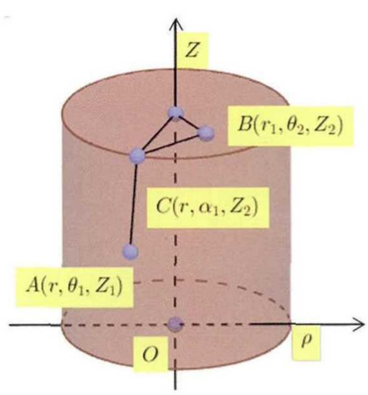

Figure 5: One point on the bottom and the other on the side

For this case (Figure 5), we can establish the cylindrical coordinate system with the origin of O [16]. C is waiting to be determined. In the cylinder, let r be its radius, Z_2 its height. A (r, θ_1, Z_1) and $B(r_1, \theta_2, Z_2)$ also are known. Obviously, in the intersection of bottom and side, there will be a point C satisfied the shortest distance between A and B. Let C be (r, α_1, Z_2). Using Pythagorean Theorem and Cosine Theorem, we can establish the objective function as follows.

$$Arg\,min\,F(\alpha_1) = \sqrt{r^2 + r_1^2 + 2rr_1\cos(\alpha_1 - \theta_2)} + \sqrt{(|(\alpha_1 - \theta_1)|r)^2 + (Z_1 - Z_2)^2} \tag{8}$$

Let the derivative of $F(\alpha_1)$ be equal to 0:

$$\frac{dF}{d\alpha_1} = \frac{rr_1\sin(\alpha_1 - \theta_1)}{\sqrt{r_1^2 + r^2 + 2rr_1\cos(\alpha_1 - \theta_2)}} - \frac{r(\alpha_1 - \theta_1)^2}{\sqrt{(Z_1 - Z_2)^2 + (r(\alpha_1 - \theta_1))^2}} = 0 \tag{9}$$

From Eq.9, we can obtain the value of α_1. In fact, there is a minimum distance between A and B on the cylinder surface. Thus, its numerical solution can be computed by O-TSA.

3.3 Two points on the different bottoms

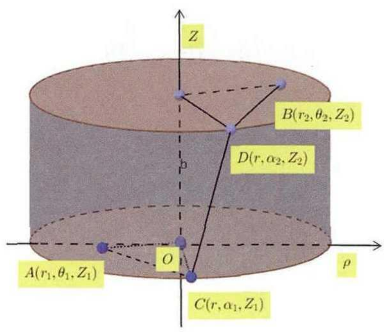

Figure 6: Two points on the different bottoms

In this case (Figure 6), we have to determine two points on the edges of the different bottoms to find the shortest distance between A and B. Let $A(r_1, \theta_1, Z_1)$ and $B(r_2, \theta_2, Z_2)$ be known. Assume C to be (r, α_1, Z_1), D (r, α_2, Z_2). We can obtain the objective function as follows.

$$\begin{aligned} Arg\,min\,F(\alpha_1, \alpha_2) = &\sqrt{r^2 + r_1^2 + 2rr_1\cos(\alpha_1 - \theta_1)} + \sqrt{r^2 + r_2^2 + 2rr_2\cos(\alpha_2 - \theta_2)} \\ &+ \sqrt{(|(\alpha_1 - \alpha_2)|r)^2 + (Z_1 - Z_2)^2} \end{aligned} \tag{10}$$

Partial derivative and solving α_1 and α_2:

$$\begin{cases} \dfrac{\partial F}{\partial \alpha_1} = \dfrac{rr_1\sin(\alpha_1 - \theta_1)}{r_1^2 + r^2 + 2rr_1\cos(\alpha_1 - \theta_1)} - \dfrac{r^2(\alpha_1 - \alpha_2)}{\sqrt{(Z_1 - Z_2)^2 + (r(\alpha_1 - \alpha_2))^2}} = 0(\alpha_1 - \alpha_2 > 0) \\ \dfrac{\partial F}{\partial \alpha_2} = \dfrac{rr_2\sin(\alpha_2 - \theta_2)}{r_2^2 + r^2 + 2rr_2\cos(\alpha_2 - \theta_2)} - \dfrac{r^2(\alpha_1 - \alpha_2)}{2\sqrt{(Z_1 - Z_2)^2 + (r(\alpha_1 - \alpha_2))^2}} = 0(\alpha_1 - \alpha_2 > 0) \end{cases}$$

α_1 and α_2 can be received by solving the simultaneous equations. We need to know whether the matrix $\Sigma(\alpha_1, \alpha_2)$ is a positive definite matrix or a negative one to determine whether the solution is a maximum or a minimum. It can be seen that the analytic solutions to two unknown quantities are not easily obtained. Furthermore, We can' t also give an effective way by Matlab. Therefore, O-TSA is used to gain the numerical solution.

$$\Sigma(\alpha_1,\alpha_2)=\begin{vmatrix}\frac{\partial^2 F}{\partial\alpha_1^2} & \frac{\partial^2 F}{\partial\alpha_1\partial\alpha_2}\\ \frac{\partial^2 F}{\partial\alpha_2\partial\alpha_1} & \frac{\partial^2 F}{\partial\alpha_2^2}\end{vmatrix} \tag{11}$$

4 Numerical simulation

In this section, we will carry out O-TSA to verify the performance of computing time in numerical simulation. In order to make a comparison, TSA and genetic algorithm (GA) are also dealing with the shortest path between two points on the cylindrical surface. In the same machine, the codes are designed by Python.

Algorithm 2 Solving the extreme value of bivariate function

Input: interval: $[\theta_1,\theta_2]$; objective function: $f(x_1,x_2)$; accuracy: ε; $count=0$.
Output: the shortest distance between two points: S; α_1; α_2

$\alpha_1=\theta_1$;
let C(r, θ_1, Z_2) as initial point.
use algorithm 1, compute S_1 and α_2
$count = count{+}1$;
use algorithm 1, compute S_2 and α_1.
let D(r, α_2, Z_2) as initial point.
$count = count + 1$;
while S_1 - $S_2 > \varepsilon$ **do**.
    $S_1 = S_2$;
    if mod(count,2)==1 **then**
        using algorithm 1, compute α_1;S_2;
    else
        using algorithm 1, compute α_2;S_2;
    end if
    $count = count + 1$;
end while
$S=S_1$
Return α_1; α_2; S .

Firstly, we simulate the case where one point is on the bottom and the other is on the side (Figure 7). Randomly, let the radius of a cylinder be $5cm(r=5cm)$, A (5,–30°,5), B(3,30°,10). Compute the shortest distance between A and B on the cylinder surface. Using O-TSA, TSA and GA, we can compute the shortest distance $AB = 8.4662cm$ and $\alpha = 33.28^o$. Obviously the results are realistic and consistent with the analytical solution. The time cost of these three methods is shown in Table 2.

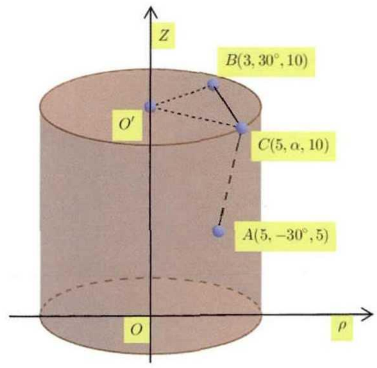

Figure 7: Numerical simulation 1 on the cylinder surface

Table 2: Time cost of the three methods in simulation 1

	O-TSA	TSA	GA
1	0.0032	0.0115	0.1953
2	0.0023	0.0163	0.1779
3	0.0028	0.0245	0.1932
4	0.0021	0.0168	0.1746
5	0.0027	0.0159	0.1673
average	0.0026	0.0170	0.1817

Then, we simulate another case that two points are on the different bottoms (Figure 8). According to the data from ACM (question A, 2016), let the radius and height of a cylinder be 90 and 49 respectively. Meanwhile, let $A(65, 52^o, 0)$ and $B(39, 312^o, 49)$. The shortest distances of five simulations using O-TSA(D_{O-TSA}), TSA (D_{TSA}) and GA (D_{GA}) are calculated and shown in Table 3. Meanwhile, the time cost (T_{O-TSA}, T_{TSA} and T_{GA})of these tests is also described in Table 3. In the simulations, the shortest distance is consistent with reference answer in O-TSA and TSA. It fluctuates around the reference value in GA. In the process, we can obtained $\alpha_1 = 26.19^o$, $\alpha_2 = 40.95^o$. Certainly, $C(90, 40.95^o, 0)$ and $D(90, 26.19^o, 49)$.

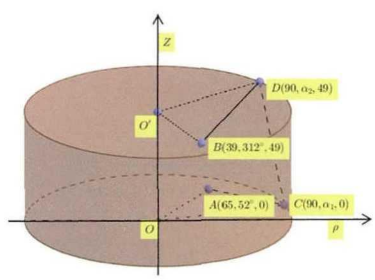

Figure 8: Numerical simulation 2 on the cylinder surface

From Table 2 and 3, obviously, O-TSA has an advantage of saving compute time compared with TSA and GA. Furthermore, the extreme value in O-TSA is more stable than that of GA.

Table 3: The results of the three methods in simulation 2

	D_{O-TSA}	T_{O-TSA}	D_{TSA}	T_{TSA}	D_{GA}	T_{GA}
1	171.0216	0.1476	171.0216	0.2679	171.4875	0.1856
2	171.0216	0.1367	171.0216	0.2258	172.0834	0.1490
3	171.0216	0.1413	171.0216	0.2724	172.5168	0.1463
4	171.0216	0.1455	171.0216	0.2755	171.2614	0.1587
5	171.0216	0.1320	171.0216	0.2200	171.5431	0.1473
average	171.0216	0.1406	171.0216	0.2532	171.7784	0.1574

5 Application in surgery field

It's well-known that the methods of solving the shortest distance between two points are applied in geodesic problem[4]. As a simple and fast convergence method, O-TSA can effectively solve these problems, especially on the surface of some geometries such as cylinder, cone, frustum of a cone and so on. In surgery, how to reduce the length of the wound is an important problem in modern medicine. Some parts of human body can be seen simple cubes like cylinder, cone or their combination. So how to get shortest wound is equal to how to calculate the shortest distance among the surface of cubes. In Figure 9, if we regard an arm as a cylinder and a thigh as a frustum of cone, the shortest routes on them can be found. Accordingly, O-TSA can be applied in this field and more beneficial to the surgery.

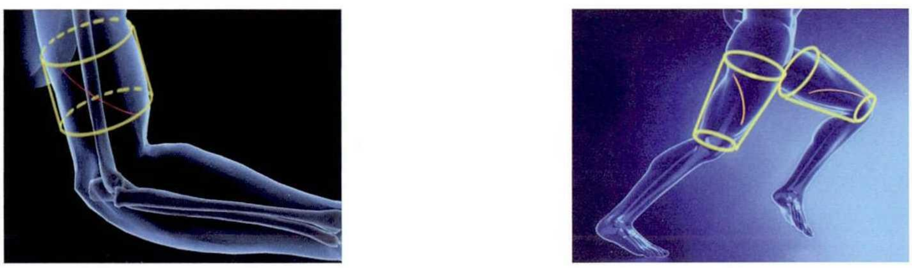

Figure 9: looking an arm as a cylinder (left) and a thigh as a frustum of cone (right)

6 Conclusion

As an iterative approach to extreme values, the ternary search algorithm has some advantages such as easy understanding, accurate conclusion, simple operation and so on. In this paper, we propose the optimized ternary search algorithm based on the original. This algorithm constructs the interval reduction factor. When the factor is smaller, the convergence rate of interval in each iteration is faster. The experiments on computing the extremum value of two unimodal functions and the shortest distance on the surface of cylinder prove the good performance of the proposed method. In real life, like in the surgery field, the optimized ternary search algorithm can be used to solve the shortest wound problem.

However, the optimized ternary search algorithm has some drawbacks. It can only solve the extremum value problem of the unimodal function. In addition, for performance in experiments, we only compare with the ternary search algorithm and genetic algorithm. It is unknown whether the optimized ternary search algorithm is superior to the other methods such as Newton's iteration, binary search , secant method, simulated annealing algorithm, particle swarm algorithm and so on . In further work, we will study the better methods of solving extremum value problems to all kinds of complicated functions.

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改进三分法及其应用研究

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摘 要：在计算科学领域，可以利用三分算法将区间三等分来解决单峰极值函数的最值问题。本文通过引入一个缩放因子改进最初的三分算法。对于一个先严格单调递增再严格单调递减的函数（反之亦然），改进后的三分算法通过减少迭代次数而节约计算时间。同时，本文通过求解圆柱表面任意两点的最短距离来测试其性能。结果表明，相比于最初的三分算法与遗传算法，改进后的三分算法具有更优的性能。

关键词：改进三分算法；两点间最短距离；时间开销；遗传算法

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