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Optimization of Sensor Structural Parameters and Image Reconstruction for Electrical Capacitance Tomography

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Abstract

Sensitivity field distribution of the sensor in ECT system is affected by the distribution of the mixture, The "soft field" property of sensitive field bring great difficulty in image reconstruction, on the basis of analyzing capacitance tomography sensitive mechanism, by analyzing that sensor structure parameters in ECT system have influence on the uniformity of the sensitive field, this paper proposed a structural parameters optimization algorithm based on the ant colony algorithm. The algorithm first determines the parameter optimization design evaluation function, and then rapidly identifies several suboptimal paths by using particle swarm optimization and initializes the pheromones in the path, Ant colony algorithm finds the optimal solution according to the initialization pheromones and using the characteristics of rapid convergence. The experimental results show that, compared with the orthogonal algorithm, the performance of the sensor designed by using the structure parameters obtained by ant colony optimization algorithm is obviously improved, Alleviate the difficulty of data acquisition circuit design and improve the accuracy and uniformity of the sensitive field, the quality of image reconstruction is improved, the relative error of image reconstruction is reduced.

Keywords: *capacitance sensor structure parameter; optimization design evaluation function; particle swarm ant colony algorithm*

1. Introduction

Electrical capacitance tomography is a new computer tomography technology based on the medical Computerized Tomography; it is put forward by the University of Manchester Institute of Science and Technology in the 80's of the last century [1]. It computes the distribution of dielectric constant that is the distribution of each phase by measuring the surface electrode capacitance value between the surrounding. Compared with other techniques, electrical capacitance tomography technology has many advantages such as wide applicability, no invasion, good security and low cost, it has become one of the mainstream technologies of PT [2].

Capacitance sensor is a kind of senor that can convert changes in non-electricity to capacitance change value. It has many advantages such as simple structure, small volume, high resolution, and it can carry out non-contact measurement, which is widely used for measuring the liquid level, displacement and content etc. With the rapid development of capacitance measurement, capacitance sensor has been widely used in no electrical measurement and automatic measurement [3]. Because the various structure parameters of the sensor will directly affect the accuracy of measurement, it is important to develop the research on Optimization Design of sensor.

This paper presents an optimization design method of the sensor structure parameters of particle based on ant colony. The optimal parameters of capacitance sensor can be obtained the approximate, and the algorithm can improve the sensor performance significantly. The experimental results show that the algorithm is effective, and data

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acquisition precision is obviously improved, sensitivity and uniformity of the sensitive field can be improved by using this algorithm [4].

2. The Basic Principle of Capacitance Sensor

2.1. Capacitance Sensor Structure

The panel capacitors are composed of two parallel metal plates separated by an insulating medium, if we do not consider the edge effect; the formula for the capacitance is as follow:

$$C = \frac{\varepsilon A}{d} \tag{1}$$

In the formula, εis the dielectric constant of the medium between the capacitor plates; A is the area covered by two parallel plate; d is the distance between two parallel plate. From the formula, the capacitance between the two plates is proportional to the substrate between the dielectric constant of the medium and the plate area, and inversely proportional to the distance between the plat [5].

Structure of the electrode capacitance sensor is as shown in Figure 1, it is similar to the panel capacitor, the sensor is installed a set of metal electrode uniformly in the lateral insulated containers or pipes. The sensor is mainly composed of the detection electrodes, insulating pipeline, radial shielding electrode and the grounded shield cover [6]. Among them, the radial electrodes can reduce capacitance value between adjacent electrodes fixed and improve capacitance corresponding sensitivity; shielding cover can shield outside electromagnetic interference and protect plate from damage.

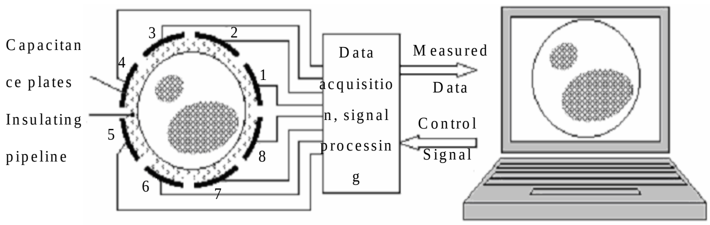


Figure 1. The Sensor Structure of ECT System

Each plate of the sensor will be numbered sequentially 1, 2,...n. In the process of measurement, we select the voltage excitation mode, which process is that the electrode 1 is as the excitation electrode, applying a fixed voltage value, and followed by the plate 2~n as the detection electrodes (electrode detection electrodes are grounded), and measuring the corresponding electrode on 1 and 2, 1 and 3,... , capacitance between 1 and N; and then select plates 2, 3,... N-1, as the excitation electrode, for systems with N electrode plate, electrode can be independent into total number: n (n-1) /2. When the sensor is working, since the number of components of the measurement area is changed flow, you can get n (n-1) /2 a change in capacitance value, in order to distribution of various internal reconstruction sensor streams, the capacitance will be convert into proportional voltage value ,and then transmit to the application center to reconstruct following image .

2.2. Analysis of the Sensor Structure Parameters

The physical size of the annular multi-electrode capacitance sensor directly affects the acquisition sensitivity of the capacitance value and signal-to-noise ratio. The design of the sensor structure directly affects the accuracy of image reconstruction. Capacitance sensor electrodes effective area is greater, the sensitivity of the sensor is higher, at the same time, the noise is more effective area; On the contrary, the plate is small, the sensor is not sensitive to the signal detection, spatial resolution image reconstruction will be lower. Therefore, the design of sensor needs to consider the overall physical parameter [7].

Influence of medium in different position sensor on the same plate capacitance value is different, namely "soft field characteristics of media", on the other hand, the same point in the sensor have different effect on different electrode on capacitance values. The main parameters that affect the performance of capacitive sensors are: the number of electrode, electrode length, angle, the pipe wall thickness electrode thickness and dielectric constant. The more the number of electrodes, can provide more projection data for image reconstruction, but also bring the problem of reduction of signal to noise ratio and edge effects increase; reduce the size of the polar plate can reduce the axial average effect of the measured object, is conducive to the improvement of image quality, but also reduces the signal level, put forward higher requirements the detection circuit; plate length increases, increase the capacitance value between the plates, easy to measure but will cause the three-dimensional weakening effect, which cannot well reflect the change of multiphase flow pipeline flow direction and phase distribution; insulated pipe wall thickness increases the sensitivity to reduce the phase distribution of different capacitance measurement data, the thickness of thin, will cause the capacitance measurement data by major plate near the multiphase flow distribution decision, reduces the pipeline center part of multiphase flow distribution of sensitivity. Radial shielding plate is inserted into the pipe wall depth h1, the pipe wall thickness and the dielectric constants of insulation material also affect the performance on sensor.

In order to analyze the effect of different structure parameters on the sensor, we choose a set of reference sensor calculating the capacitance value, and different parameters values of the reference sensor is adjusted, and then analyze the influence of the parameter on the sensor performance according to the change of capacitance value. The basic structural parameters of electrode sensor angle θ =20 °, pipe diameter R1=77mm, pipe center distance between the plates R2=86mm , distance between pipe center and shield R3=98mm, plate number N=12, a radial shielding plate, ε_1 =3.80, ε_2 =80.0. The capacitance value in the sensor with low dielectric and full of high dielectric when single structure parameter change is shown in tables 1and tables 2 .

Table 1. Structural Parameters and Empty-pipeline EC (F/m)

Structure parameters	C_{1-2}	C_{1-5}	C_{1-7}
R_2-R_1=4mm	9.32E-12	5.51E-13	4.21E-13
R_2-R_1=6mm	1.10E-11	5.56E-13	4.34E-13
R_2-R_1=8mm	1.26E-11	5.63E-13	4.61E-13
θ=20°	1.05E-11	5.92E-13	4.58E-13
θ=22°	1.23E-11	6.34E-13	4.67E-13
θ=24°	1.42E-11	7.01E-13	4.80E-13
R_3-R_2=12mm	8.96E-12	5.38E-13	4.30E-13
R_3-R_2=15mm	9.03E-12	5.43E-13	4.65E-13
R_3-R_2=20mm	9.51E-12	5.86E-13	4.69E-13
h=1mm	1.02E-11	6.21E-13	4.53E-13
h=2mm	9.32E-12	5.85E-13	4.16E-13
h=3mm	8.87E-12	5.34E-13	4.07E-13

Table 2. Structural Parameters and Full-pipeline EC (F/m)

Structure parameters	C_{1-2}	C_{1-5}	C_{1-7}
R_2-R_1=4mm	9.37E-12	5.55E-13	4.36E-13
R_2-R_1=6mm	1.56E-10	1.09E-11	8.47E-12
R_2-R_1=8mm	1.16E-11	5.68E-13	4.38E-13
θ=20°	1.01E-11	4.63E-13	4.29E-13
θ=22°	1.31E-11	6.38E-13	4.65E-13
θ=24°	2.23E-10	1.29E-11	1.02E-11
R_3-R_2=12mm	9.53E-12	5.65E-13	4.17E-13
R_3-R_2=15mm	9.62E-12	5.78E-13	8.25E-13
R_3-R_2=20mm	9.77E-12	5.90E-13	4.37E-13
H=1mm	2.06E-10	1.28E-11	9.23E-12
h=2mm	2.87E-11	8.34E-12	6.78E-12
h=3mm	8.74E-12	5.92E-13	4.16E-13

From the principle analysis of the above table capacitance data and ring capacitance sensor can be seen that the change of structural parameters of capacitance sensor can change the value of capacitor, the analysis of influence of various parameters on the performance are as follows:

The pipe wall thickness should be appropriate to thin a bit, because the pipe wall is too thick to the mechanical strength increases, and gather the high sensitive region of tube wall near the capacitance sensor; electrode angle is bigger, the measured capacitance value is greater, easy to detect, but increase the capacitance between the adjacent electrodes values , further increase the gap on the output capacitor and other plate; radial electrode reduces the static capacitance between the adjacent electrodes, so that the oil / between the adjacent electrodes around the pipe changes tend to be more uniform. Because the power line non adjacent electrode is mainly through the pipeline space, the radial electrode effects on no adjacent inter electrode capacitance is not too much[8].The radial electrode effects is associated with the width of the radial plate and the depth of the insert pipe wall.

3. The Structure Parameter Optimization of Capacitance Sensor

1

3.1. Objective Function to Determine the Optimal Sensor

Sensitivity is an important index of static characteristics of sensor. The definition is that output increment of Δ y and Δ x cause the corresponding input output increment of Y ratio. S is sensitivity,

$$S = \frac{\Delta y}{\Delta x} \tag{2}$$

It says the change of the sensor output caused by change of unit input ,the apparently, the sensitivity of S value is greater, sensor is more sensitive.

In calculating the sensitivity of ring capacitance sensor, often assisted by the finite element method analysis, that solving region is divided into continuous no overlapping, with regular shape unit, units are connected by joints. In each unit in accordance with the rules of the interpolation function, the specific physical problems into a set of state variables include the boundary conditions of the differential equation, so as to solve the problems of extreme value of multivariate function. Figure 2 is the finite element mesh for ring capacitance sensor detection area division.

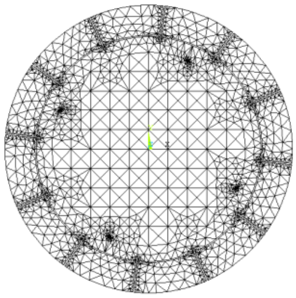


Figure 2. Plotting Model of Finite Element

According to the finite element method, the formula for sensitivity of sensitive field in annular multi-electrode capacitance sensor defines as follow:

$$S_{i,j}(p) = \frac{C^M_{i,j}(p) - C^L_{i,j}}{C^H_{i,j} - C^L_{i,j}} \cdot \frac{1}{\varepsilon_H - \varepsilon_L} \cdot \frac{Ad_{(p)}}{Ad} \tag{3}$$

In the formula, $C^H_{i,j}$ is the capacitance value between electrode I and J when the sensor is filled with high dielectric permittivity; $C^L_{i,j}$ is the capacitance value between electrode I and J when the sensor is filled with low dielectric $C^M_{i,j}(p)$ is the capacitance value between electrode i and j when finite element P are high dielectric in the measurement area, other finite element are low dielectric ; ε H is high dielectric and ε L is low dielectric; Ad is the measurement of space on sensors ; Ad (P) is the area of finite element P.

The annular multi electrode sensor structure determines the sensor sensitivity distribution not uniform, near the pipeline wall, high sensitivity, low sensitivity of pipe center. Hope that any position in the pipeline, the sensor output is equal to an area of the same dielectric constant changes caused by or tend to be equal, so the uniform of sensitivity is the goal of optimal sensor.

Due to the symmetry of the 12 electrode sensor structure, select the typical unit to analyze. Consider only the 6 sensitivity, $S_{ij}\ (i = 1, j = 2, 3, \ldots, 7)$, the N unit mean sensitivity and variance are for:

$$S^{avg}_{ij} = \frac{1}{n}\sum_{e=1}^{n} S_{ij}(e) \tag{4}$$

$$S^{dev}_{ij} = \left(\frac{1}{n-1}\sum_{e=1}^{n} (S_{ij}(e) - S^{avg}_{ij})^2\right)^{1/2} \tag{5}$$

Type: $S_{ij}(e)$ is the sensitivity e unit values; n is the unit number in measurement area .

In order to evaluate the degree of uniformity of sensitivity field, defined sensitive field distribution parameters between the pair of electrodes :

$$P_{ij} = \frac{S^{dev}_{ij}}{S^{avg}_{ij}} \tag{6}$$

Obviously, the smaller is P_{ij}, the more uniform distribution is electrode i, j sensitivity.

The definition of optimal index P is as follow:

$$P = \frac{1}{6}\left(\sum_{i=1}\sum_{j=2}^{7} |P_{ij}|\right) \tag{7}$$

P is smaller, balanced sensitive is better, sensitive degree of sensor on the regional pipeline closer together, achieve better image reconstruction. P is associated with the angle of and electrode, wall thickness of R2-R1, R2-R3, shielding layer thickness in radial electrode insertion depth of H and the dielectric constant of structure parameters.

Sensor Empty / full pipe variation can reflect the degree of sensitivity of the sensor, capacitance variation function normalized after the statistical distribution to induce uniform sample, it reflects all the units in the field of the overall sensitivity, the greater is the value of the overall sensitivity of the sensor, the better is the performance.

In addition, considering the range of angle measurement circuit, the maximum capacitance value and the minimum capacitor value should be in the range. From the capacitance value calculation formula, maximum capacitance between adjacent plates by measuring two-phase flow in pipe is determined by the dielectric permittivity, minimum capacitance is determined by between the plates by the minimum relative measurement of two-phase flow in the pipe for low dielectric constant. According to the provisions of the value of capacitance in front of said method. The definition of $K_c = C_{max} / C_{min}$, K_c is smaller, lower requirements for measuring range.

According to the analysis results, optimum design of sensor should consider many factors, is a multi- input optimization process. The optimization function defined as follows:

$$OPT(X) = \alpha K_c + \beta P + \gamma \frac{C}{\Delta C} \tag{8}$$

X is R1,R2,R3,θ,h1 of the five dimensional vectors, respectively, the pipe wall of the pipe radius of sensor radius, radius, shield plate angle and radial plate depth. Alpha, beta, gamma is the weight, three and 1. The optimization function contains three performance indexes, function value is smaller, the performance of the said sensor is the better , so the optimization design of sensor convert into function for the minimum value in the domain of the problem.

3.2. Sensor Structural Parameters Optimization Design

Particle swarm optimization algorithm is an optimization method based on iterative process. Firstly, the system is initialized by a group of random solutions and then search for the optimal value by iteration [9]. Ant colony algorithm is based on the method of natural foraging ants to find the optimal solution of the stochastic optimization algorithm, this algorithm does not need any a priori knowledge, the initial randomly selected search path, "understanding" of space randomly, search more regularly, and gradually until it reaches the global optimal approximation solution [10].

This thesis proposes particle swarm ant colony algorithm, which is the integration of the advantages of the two algorithms, complement each other. In the early stage, particle swarm algorithm is fast and global convergence, to produce the initial information pheromone distribution [11]. After the completion of the initial pheromone distribution, ant colony algorithm can be used parallel efficiency high, good effect and the characteristics of heuristic feedback to OPT (X) function is solved, the particle fusion group algorithm and ant colony algorithm is called particle swarm ant colony algorithm.

Through the above analysis and modeling of the optimization problem of capacitance sensor, capacitance sensor can be attribute to the problem that combinatorial optimization problem can be converted into shortest path problem . Then in the shortest path problem, path weight is the key to solve the optimal solution of the capacitance sensor, in order to combine capacitive sensors property with path weights, we can convert the values of capacitive sensors property into path weights through the function formula . The path weights calculated as the key parameters of the particles formed by the fusion of ant colony algorithm particle swarm optimization algorithm and ant colony algorithm of ant colony algorithm, makes the use of capacitive sensor attribute values calculated optimal path.

In this paper, each path is abstracted as a vector Bi= (Bi1, Bi2, Bi3,..., Bij|Bi1 ∈ WS1, Bi2 ∈ WS2, Bij ∈ WSj,...,) T, in order to use the improved particle swarm optimization algorithm, the vector Pi is as a particle, path vector is as the particle coordinates, the coordinates of each represents a sensor parameter number. WSj is the candidate set of parameters. The definition of speed particles I is coordinates for each iteration the moving distance, V i= (Vi1, Vi2, Vi3, Vi4... Vij) T. Suppose N is the particle size .

Initialization of the algorithm for each particle randomly assigned one coordinate (i.e., a random path), in each iteration, particles are needed to update their own coordinates based on two kinds of optimal points: the first one is the best solution found by the particle itself, called individual extreme points (expressed its position with pbest), another extreme point is the best solution found in the whole population, called the global extremum point (indicating its position with [12] gbest). When the initial position of pbest in the initialization is each particle, after each iteration, each particle by type 9, type 10 to update the fitness , if more than pbest, then replace the old pbest. gbest is a pbest fitness of the best point. The fitness function is as follows:

$$OPT(B_{ij}) = \alpha K(B_{ij}) + \beta P(B_{ij}) + \gamma T(B_{ij}) \tag{9}$$

$$f(B_i) = \sum_{j=1}^{n} POT(B_{ij}) \tag{10}$$

The alpha, beta, gamma to function are as the attribute weighting function OPT, {alpha + beta + gamma =1}, K (B), P (B), T (B) are expressed as OPT ratio and maximum value, minimum value sensitivity, capacitance and the capacitance change ratio.

After finding these two extreme points, the particles update their velocities and coordinates according to the following formula 11, type 12, type 13, type 14.

$$v_{ij}^{k+1} = v_{ij}^{k} + Select1_k(pbest_{ij}^{k} - x_{ij}^{k}) + Select2_k(gbest_j^{k} - x_{ij}^{k}) \tag{11}$$

$$Select1_k = \begin{cases} 1, cp \times rand_p > cg \times rand_g \\ 0, \qquad\qquad\qquad or \end{cases}, \ randp = \frac{pbest_{ij}^{k}}{pbest_{ij}^{k} + gbest_j^{k}} \tag{12}$$

$$Select2_k = \begin{cases} 1, cp \times rand_p \leq cg \times rand_g \\ 0, \qquad\qquad\qquad or \end{cases}, randg = \frac{gbest_j^{k}}{pbest_i j^{k} + gbest_j^{k}} \tag{13}$$

$$x_{ij}^{k+1} = x_{ij}^{k} + v_{ij}^{k+1} \tag{14}$$

Among them, cp, cg is the location selection coefficient, cp is the individual extreme alternative factor, representing the particle coordinates deviation instead of individual extremum ; cg is the global extremum alternative factor, representing the particle coordinates tend to use global extreme value point of the degree of substitution, cp+cg=1; randp represents the updated probability of individual extreme points which particle coordinates selected, randg represents the updated probability of global extreme points which particle coordinates selected, define randp+randg=1, x_{ij}^{k} is the j-dimensional current position of the particle i in the K iterations; $pbest_{ij}^{k}$ is the j-dimensional current position of the particle i in individual extreme points(i.e. coordinate); $gbest_j^{k}$ is the position of the entire group in the j dimension of the global extremum point location[13].

In order to increase the convergence speed, improve the efficiency of the algorithm applies an elimination mechanism, a particle iteration algorithm is N, adaptive threshold is Q, N min $\leq$ N $\leq$ N max, the maximum number of iterations is N max, the minimum number of iterations is Nmin, set threshold Q by artificial , when more than half the number of iterations, if the individual extremum of a particle is did not reach the threshold of Q requirements, at this time that the particle is trapped in a local optimum, shall terminate the iterative [14]. After reaching cycles, the path corresponding to individual extremum point all the particles of the normal exit into the suboptimal solution concentration, into the ant colony algorithm.

After the end of the particle swarm algorithm into ant colony algorithm, obtains several groups suboptimal path from the initial node S to the end node F , remove the top 20% of the former path of fitness, set to O .According to each set of solution in O, using ant colony algorithm to set initial information , the specific formula such as type 15:

$$\tau_{ij} = C_1 \times OPT\ (O_{ij}) \tag{15}$$

τij is the initial pheromone of edge (i, j) , C1 is a constant, OPT (Oij) is t the fitness function of he edge (i, j) and i≠ j, calculate from the edge into the node, when there is a plurality of path edges (i, j), accumulate on τij. In order to avoid premature convergence of the ant algorithm early, we use the max min ant algorithm (MMAS), then the initial pheromone expression for τ S= τmin+ τij, τmin is the minimum information for each path.

The ant colony algorithm path changes will use called random proportional rule state transition rules, it gives the probability which the ant k in node i option to move on to another node j. In the t iterations, the transition probability which ant K in node j select to move on to node j is $p_{ij}^k(t)$, probability formula such as type 16:

$$p_{ij}^k(t) = \begin{cases} \dfrac{\tau_{ij}^{\alpha}(t)\eta_{ij}^{\beta}(t)}{\sum_{s \in allowed_k} \tau_{is}^{\alpha}(t)\eta_{is}^{\beta}(t)} & j \in allowed_k \\ 0 & or \end{cases} \tag{16}$$

The allowed k is the node which allows the ant K next selects; α is information concentration factor, which means that the relative importance of an existing path on route choice, reflecting the pheromone in the ant movement; beta is heuristic factor, reflecting the ant movement in the process of spontaneous choice of optimal path selection in ants by the degree of attention in the path. The OPT function heuristic function are closely related to choose the ring capacitance sensor , $\eta_{i,j} = kq_{i,j}$, where k is a constant, qij ring capacitance sensor to choose a parameter j OPT heuristic function, heuristic function such as type 17.

$$q_{ij} = \sqrt{\alpha K^2 + \beta P^2 + \gamma T^2} \tag{17}$$

Among them, alpha + beta + gamma =1. In order to avoid residual pheromone caused by too much residual information flooded the heuristic information, let the ant routing more efficient, the provisions of this article when ants go all the service nodes, update path (i, j) of the pheromone, updating formula such as type 18, type 19:

$$\tau_{ij}(t+1) = \rho\tau_{ij}(t) + \tau_{ij}(t) \tag{18}$$

$$\tau_{ij}(t) = \sum_{k=1}^{m} \tau_{i,j}^{k}(t) \tag{19}$$

ρ represents residual factor, in order to prevent unlimited information accumulation, ρ ∈ [0,1], τij (t) represents the iteration (i, j) of the pheromone increment, $\tau_{ij}^k(t)$ is the first k ant in the own way (i, j) on the pheromone increment. In order to prevent that the wheel increase information too high or too low to affect the ants next choice, the limit is $\tau_{\min} \le \tau_{ij}(t) \le \tau_{\max}$.

This paper uses the ant cycle model (ant-cycle) to update pheromone increment, updating formula as formula (20) and (21):

$$\begin{cases} \tau_{ij}^k(t) = \dfrac{q_{ij}}{L_k} & ant\ K\ pass\ \ the\ edge\ (i,j) \\ 0 & or \end{cases} \tag{20}$$

$$L_k = C\sqrt{\sum_{i=1}^{n-1}\left(\frac{1}{q_{i,i+1}}\right)^2} \tag{21}$$

Lk is the path of the ant K is the walked length, C is a constant parameter. After each ant cycle N times, the path with most ant should be identified for the path to the optimal path. Figure 3 is a flow chart of particle ant colony algorithm.

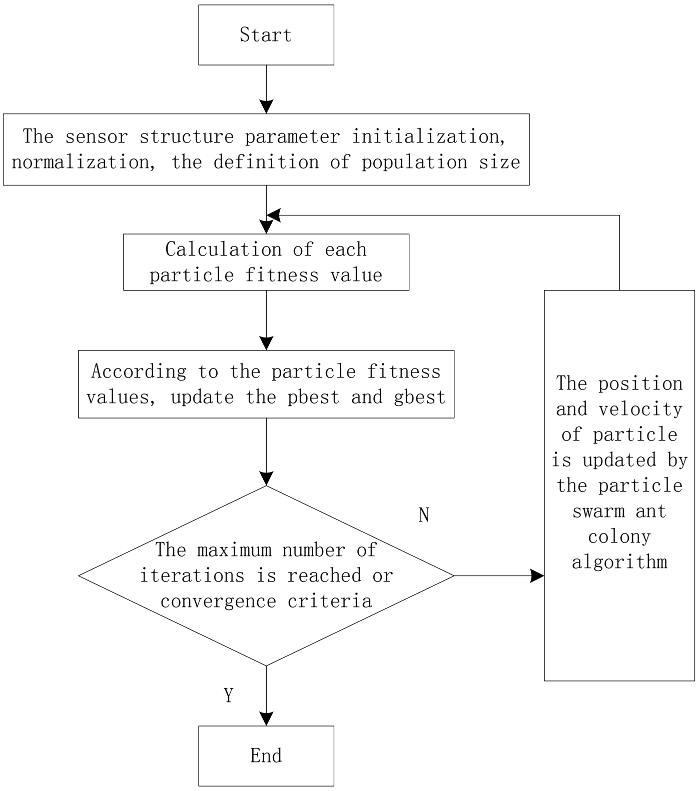


Figure 3. The Process of Optimizing Structure Parameters of Sensor based on PACA

4. Experimental Results and Analysis

According to the actual situation, choose sample test points in the optimization space D, due to only five parameters, ,determine the 5 factor levels by using the orthogonal test method, and then arrange experiments with the 5 level orthogonal table L25 (55). The orthogonal experiment is shown in Table 3.

Table 3. Scheme of Orthogonal Experiment

test number	θ/°	R2/mm	R2-R1/mm	R3-R2/mm	h1/mm
1	18	80	12	10	0
2	18	82	14	15	1.5
3	18	84	16	20	3.0
4	18	86	8	25	4.5
5	18	88	10	30	6.0
6	20	82	12	20	4.5
7	20	84	14	25	6.0
8	20	86	16	30	0
9	20	88	8	10	1.5
10	20	80	10	15	3.0
11	22	84	12	30	1.5
12	22	86	14	10	3.0
13	22	88	16	15	4.5
14	22	80	8	20	6.0
15	22	82	10	25	0

16	24	86	12	15	6.0
17	24	88	14	20	0
18	24	80	16	25	1.5
19	24	82	8	30	3.0
20	24	84	10	10	4.5
21	26	88	12	25	3.0
22	26	80	14	30	4.5
23	26	82	16	10	6.0
24	26	84	8	15	0
25	26	86	10	20	1.5

In this paper, two sensor optimal structure parameters by orthogonal experimental method and the particle swarm ant colony algorithm, as shown in Table 4.

Table 4.Two Kinds of Optimization Structural Parameters

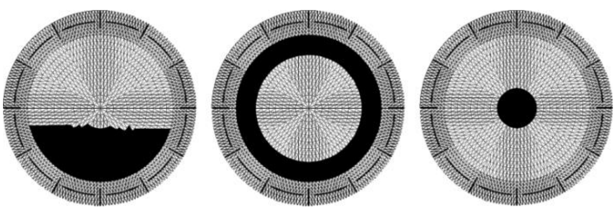
Structure parameters	Orthogonal test method	Particle swarm ant colony algorithm
θ/°	24	24
R2/mm	85.5	85
R2-R1/mm	9.0	8.5
R3-R2/mm	12.3	11.3
h1/mm	3.4	3.6
OPT	7.59	6.02

Table 4 shows that, two kinds of structure parameters of the OPT values are 7.59 and 6.02, OPT increased by 20% by using particle swarm ant colony algorithm compared with the orthogonal experiment method.

The design of annular sensor based on the parameters of capacitance sensor that is obtained with particle of ant colony algorithm is as shown in Figure 4.

Figure 4. Structure of Capacitance Sensor

We set laminar flow, circulation and center three popular experiments. Figure 5 is the original images of three typical flow regimes. The duty ratio is 38%, 43%, 6%.



(a) Laminar (b) Circulation (c) Center

Figure 5. The Original Image of Three Typical Flow Pattern

Because the capacitance value that is obtained through single electrode excitations and single electrode detection is small, this experiment adopts the method of multi electrode detection to measure the capacitance value[15]. We detect capacitance value by using the capacitance sensor designed by ant colony algorithm particle, and reconstruct image according image reconstruction algorithm based on trust region[16]. The reconstruction results as shown in Figure 6.

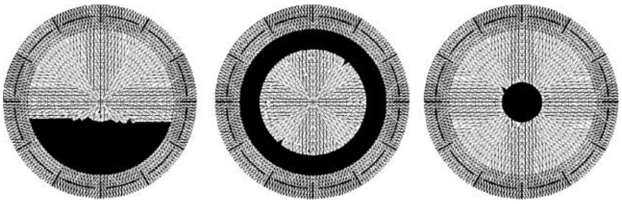


Figure 6. The Image Reconstruction Results of PACA Sensor

Under the same conditions, image reconstruction was performed on the data that is collected from capacitance sensor designed by orthogonal test method, the reconstruction results as shown in Figure 7.

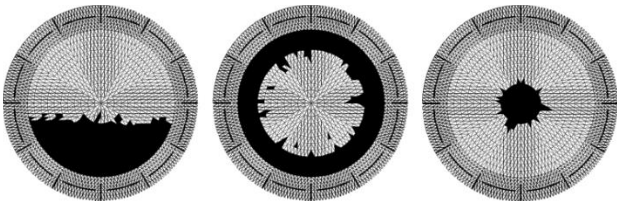


Figure 7. The Image Reconstruction Results of Orthogonal Experiment Sensor

According to the above results, we calculate the relative error of image reconstruction location and duty ratio.

Spatial image relative error (SIE) is the error of area, location and shape between reconstruction of images and the actual test model, formula is as follow[17]:

$$SIE = \frac{\sum_{i=1}^{n} \left| g_{s(i)} - g_{r(i)} \right|}{\sum_{i=1}^{n} g_{s(i)}} \tag{22}$$

In the formula: gs(i) and gr(j) respective for gray values in the scale i of the prototype and the image reconstruction; n is the number of cells in the imaging space division.

The duty ratio formula is as follow:

$$OSR = \frac{S_I}{S} \tag{23}$$

In the formula: SI is the image area; S is the imaging area.

Table 5 and Table 6 give the experimental comparison of two kinds of algorithms for capacitance sensor parameter design. Table 5 is the spatial position error of reconstruction images, which data is collected from two kinds of sensor structure. Table 6 is the duty ratio of reconstruction images, which data is collected from two kinds of sensor structure.

Table 5. Images Error (%)

Test method	laminar	circulation	center
Orthogonal test method	9.67	8.31	12.36
Particle swarm ant colony algorithm	4.34	4.61	7.63

Table 6. Duty Cycle (%)

Test method	laminar	circulation	center
Orthogonal test method	47	52	10
Particle swarm ant colony algorithm	40	46	8

From Table 5 and Table 6 show that, compared the sensor by using orthogonal experimental method and by using ant colony algorithm, imaging accuracy by using ant colony algorithm is improved, and the collected image reconstruction error data is relatively small (maximum value decreased from 12.36% to 7.63%), and the duty ratio of the prototype is more close to original image. The sensitivity and uniformity of sensitive field has been greatly improved, and the cost and time has been greatly reduced.

From the experimental results can be seen, the prototype of different shape and the sensor measurement intervals for different positions of image reconstruction results have a certain impact, imaging the laminar flow and circulation have more satisfactory results, that largely reflect the basic information of the original image. Image edge flow display is not smooth, the above phenomenon maybe because, sensitivity of the sensor measurement area measured is affected by medium distribution; sensitivity in closer from the plate is relatively strong and affected greatly by the medium. Therefore, we should start further research from the aspects to improve the quality of image reconstruction.

5. Conclusions

Because different parameters of ECT sensor structure have different effects on the performance of the sensor, the sensor should be reasonably designed considering various parameters from the perspective of the overall integrated system. In this paper, firstly, the sensor structure parameters of various capacitances are obtained by simulation, influence of various structural parameters on the performance of capacitive sensor is given, and then the evaluation function for parameter optimization is designed. The orthogonal design method to get the simulation data as basic data, on the basis of this, this paper puts forward a kind of particle swarm ant colony search hybrid algorithm. Particle swarm algorithm can improve searching speed, at the same time, ant colony algorithm can solve the particle swarm search into local optimal solution, and a set of optimum parameters of sensor can be obtained. Compared with the method of orthogonal experiment, the performance of the sensor that is designed by the structure parameters is improved obviously. The algorithm in this paper can reduce the design difficulty of data acquisition circuit by reducing the dynamic range of capacitance values measured by radial electrode. It can improve the sensitivity and uniformity of sensitive field, improve image reconstruction quality, and reduce relative error image reconstruction.

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References

[1] H. M. Chen, L. Xie and K. B. Xie, "A comparative study on architectures and implementation methodologies of internet of things", Chinese Journal of Computers, vol. 1, no. 36, **(2013)**.
[2] N. Kosnizuka and K. Sakamura, "Standards for ubiquitous computing and the Internet of Things", IEEE pervasive Computing, vol. 4, no. 19, **(2010)**.
[3] Y. L. Hu, Y. F. Sun and B. C. Yin, "Information sensing and interaction technology in internet of things", Chinese Journal of Computers, vol. 6, no. 35, **(2012)**.
[4] J. C. Yang, X. B. Fang and L. D. Zhai, "Research towards IoT-oriented universal control system security model", Journal on Communications, vol. 11, no. 33, **(2012)**.
[5] W. D. Ding, F. Li and Q. G. Zhang, "Calibration of the capacitive sensor used in the very fast transient overvoltage measurement of ultra high voltage gas insulated switchgear", Proceedings of the CSEE, vol. 31, no. 31, **(2011)**.
[6] D. Y. Chen, M. Gao and W. Li, "Design and implementation of data acquisition system for the new electrical capacitance tomography", Electric Machines And Control, vol. 5, no. 17, **(2013)**.
[7] Y. L. Zhao, B. L. Guo and Y. Y. Yan, "Latest development and analysis of electrical capacitance tomography technology", Chinese Journal of Scientific Instrument, vol. 8, no. 33, **(2012)**.
[8] Y. Chen, D. Y. Chen and G. B. Zheng, "Effects of radial electrodes on the performance and capacitance sensitivity distributions of sensor for electrical capacitance tomography system", Proceedings of the CSEE, vol. 21, no. 25, **(2005)**.
[9] P. Jiang, H. H. Song and G. Lin, "Target tracking algorithm for wireless sensor networks based on particle swarm optimization and metropolis-hasting sampling particle filter", Journal on Communications, vol. 11, no. 34, **(2013)**.
[10] H. F. Wu, X. Q. Chen and Q. H. Mao, "Improved ant colony algorithm based on natural selection strategy for solving TSP problem", Journal on Communications, vol. 4, no. 34, **(2013)**.
[11] T. Wen, G. J. Sheng and Q. Guo, "Web service composition based on modified particle swarm optimization", Chinese Journal of Computers, vol. 5, no. 36, **(2013)**.
[12] J. Chen, M. B. Salim and M. Matsumoto, "A single mobile target tracking in voronoi-based clustered wireless sensor network", Journal of Information Processing Systems, vol. 1, no. 7, **(2011)**.
[13] S. Kumar, J. Prakash and P. Kanagasabapathy, "A Critical Evaluation and Experimental Verification of Extended Kalman Filter", Unscented Kalman Filter and Neural State Filter for State Estimationof Three Phase Induction Motor, Applied Soft Computing, vol. 3, no. 11, **(2011)**.
[14] D. An, C. Q. Rong and D. Yang, "Speaker recognition method based on PSOA clustering and KMP algorithm", Chinese Journal of Scientific Instrument, vol. 6, no. 34, **(2013)**.
[15] L. Li, M. Gao and D. Y. Chen, "A novel multiple-electrodes excitation method for electrical capacitance tomography system", Electric Machines and Control, vol. 9, no. 15, **(2011)**.
[16] L. L. Wang, Y. Chen and D. Y. Chen, "An improve trust region image reconstruction algorithm for electrical capacitance tomography System", Chinese Journal of Scientific Instrument, vol. 5, no. 31, **(2010)**.
[17] D. Y. Chen, Z. Q. Li and M. Gao, "A super resolution image reconstruction algorithm based on Landweber in electrical capacitance tomography", Mathematical Problems in Engineering, vol. 20, no. 13, **(2013)**.