

Bayesian Optimization Based on Student's T Process for Microstrip Antenna Design

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Abstract – Bayesian Optimization (BO) is an efficient global optimization algorithm, which is widely used in the field of engineering design. The probabilistic surrogate model and acquisition function are the two keys to the algorithm. Building an efficient probabilistic surrogate model and designing a collection function with excellent exploring capabilities can improve the performance of BO algorithm, allowing it to find the optimal value of the objective function with fewer iterations. Due to the characteristics of small samples and non-parametric derivation of the Gaussian Process (GP), traditional BO algorithms usually use the GP as a surrogate model. Compared with the GP, the Student's T Process (STP) retains the excellent properties of GP, and has more flexible posterior variance and stronger robustness. In this paper, STP is used as the surrogate model in BO algorithm, the hyperparameters of the model are optimized by STP, and the estimation strategy function (EST) is improved based on the posterior output of the optimized STP, thus realizing the improved BO algorithm based on the STP. To verify the performance of the proposed algorithm, numerical experiments are designed to compare the performances of the traditional BO algorithm, which includes the lower confidence bound function (LCB) and EST as acquisition function respectively and GP as the surrogate model, and the proposed BO algorithm with STP as the surrogate model and LCB, expected improvement function (EI), expected regret minimization function (ERM) as acquisi-

tion function respectively. The results show that the proposed algorithm in this paper performs well when finding the global minimum of multimodal functions. Based on the developed algorithm in this paper, the resonant frequency of printed dipole antenna and E-shaped antenna is modeled and optimized, which further confirms the good design ability and design accuracy of the BO algorithm proposed in this paper.

Index Terms – acquisition function; antenna optimization; Bayesian optimization; Gaussian process; Student's T process

I. INTRODUCTION

Constructing efficient global optimization algorithms has always been the focus of research topic. As an advanced and efficient global optimization algorithm, the Bayesian optimization (BO) algorithm has received extensive attention and research [1]. The BO algorithm is a kind of acquisition function and surrogate model as its cores to fit the objective function, collecting new sample observations to achieve fast iteration and find the maximum or minimum value of the objective function [2].

In recent years, the research on the BO algorithm is inseparable from three aspects: the establishment of a new surrogate model [3], the optimization of the surrogate model [4], and the design of the acquisition function [5]. The performance of BO algorithms can be improved by constructing efficient surrogate models, such as ran-

dom forests surrogate models [6], making multiple decision trees to improve computational efficiency and accuracy, and deep neural network surrogate models [7] to improve the model's ability to handle large-scale data. In recent years, the optimization of surrogate models in BO algorithms has also become a research hotspot. Chowdhury [8] proposed a scheme to dynamically adjust the domain boundary of the surrogate model to solve the complex problem of high-dimensional data analysis. Yenicelik [4] designed an algorithm named BORING to deal with the dimensionality reduction of data. The acquisition function in parallel BO can collect multiple sample points simultaneously to improve its efficiency. Ginsburg et al. [9] studied Monte Carlo to simulate the acquisition function to generate multiple sample points at a time. Some scholars [10] also use the multimodal method to solve multiple candidate sample points, reducing the time-consuming problem of the simulation.

As a classical surrogate model in BO, Gaussian Process (GP) has a rigorous mathematical theoretical foundation and can deal with complex problems [11, 12]. However, GP has two apparent shortcomings. Its posterior variance depends on the observed sample points, and its outliers are based on a prior assumption, which makes GP not very good at rejecting outlier ability. Student's T Process (STP) is a generalization of the GP, which obeys the Student's T distribution rather than the Gaussian distribution [13]. The study of STP makes up for the lack of robustness of GP, and it has a more flexible posterior variance. Shah [14] proposed to perform the inverse Wishart process on the kernel function of the GP to realize the STP and use it to deal with outliers in the data. This is because the kurtosis of the Student's T distribution is higher than that of the Gaussian distribution, which means it can contain outliers. More likely.

Särkkä [15] uses an STP instead of a GP and incorporates the noise term into the kernel function to simplify the computation. Tang et al. [16] proposed that when the input has noise that depends on the Student's T distribution, if the kernel function does not have the β property, the STP has a better ability to handle abnormal data. Chen et al. [17] proposed a multi-output GP and a multi-output STP, which solved the multi-output problem under the matrix variable of the STP. An effective way of improving the prediction accuracy and enhancing the performance of the model is to optimize the model's hyperparameters. For example, the gradient descent method [18], particle swarm optimization algorithm [19], and ant colony algorithm [20] are used to optimize the super parameters of the nonparametric model, so as to improve the performance of the model.

Scholars have also studied the combination of STP and BO algorithm. In 2013, Shah [21] implemented the Bayesian algorithm using STP and the

expected improvement function, and compared it with the Bayesian algorithm using the GP as a surrogate model for the function optimization problem. In 2018, Tracey [22] implemented the Bayesian algorithm combining the STP and the expected improvement function, and applied it to the design of aerodynamic structures. In 2020, Clare [23] used the improved expected regret minimization function and confidence bound minimization function, respectively, to combine with STP to form a new Bayesian algorithm, enhancing the ability of BO.

As we all know, the optimization of electromagnetic devices through full-wave electromagnetic simulation software requires enormous computing resources, which is very time-consuming. Therefore, exploiting optimizing algorithms to design electromagnetic devices quickly is a good solution [24]. Gao [25] proposed a semi-supervised algorithm for antenna design, but this algorithm requires an additional round of antenna size. Torun [26] designed a two-stage BO algorithm and applied it to the minimization optimization of integrated circuits, and the surrogate model used in this algorithm is the GP model.

In this paper, a BO algorithm is proposed, which uses the combination of an improved maximum evaluation policy function [27] and a hyperparameter-optimized STP. Moreover, it is applied to optimize multimodal functions, printed dipole antenna, and E-shaped antenna. The results show that the proposed BO algorithm has better exploration and global optimization abilities than the traditional BO algorithm.

The rest of the paper is organized as follows. The second part briefly reviews the derivation of GP and STP. The third part cover the proposed BO algorithm, including the hyperparameters for the STP, optimization and improvement of the maximum evaluation policy function. The fourth part is the numerical experiment, which verifies the performance of the proposed algorithm. The fifth part is the application of the proposed algorithm to two microstrip antennas, including printed dipole antenna and E-shaped antenna. The subsequent parts is the summary and outlook.

II. BACKGROUND

A. Gaussian process

Gaussian Process (GP), as a non-parametric model being suitable for small sample, has strict mathematical theoretical derivation. Generally, we use (1) to describe the GP [28, 29]:

$$f(x) \sim GP(\mu(x), k(x, x)), \quad (1)$$

where the $\mu(x)$ is the mean function and the $k(x, x')$ is the covariance function. If $D_{1:n} = \{\{x_1, y_1\}, \{x_2, y_2\}, \dots, \{x_n, y_n\}\}$ represents the observed

set, then the covariance matrix K is recorded as:

$$K = \begin{bmatrix} k(x_1, x_1) & \cdots & k(x_1, x_n) \\ \vdots & \ddots & \vdots \\ k(x_n, x_1) & \cdots & k(x_n, x_n) \end{bmatrix}. \quad (2)$$

For each input new observation x_{n+1} , assuming that the mean of the GP is zero, the joint Gaussian distribution of the outputs $y_{1:n}$ and y_{n+1} can be expressed as:

$$\begin{bmatrix} y_{1:n} \\ y_{n+1} \end{bmatrix} \sim N \left(0, \begin{bmatrix} K(X, X) & K(X, X_{n+1}) \\ K(X_{n+1}, X) & K(X_{n+1}, X_{n+1}) \end{bmatrix} \right). \quad (3)$$

Where, $K(X, X_{n+1})$ is the covariance matrix of the order $n \times (n+1)$ between the observation value and the training input samples, and is the covariance matrix of the observation value itself.

The posterior probability is obtained by calculating formula (4):

$$p(y_{n+1} | D_{1:n}, x_{n+1}) = N(\mu(x_{n+1}), \sigma^2(x_{n+1})), \quad (4)$$

Here:

$$\mu(x_{n+1}) = k^T K^{-1} y_{1:n}, \quad (5)$$

$$\sigma^2(x_{n+1}) = k(x_{n+1}, x_{n+1}) - k^T K^{-1} k. \quad (6)$$

The GP can fit the corresponding test output value by calculating the above Process. It can be seen from equation (6) that the posterior variance of the GP depends on the test sample points. In BO, the acquisition function can use the information of the predicted mean and predicted variance of the GP to mine the next observation with high reliability. The acquisition function is introduced in Section 3.1.

B. Student's T process

Student's T Process (STP) is a generalization of GP, which refers to a functional distribution of an infinite set of random variables that obeys the joint Student's T distribution. For the Student's T distribution, we describe it as [18]:

$$T(\mu, \Sigma, \nu) = \frac{\Gamma((\nu+d)/2)}{\Gamma(\nu/2)\nu^{d/2}2\pi^{d/2}|\Sigma|^{1/2}} \cdot \left(1 + \frac{1}{\nu}(y-\mu)^T \Sigma^{-1}(y-\mu) \right)^{-(\nu+d)/2}, \quad (7)$$

where d is the size of the T distribution, μ is the position parameter of the T distribution, Σ is the symmetric positive definite scattering matrix parameter of the T distribution, and $\nu > 2$ is the degree of freedom.

$$E[(y-\mu)^T(y-\mu)] = \frac{\nu}{\nu-2} \Sigma. \quad (8)$$

STP is parameterized by the mean function $m(x)$ and the covariance function $k(x, x')$; however, it has an additional parameter, the degrees of freedom ν . The properties of STP can be determined jointly by $m(x)$, $k(x, x')$ and ν , $x, x' \in R^d$ is an arbitrary random variable. Therefore, STP can be expressed as:

$$f(x) \sim STP(m(x), k(x, x'), \nu). \quad (9)$$

With increasing degrees of freedom, the multivariate Student's T distribution converges to a multivariate

Gaussian distribution with the same mean, and the scattering parameter matrix approaches infinity.

In STP, $m(x)$ defines the prior expected value of each location, the kernel function represents the covariance of the objective function between the values of any two locations x and x_0 , the joint distribution probability of a finite subset of locations is:

$$p(y | x) = T(\mu, \Sigma, \nu)(y) = T\left(\mu, \frac{\nu-2}{\nu}K, \nu\right)(y), \quad (10)$$

Where μ is the mean vector, $\mu_i = m(x_i)$, $K_{i,j} = k(x_i, x_j)$ is the kernel matrix.

Given a set of samples $D = [(x_1, y_1), \dots, (x_n, y_n)]$, the posterior of STP is given by (11), (12), (13), (14).

$$p(y | x, D) = T\left(\mu, \frac{\nu-2}{\nu}K, \nu\right)(y), \quad (11)$$

$$\hat{\mu} = K_{x,x} K_{\bar{x},\bar{x}}^{-1} \bar{y}, \quad (12)$$

$$\hat{K} = \frac{\left(\nu + \bar{y}^T K_{\bar{x},\bar{x}}^{-1} \bar{y} - 2\right) \cdot \left(K_{x,x} - K_{x,\bar{x}} K_{\bar{x},\bar{x}}^{-1} K_{\bar{x},x}\right)}{\nu + |D| - 2}, \quad (13)$$

$$\hat{\nu} = \nu + |D|. \quad (14)$$

In general, the square exponential kernel is selected [30]:

$$K_{SEard}(x, x') = \sigma_f^2 \exp\left(-\frac{(x-x')^T(x-x')}{2\ell^2}\right), \quad (15)$$

where σ_f^2 is the signal variance, which also is the output scale amplitude, and the parameter ℓ is the input (length or time) scale.

Combining equation (13) with the kernel function, we can see that the posterior covariance of the STP depends on not only the test observations, but also the training observations [31]. Therefore, using a STP as a surrogate model for a BO will have a more flexible posterior variance than a GP. The hyperparameter optimization of the STP is obtained by maximizing the likelihood function, whose negative log-likelihood function has the form:

$$\begin{aligned} L(\theta) &= -\log p(y | x, \theta) \\ &= \frac{N}{2} \log((\nu-2)\pi) + \frac{1}{2} \log |K_\theta| \\ &\quad - \log \Gamma\left(\frac{\nu+N}{2}\right) + \log \Gamma\left(\frac{\nu}{2}\right) \\ &\quad + \frac{\nu+N}{2} \log\left(1 + \frac{\beta}{\nu-2}\right). \end{aligned} \quad (16)$$

III. THE PROPOSED BAYESIAN OPTIMIZATION ALGORITHM

As a supervised learning method, BO can effectively seek the global optimal solution of the black-box objective function within the design space. By updating the prior knowledge of the objective function, we can obtain the corresponding observation value to update the posterior distribution closer, and find the optimal solution quickly [32].

The BO algorithm consists of two modules, the surrogate model module for fitting the objective function and the acquisition function module for acquiring new observations. The framework is shown in Fig. 1. The study of Bayesian architecture is inseparable from three directions: the construction of the surrogate model, the optimization of the surrogate model, and the design of the acquisition function.

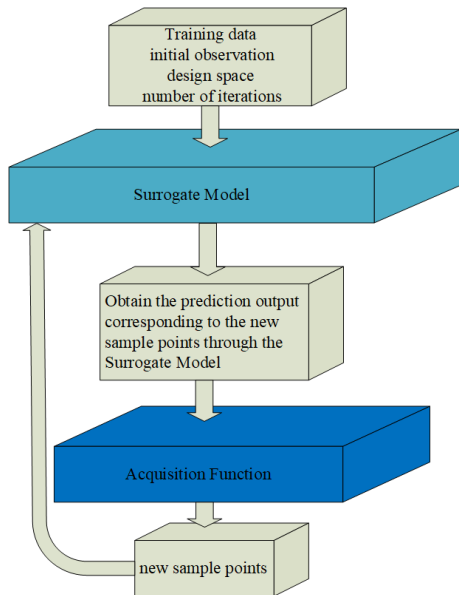


Fig. 1. Bayesian optimization framework.

In this paper, the STP is used as the surrogate model of BO, and the kernel function (17) without the β property is selected. The hyperparameters of the STP, including the degrees of freedom, noise variance, and hyperparameters of the kernel function, are globally optimized using the pattern search algorithm toolbox [33]. The optimization flowchart is shown in Fig. 2.

$$K_{SEisoU} = \exp\left(-\frac{1}{2\ell^2}(x-z)^T(x-z)\right). \quad (17)$$

The pattern search algorithm uses the negative log-likelihood of STP as the objective function to perform global optimization, obtain the final hyperparameters, and then determine the STP model. The model can output the corresponding prediction function value when given a new observation.

In the BO framework, the acquisition function use the information outputted by the surrogate model to explore the next observation. Common acquisition functions include confidence UCB/LCB [34, 35], EI [36], probability improvement (PI) function [26], entropy search (ES) function [37], EST [38] and ERM [39].

Martín presented a detailed derivation of GP upper/lower-confidence bound functions [36]:

$$\alpha_{UCB}(x) = \mu_{t-1}(x) + \sqrt{\beta_t}\sigma_{t-1}(x), \quad (18)$$

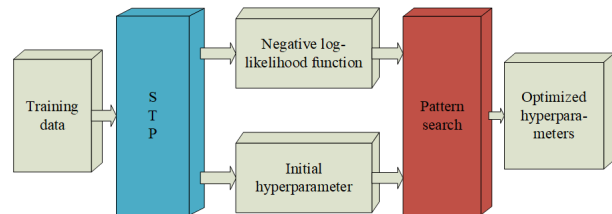


Fig. 2. Pattern search toolbox to optimize STP hyperparameters.

$$\alpha_{LCB}(x) = \mu_{t-1}(x) - \sqrt{\beta_t}\sigma_{t-1}(x). \quad (19)$$

Where β_t is the assumed given learning rate, which are different from the LCB function under the GP. In this paper, the $\mu(x)$, $\sigma(x)$ in LCB are changed to the prediction mean and prediction variance of STP.

Shah proposes a closed-form solution to the EI function for the STP [21]:

$$\alpha_{EI}(x; (x_n, y_n), \theta) = \gamma\sigma\Phi_v + N(\gamma(x)) + \sigma\left(1 + \frac{\gamma(x)^2 - 1}{v + N - 1}\right)\phi_v, \quad (20)$$

where

$$\gamma(x) = \sigma((x_n, y_n), \theta)^{-1} [f(x_{best}) - \mu((x_n, y_n), \theta)]. \quad (21)$$

$\mu((x_n, y_n), \theta)$ and $\sigma((x_n, y_n), \theta)$ are represent the predicted mean and variance of STP, respectively, ϕ, Φ represent the probability density function and distribution function of T distribution, and θ define the set of hyperparameters of STP.

The estimation strategy function selects the maximum posterior value m in each iteration, which can be expressed as $\arg\max_{x \in \mathcal{X}} \Pr(M_x | m, D_t)$, M_x is the event when the point reaches the maximum value. The EST function can be defined explicitly as:

$$\alpha_{EST}(x) = \frac{\hat{m} - \mu_{t-1}(x)}{\sigma_{t-1}(x)}. \quad (22)$$

Obtained by approximation, in this paper, the EST method mentioned in the literature [27] is used to obtain approximately \hat{m} . Unlike wang [27], we replace the predicted mean and predicted standard deviation of STP in the function $\mu(x)$, $\sigma(x)$ respectively.

As a result, the pseudocode of the proposed BO algorithm, called BO-STP-EST in the paper, is presented in Algorithm 1.

IV. NUMERICAL EXPERIMENT

In order to verify the generalization performance and global optimization effect of the proposed BO-STP-EST algorithm, numerical experiment is carried out based on the multimodal function (23), where the independent variable interval is $[-512, 512]$. So we finally obtained the training data $X \in 50 \times 1, Y \in 50 \times 1$ through the program. The experimental goal is to find the global minimum of this function, and the total number of itera-

Algorithm 1 BO-STP-EST.

Require:

Sample set, $D_{1:n} = ((\tilde{x}_1, \tilde{y}_1), \dots, (\tilde{x}_n, \tilde{y}_n))$;
 Initial point, $x_0 = [x_1, x_2, \dots, x_m]^T$;
 The number of iterations, $iters$;
 Lower bound and upper bound of the design space;

- 1: **for** each $i \in [1, iters]$ **do**
- 2: $D_{1:n} \rightarrow$ Optimize Hyperparameters for STP using pattern search algorithm, and then train STP;
- 3: $x_0 \rightarrow$ Obtain the posterior prediction mean μ_{i-1} and posterior variance σ_{i-1}^2 of x_0 by the trained STP;
- 4: $\arg \min \frac{\hat{m} - \mu_{i-1}(x)}{\sigma_{i-1}(x)} \rightarrow x_i^{opt}$, Get the new sample points by the acquisition function;
- 5: $x_i^{opt} \rightarrow STP \rightarrow f_i^{opt}$, Use the trained STP to predict the objective function value corresponding to the input sample point;
- 6: f_{best} take the current minimum value, x_{best} take the corresponding sample value;
- 7: **end for**

tions is set to 50. To verify the performance of the algorithm, we compare it with the BO-GP-LCB [1], BO-GP-EST [27], BO-STP-ERM [23], BO-STP-EI [21], and BO-STP-LCB. For the STP in the models of BO-STP-ERM, BO-STP-LCB, and BO-STP-EI, global optimization is not implemented. The experimental results are shown in Figs. 3 and 4.

$$y = -(x + 47) \times \sin(\sqrt{|x + 47|}) - 512 \times \sin(\sqrt{465 - x}). \quad (23)$$

It can be seen intuitively from Fig. 3 that only the

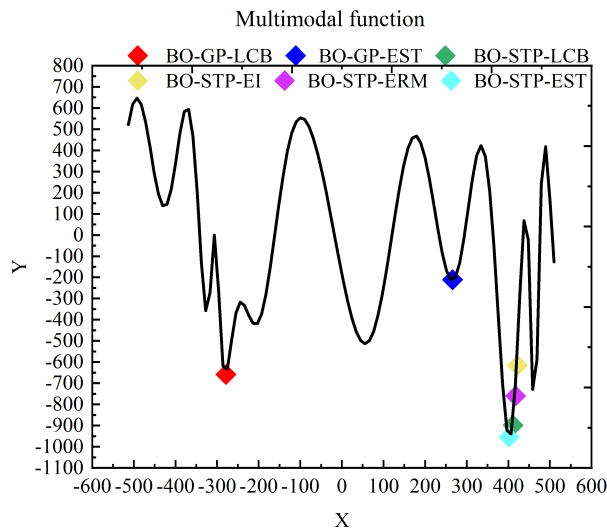


Fig. 3. The found minimum value by different models.

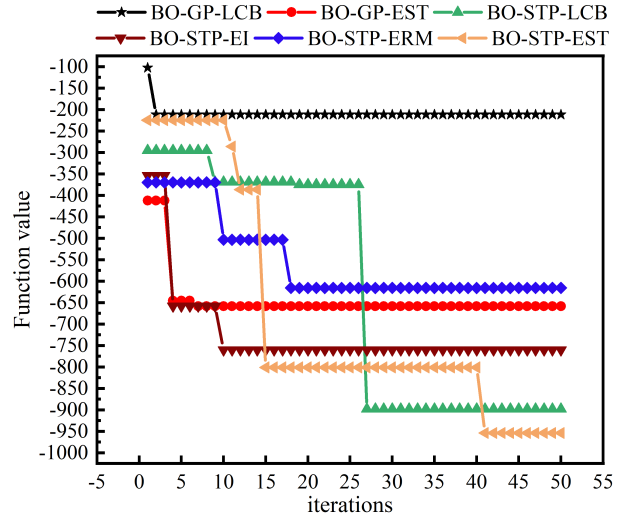


Fig. 4. Function value vs. iteration numbers of different models.

BO-STP-EST proposed in this paper finds the global minimum of the multimodal function. Models such as BO-GP-LCB and BO-GP-EST are trapped in the local minimum of the function, and other BO algorithms are close to the global minimum of the function, which shows that the proposed BO algorithm has a strong global optimization ability. As can be seen from Fig. 4, since we set the first iteration to be the new sample point explored by the model corresponding to the objective function value, the starting points in the figure are inconsistent, which also just shows that the ability of different models to explore sample points is different.

Although the objective function value obtained by BO-GP-LCB for the first time is the smallest, it never explores a function value smaller than the current value after 4th time. Compared with the same acquisition function with EST, the exploration ability of the BO algorithm with the GP as the surrogate model is much lower than that of the BO algorithm with the STP as the surrogate model. Compared with the same surrogate model algorithm, the prediction accuracy of the proposed BO-STP-EST algorithm after hyperparameter optimization is significantly higher than that of other models.

V. OPTIMAL DESIGN OF MICROSTRIP ANTENNAS

A. Printed dipole antenna

The printed dipole antenna comes from the literature [40] and its structure is shown in Fig. 5. The whole antenna can be divided into five parts, which are the dielectric layer, the dipole antenna arm, the microstrip balun line, the microstrip transmission line, and the antenna feeding surface, The dimensional parameters of

Table 1: Antenna size parameters

Variable	Value/mm
L1	21.5
L2	21.5
L3	9.8
W1	3
W2	3
W3	3.5
ϵ_r	4.4
h	1.6

the antenna are shown in Table 1. The working frequency of the antenna is 2.25 GHz-2.72 GHz, and the design index include that its working frequency is 2.45 GHz, and the return loss S11 is less than -15 dB.

As shown in Fig. 5, the antenna has many variables that affect its performance. We select five size variables that have more significant impact as input, as shown in Table 2, including the transmission line length L1, one dipole arm the length L2, the side length L3 of the balun triangle, the right angle length L4 of the base of the balun triangle, and the width W3 of the balun rectangle.

Therefore, the input is $X = [L_1, L_2, L_3, L_4, W_3]$, the output is the resonant frequency, while other parameters are fixed. The HFSS-MATLAB-API [41] program is used for the co-simulation of the antenna using the orthogonal experiment method. The frequency sweep range is 2 GHz through 3 GHz, and the step size is 0.01 GHz. So, each group of antenna size variables corresponds to 100 resonance frequency points. The training sample size is $X \in 50 \times 5, Y \in 50 \times 1$.

According to the design index of the antenna, the design objective function is (24), where $f_{resonant} = 2.45$ GHz, $f_{prediction}$ is the predicted resonant frequency.

$$f_{objective} = |2.45 - f_{prediction}|^2 \& f_{resonant} < -15 \text{ dB}. \quad (24)$$

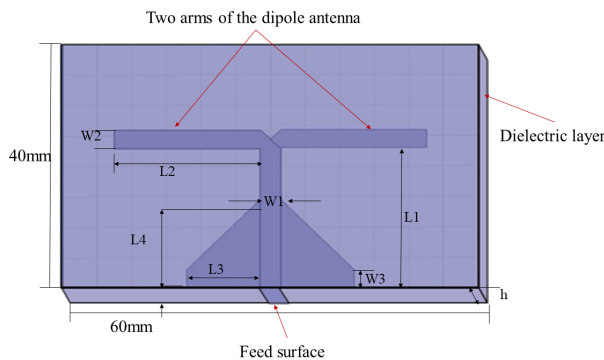


Fig. 5. The found minimum value by different models.

Table 2: Design range and initial design value of the printed dipole antenna

Variable	Min/mm	Max/mm	Initial value/mm
L1	21	23	21.5
L2	20	22.5	21.5
L3	9	10.5	9.8
L4	11.5	13	12.6
W3	3	5	3.5

In order to verify the effectiveness of the BO-STP-EST algorithm proposed in this paper, the BO-GP-LCB, BO-GP-EST, BO-STP-LCB, BO-STP-EI, BO-STP-ERM, and the BO-STP-EST are compared. The iterative performance of the objective function under different models, the optimization results of the antenna size and the actual simulation results of the optimized antenna size are verified by experiments. The design space and initial sample points are shown in Table 2, and the total number of iterations is 50 times. The experimental environment is Inter(R)Corte(TM)i5-7500 CPU @ 3.40 GHz 16GB RAM, MATLAB2019b.

From Fig. 6 and Table 3, we can see that the proposed BO-STP-EST exhibits a good generalization ability, and it can find the minimum in a few iterations. Compared with the BO algorithm with GP as the surrogate model, BO-GP-LCB find a smaller value in the 41st time, but this minimum value is very different from other models. For the same acquisition function, BO-GP-EST takes more time to find the minimum at the 8th iteration, and the proposed BO-STP-EST performs much better than BO-GP-EST, where it finds the minimum value at the 3rd

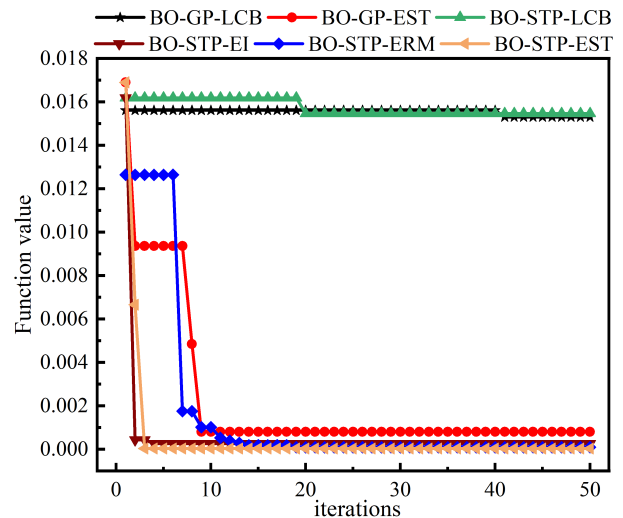


Fig. 6. The found minimum value by different models.

Table 3: Optimization results of different models of the printed dipole antenna

Model	L1	L2	L3	L4	W3	Iteration	$f_{objective}$	time
BO-GP-LCB	23	20.1999	9.0208	12.6053	3	41	1.53e-02	106.8259
BO-GP-EST	22.4373	20.7785	9	12.9988	3.2000	8	8.03e-04	105.4107
BO-STP-LCB	23	22.5000	10.6000	11.5000	3	20	1.55e-02	60.3916
BO-STP-EI	22.8226	21.2913	9.6366	12.1941	3.8591	5	2.65e-04	115.4727
BO-STP-ERM	22.4044	20.0226	9.9722	11.5997	4.5191	19	8.60e-05	137.3362
BO-STP-EST	23	21.0537	10.5999	11.5000	3	3	2.88e-05	93.5832

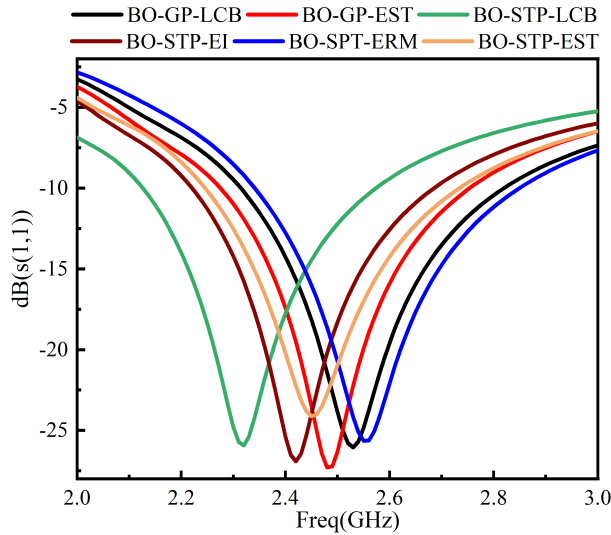


Fig. 7. The found minimum value by different models.

iteration. Compared with other models with STP, BO-STP-EI and BO-STP-ERM are not as good as BO-STP-EST in terms of the objective function and time consumption because the optimized STP has fitting higher-degree posterior outputs which makes the EST collection function have stronger exploration ability.

The antenna optimization results in Fig. 7 verified by HFSS illustrate that, for the design index of the resonant frequency of the antenna, only the proposed BO-STP-EST achieves the design targets with the resonant frequency 2.45 GHz and where $S_{11} < -15$ dB. The resonant frequency points predicted by other models have certain errors, which are also in line with the prediction results of the objective function in Table 3 and Table 4. It can be concluded from the above tables and figures that the proposed BO-STP-EST has greater advantages in convergent speed and accuracy than other models.

B. E-shaped antenna

The E-shaped antenna is evolved from the rectangular patch antenna, and two identical parallel slot antennas are formed by using the slot-loading method [42]. For the E-shaped antenna, it is easy to obtain good perfor-

Table 4: The actual resonant frequencies optimized by different models of the printed dipole antenna

Model	Resonant frequency/GHz	Return loss/dB
BO-GP-LCB	2.53	-26.0488
BO-GP-EST	2.49	-27.2250
BO-STP-LCB	2.32	-25.9310
BO-STP-EI	2.42	-26.9227
BO-STP-ERM	2.56	-25.6303
BO-STP-EST	2.45	-24.1248

Table 5: Design range and initial design value of the E-shape antenna

Variable	Min/mm	Max/mm	Initial value/mm
L	25	35	26
W	20	28	29
ls	2	8	4
ws	4	18	7
h	1.57	3.57	1.6

mance by adjusting the shape of the slot, which is very suitable for use in portable communication and miniaturized equipment. The E-shaped antenna is shown in Fig. 8, which consists of a radiation patch, a ground plane, a dielectric plate, and a feeding point.

The design index is the working frequency 3.50 GHz, where the return loss S_{11} is less than -10 dB. According to the structure of the antenna, several parameters that greatly affect the performance of the antenna, including L, W, ls, ws, h , are selected as the training input of the model, and the rests are unchanged, including the dielectric material $\epsilon_r = 2.33$, as shown in Table 5.

Therefore, the input is $X = [L, W, ls, ws, h]$, and the output is $f_{resonant}$. The frequency sweep range is 2 GHz-5 GHz, the step size is 0.01 GHz. So, each group of antenna size variables corresponds to 100 resonance frequency points, and the training data $X \in 41 \times 4, Y \in 41 \times 1$ is finally obtained.

To verify the generalization and optimization performance of the proposed BO-STP-EST, we compare

Table 6: Results obtained by different models for the E-shape antenna

Model	L	W	ls	ws	h	Iteration	$f_{objective}$	time
BO-GP-LCB	35	28	2	4.84	3.57	6	0.105	106.83
BO-GP-EST	30.09	24.12	5	14.5	2.57	12	1.616e-05	115.19
BO-STP-LCB	25	28	2	18	1.64	28	0.0424	165.4
BO-STP-EI	30.89	20.30	2.50	16.05	2.77	41	0.0372	198.42
BO-STP-ERM	26.20	27.71	8	16.10	2.62	42	7.626e-05	220
BO-STP-EST	35	28	8	4.95	3.57	7	5.313e-05	197.03

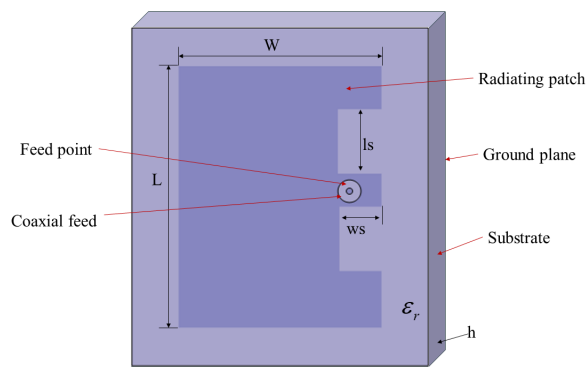


Fig. 8. E-shaped antenna structure diagram.

the performances of the BO-GP-LCB, BO-GP-EST, BO-STP-LCB, BO-STP-EI, and BO-STP-ERM. The design objective function is (25), where $f_{resonant} = 3.50 \text{ GHz}$, $f_{prediction}$ is the predicted resonant frequency.

$$f_{opt} = |3.50 - f_{prediction}|^2 \& f_{resonant} < -10 \text{ dB}. \quad (25)$$

The experiment compares the differences in the number of iterations, the minimum value, and the duration of the six models. The results are shown in Table 6. The return loss of the antenna obtained by the final optimization of each model is also compared, and the results are shown in Fig. 9 and Table 6.

As can be seen from Fig. 9, since the sample points recorded in the first setting of the model program are ones collected by the acquisition function, we can see the ability of different models to explore the sample points in the sample space. Compared with the same acquisition function EST, although the value of the objective function corresponding to the sample points first explored by the proposed BO-STP-EST algorithm is greater than BO-GP-EST, it is much stronger than BO-GP-EST in the subsequent exploration ability. It finds the global minimum value in the 7th iteration and is better than that found by BO-GP-EST in the 12th iteration.

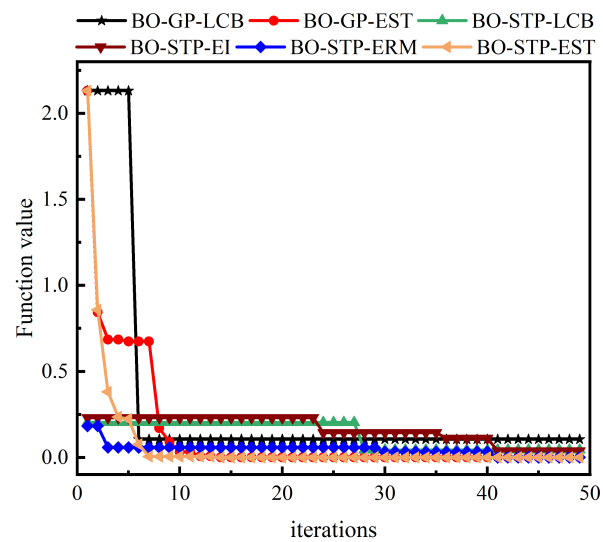


Fig. 9. Objective functions vs. iteration of different model for the E-shape antenna.

Compared with other models by STP, BO-STP-EST can find the minimum value of objective function which is much smaller than BO-STP-LCB and BO-STP-EI. As we can see from table 6,7, although the final objective function value found by BO-STP-ERM is close to BO-STP-EST, it takes more time. Therefore, BO-STP-EST is still the most competitive among several models in terms of minimum value and time-consuming of objective function.

In the experiment of this part, we deliberately reduce the number of training samples, so as to verify that the hyperparametric optimization of the model can improve the prediction ability of the algorithm proposed in this paper when the training samples are reduced. The simulation results (Fig. 10) verified by HFSS show that when the training samples are reduced (Table 7), the prediction accuracy of the different models mentioned in the

Table 7: The actual resonant frequencies optimized by different models of the printed dipole antenna

Model	Resonant frequency/GHz	Return loss/dB
BO-GP-LCB	3.49	-13.460
BO-GP-EST	3.69	-33.945
BO-STP-LCB	3.30	-17.399
BO-STP-EI	4.27	-20.067
BO-STP-ERM	3.19	-28.231
BO-STP-EST	3.50	-12.837

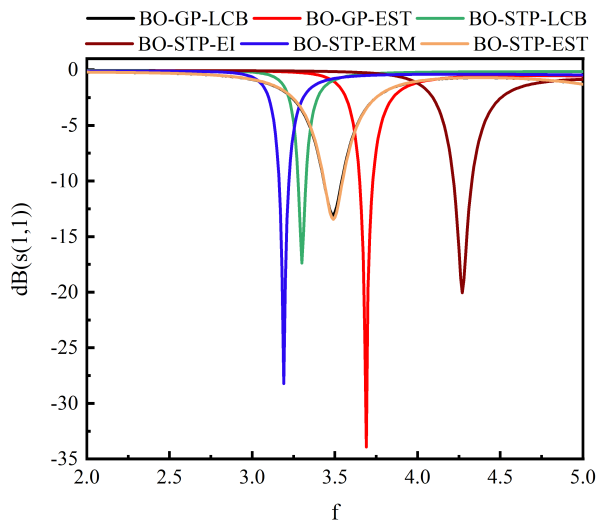


Fig. 10. Simulation results obtained by different models for the E-shape antenna.

paper begins to decline, however, the accuracy of the BO-STP-EST is much higher than that of the algorithm without global hyperparameter optimization. Taking the STP as surrogate model, the algorithm still maintains good prediction accuracy under the condition of reducing the number of training samples. At the same time, the proposed BO-STP-EST realizes the design index of $S_{11} < -10$ dB at the resonant frequency at 3.5 GHz. It shows that the hyper-parameter optimization of surrogate model can improve the accuracy and optimization performance of Bayesian optimization algorithm.

VI. CONCLUSION

This paper proposes a BO algorithm that combines an improved maximum evaluation policy function with a hyperparameter-optimized STP. Numerical experimental verification of finding the minimum value through multimodal functions shows that the proposed BO algorithm with the STP as the surrogate model has better prediction accuracy than these with the GP as the surrogate model. At the same time, the acquisition function EST can improve the exploration ability of the BO algorithm.

The proposed algorithm in this paper is applied to the antenna modeling problems, and the design index can be well completed. The simulation results of electromagnetic simulation software also verify the effectiveness of the algorithm.

Although the proposed algorithm is only applied to the optimization problem of single-band antennas in this paper, following, we will study the multi-band antenna optimization by the proposed algorithm.

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