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Improving the Performance of IWDM FBG Sensing System Using Tabu-Gradient Search Algorithm

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Abstract — A Tabu-gradient search algorithm is presented for improving the performance of FBG sensors in an intensity and wavelength-division multiplexed sensing system. Simulation results demonstrated that by using this technique the Bragg wavelengths of the FBG sensors can be accurately and quickly detect even when the original spectrums of FBG sensors can not be pre-determined.

I. INTRODUCTION

The multiplexing of sensors is a particularly a key issue for a fiber Bragg grating (FBG) sensing system that can provide a distributed measurement along a single fiber. The following multiplexing techniques have been applied to optical sensor: time, wavelength, spatial, and frequency [1], among which the wavelength division multiplexing (WDM) technique is most widely used. The maximum number of sensors associated with WDM is limited by the ratio of the source spectral width over the spacing between the Bragg wavelengths variation range of the FBGs. Recently, many advanced multiplexing techniques are developed to improve the multiplexing capacity of FBG sensing systems such as intensity and wavelength-division multiplexing (IWDM), mixed WDM/TDM multiplexing, code-division multiplexing access (CDMA) multiplexing and frequency-modulated continuous-wave (FMCW) multiplexing [2]-[5]. In particular, IWDM technique has the advantages of low complexity and enables the system to have twice the number of FBGs as the conventional WDM technique. Moreover, with a demodulation technique called minimum variance shift (MVS), the IWDM scheme can be implemented using common FBG sensors [6]. However, this technique requires long processing times to gain high detection accuracy, which significantly limit the applications of the system.

This paper employs the tabu search (TS) method combined with the gradient algorithm (TG) to improve the performance of the IWDM-based FBG sensing system. This technique can quickly determine the Bragg wavelengths without sacrificing the wavelength detection accuracy. The system model of IWDM-based FBG sensing system is introduced in Section 2. The Implementation of TG on IWDM-based FBG sensing system is shown in Section 3. The simulation result is presented in Section 4 and the conclusion is given in Section 5.

II. SYSTEM MODEL

In this paper we consider the IWDM based FBG sensing system with two FBG sensors shown in Fig 1. Note that the two FBG sensors of the system have different reflectivity.

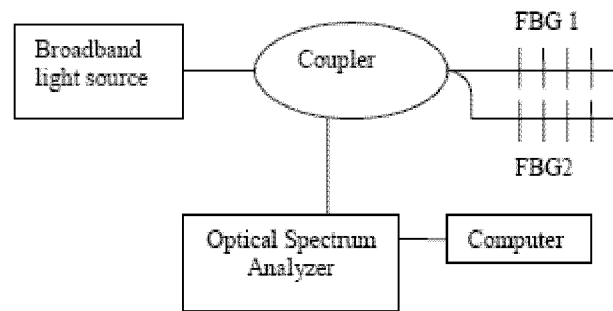


Fig.1. System diagram

With the optical spectrum analyser, the spectrum of the light reflected from the two sensors can be measured which can be expressed as:

$$R(\lambda) = R_1 g_1(\lambda - \lambda_{B1}) + R_2 g_2(\lambda - \lambda_{B2}) + N(\lambda) \quad (1)$$

where $g_1(\lambda)$ and $g_2(\lambda)$ are the reflection spectrums, λ_{B1} , λ_{B2} and R_1 , R_2 ($R_1 \neq R_2$) are the Bragg wavelengths and the peak reflectivity of the two FBGs respectively. $N(\lambda)$ is a random spectral fluctuation introduced by the noise that occurs in the system.

Our purpose is to determine the values of λ_{B1} , λ_{B2} respectively. However, as we want that λ_{B1} and λ_{B2} are as close as possible, $g_1(\lambda)$ and $g_2(\lambda)$ are overlapped and it is difficult to identify λ_{B1} and λ_{B2} directly from the shape of $R(\lambda)$. For this reason we use the model fitting technique as follows.

Extensive research has been done to investigate the spectrum shape of the reflected light from FBG sensors, which were found to be Gaussian functions. Therefore we can assume that the reflected spectrum in Figure 1 is as follows:

$$\begin{aligned} R_m(\lambda, \hat{\lambda}_{B1}, \hat{\lambda}_{B2}) &= R_{m1}(\lambda, \hat{\lambda}_{B1}) + R_{m2}(\lambda, \hat{\lambda}_{B2}) \\ &= R_1 g_1(\lambda - \hat{\lambda}_{B1}) + R_2 g_2(\lambda - \hat{\lambda}_{B2}) \end{aligned} \quad (2)$$

where $\hat{\lambda}_{B1}$ and $\hat{\lambda}_{B2}$ are the estimated Bragg wavelengths of the two sensors, and $g_i = \exp(-4 \ln 2 \frac{(\lambda - \hat{\lambda}_{Bi})^2}{\alpha_i^2})$ is a Gaussian function with α_i being the spectral full width at half-maximum (FWHM) of i -th FBG sensor. We are tried to determine the two FBG wavelengths by minimizing the following cost function with respect to $\hat{\lambda}_{B1}$ and $\hat{\lambda}_{B2}$ respectively:

$$D(\hat{\lambda}_{B1}, \hat{\lambda}_{B2}) = \frac{1}{\lambda_2 - \lambda_1} \int_{\lambda_1}^{\lambda_2} [R(\lambda) - R_m(\lambda, \hat{\lambda}_{B1}, \hat{\lambda}_{B2})]^2 d\lambda \quad (3)$$

where $[\lambda_1, \lambda_2]$ is possible range for the FBG wavelength range. It is obvious that $D(\hat{\lambda}_{B1}, \hat{\lambda}_{B2})$ is minimized when $\hat{\lambda}_{B1} = \lambda_{B1}$, $\hat{\lambda}_{B2} = \lambda_{B2}$. Therefore, by scanning $\hat{\lambda}_{B1}$ and $\hat{\lambda}_{B2}$ through specified ranges with a small step size, the minimum $D(\hat{\lambda}_{B1}, \hat{\lambda}_{B2})$ and corresponding λ_{B1} and λ_{B2} can be determined by:

$$D(\hat{\lambda}_{B1}, \hat{\lambda}_{B2})_{\min} = D(\hat{\lambda}_{B1}, \hat{\lambda}_{B2}) \Big|_{\hat{\lambda}_{B1}=\lambda_{B1}, \hat{\lambda}_{B2}=\lambda_{B2}} \quad (4)$$

Using this method, the Bragg wavelengths of the multiplexed FBG sensors can be located even when their reflection spectrums overlap with each other. Therefore, the system can have twice the number of FBGs as the conventional WDM sensor array. However, the computational burden of this algorithm is heavy, especially when the original spectrum of FBG sensors can not be pre-determined (i.e. R_i and α_i are unknown). To solve this problem, we propose to use tabu-gradient optimal algorithm in the following section.

III. APPLYING TABU-GRADIENT ALGORITHM ON IWDM FBG SENSING SYSTEM

TS is a probabilistic global search algorithm for solving combinatorial optimization problem [7]. The aim is to find an optimum solution $s = s^*$ in the whole solution space S . As discussed in last section, if parameters of the original spectrums of FBG sensors is unknown, then six parameters $\hat{R}_1, \hat{R}_2, \hat{\alpha}_1, \hat{\alpha}_2, \hat{\lambda}_{B1}$ and $\hat{\lambda}_{B2}$ need to be determined. In order to apply the TS algorithm on IWDM FBG sensing system, a solution space that contains all sets of parameters $S = \{\hat{R}_1, \hat{R}_2, \hat{\alpha}_1, \hat{\alpha}_2, \hat{\lambda}_{B1}, \hat{\lambda}_{B2}\}$ is constructed and the working principle of TS is shown in Fig. 1.

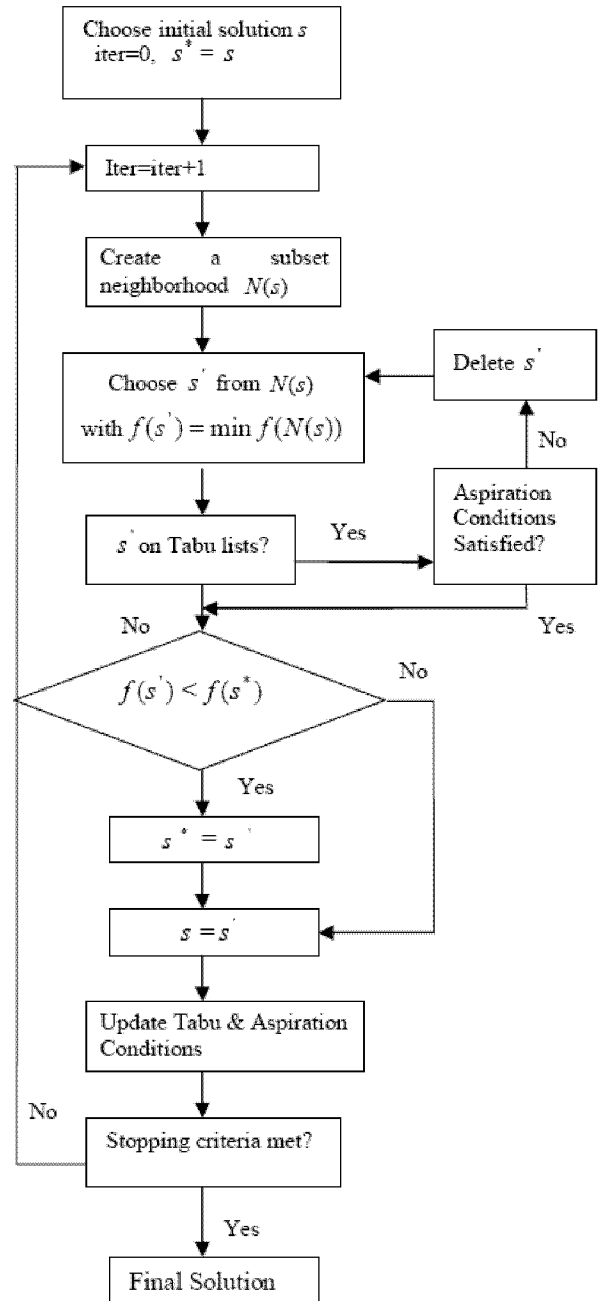


Fig.2 Flowchart of Tabu Search algorithm

To begin with, a starting solution s is randomly generated. Also, s is evaluated by an object function $f(s)$. Then a neighbourhood solution $N(s)$ is produced according to the current solution s . A local search algorithm is then carried out to find the best solution s' for the object function in this subset neighbourhood $N(i)$. s' will be recorded as the best new neighbour and the starting point for the next iteration if it is not on the tabu list. This process repeats until the stopping condition is met.

The tabu list is used to implement tabu restrictions based on regency or frequency. The most widely used tabu list is based on regency which records the latest visit

solutions and maintains them for a given time, called tabu tenure. This type of tabu list is often called short term memory. According to the tabu list, the local search algorithm will not reuse the solutions recorded on the tabu list. Because TS can accept non-improving solutions and thus escape from local minima, it is possible to find the global optimum of the objective function. Typically, the length of a tabu list is pre-specified and the tabu list is stored in a memory. At each iteration, the tabu list is updated by adding a new solution and removing other solutions, using a FIFO (first-in-first-out) discipline.

Using TS algorithm, the computation time of achieve best solution will be reduced. However, it still takes a relatively long time. The reason is that the TS may miss some near global solution during the search process. For instance, as shown in Fig. 3, solutions A and B are neighbourhoods of C, which is the starting point of iteration. By TS algorithm, solution A may be selected as the best neighbourhood solution for $f(A) < f(C)$ although B is the global minimum. This phenomenon is due to the random move principle of the TS, by which the TS may lose the nearby global minimum.

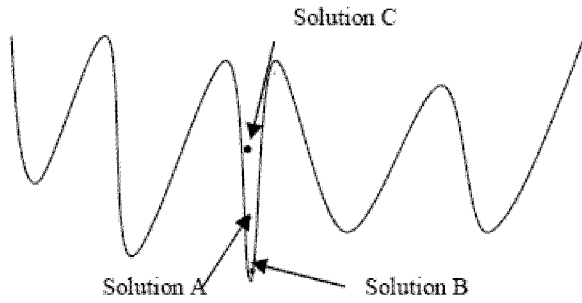


Fig. 3 The reason that TS may miss a close global minimum Bragg wavelength

To solve this problem and further improve the performance of TS, we proposed a tabu-gradient combination optimization algorithm. The implementation of TG algorithm is very simple. Based on TS algorithm, the best neighbourhood s' is applied as the initial solution of the gradient algorithm. Then the solution obtained from the gradient algorithm is the best neighbourhood solution within $N(s)$, because it achieves minimum value of the object function compared with its neighbour. The neighbours of this solution will be evaluated in the next iteration unless they are not in the tabu list. By using TG algorithm, the search process will not miss the global minimum nearby.

In this particular application, the components of TG are defined as follows.

A. Search Space

Search space depends on the type of parameter. For instance, $R_1, R_2 \in (0,1)$, $\alpha_1, \alpha_2 \in (0,0.5)nm$. The search range of $\hat{\lambda}_{B1}$ and $\hat{\lambda}_{B2}$ are decided according to the experimental requirement.

B. Neighbourhood Generation

A single parameter generation strategy is adopted. Using this strategy, new solutions are generated by varying only one parameter and keeping the others fixed. The parameter is varied using a random coefficient β :

$$\beta = \delta r_i (X_t - X_b) \quad (5)$$

where δ is a [-1,1] random number, r_i is a constant factor according to different parameters which decide the estimation precision and $X_t - X_b$ is the search space of the parameter. Thus,

$$X_{new} = X_{old} + \beta \quad (6)$$

C. Object Function

The object function is the mean square function:

$$f = \frac{1}{L} \sum_{\lambda=n_1}^{n_2} [R(\lambda) - (\hat{R}_1 g_1(\lambda - \hat{\lambda}_{B1}) + \hat{R}_2 g_2(\lambda - \hat{\lambda}_{B2}))]^2 \quad (7)$$

where $[n_1, n_2]$ is the wavelength range, L is the sampled number of wavelength range.

D. Memory Type

In this application, we use short term memory and a tabu list is employed based on recency. The length of the tabu list is set to 20. Therefore, the 20 most recently changed variables are kept in the tabu list.

E. Criteria for Stopping the Search

The search will stop as $F < 10^{-4}$ or when the iteration number is larger than 10^5 .

F. Gradient Algorithm

Using gradient based algorithm, the solution is estimated in an iterative way and converges to a constant value, which minimizes the object functions:

$$\begin{aligned} \hat{R}(n+1) &= \hat{R}(n) - \mu \nabla f(\hat{R}(n)) \\ \hat{\alpha}(n+1) &= \hat{\alpha}(n) - \mu \nabla f(\hat{\alpha}(n)) \end{aligned} \quad (8)$$

$$\hat{\lambda}_{B1}(n+1) = \hat{\lambda}_{B1}(n) - \mu \nabla J(\hat{\lambda}_{B1}(n))$$

$$\hat{\lambda}_{B2}(n+1) = \hat{\lambda}_{B2}(n) - \mu \nabla J(\hat{\lambda}_{B2}(n))$$

where μ is the step size,

IV. SIMULATIONS

Computer simulation is carried out using two FBG sensing systems as shown in Fig.1. In the simulation, the spectrum of the measured signal $R(\lambda)$ is generated using (1) and the coefficients of $R(\lambda)$ were assumed as: $\lambda_{B1} = 1530 \text{ nm}$, $\lambda_{B2} = 1530.1$, $R_1=0.8$, $R_2=0.5$, $\alpha_1=\alpha_2=0.2 \text{ nm}$, $N(\lambda)$ is white noise with a signal to noise ratio (SNR) of about 10db. The measured spectrum is sampled into 2000 samples within the spectral range from 1529 nm to 1531 nm.

Simulation is conducted to detect the Bragg wavelength λ_{B1} and λ_{B2} using TG. The search range of $\hat{\lambda}_{B1}$ and $\hat{\lambda}_{B2}$ is $[1529, 1531] \text{ nm}$. The constant factors of the movement of the parameters are selected as $r_{\hat{\lambda}_{B1}} = r_{\hat{\lambda}_{B2}} = 10^{-4}$, $r_{R_1} = r_{R_2} = 0.01$, $r_{\alpha_1} = r_{\alpha_2} = 0.01$. The TG procedure is described as follows:

1. The TG is started from a random initial solution $s = [\hat{R}_1, \hat{R}_2, \hat{\alpha}_1, \hat{\alpha}_2, \hat{\lambda}_{B1}, \hat{\lambda}_{B2}]$, then set for the best solution $s^* = s$.
2. The neighbourhood solutions $N(s)$ of s are generated by randomly moving only one of the parameters of s using (5) and (6).
3. Choosing the best neighbourhood s^i from $N(i)$ and implement gradient algorithm.
4. Checking whether it is on the tabu list.
5. If $f(s^i) < f(s)$, $s = s^i$; If $f(s) < f(s^*)$, $s^* = s$
6. If $f(s) > f(s^*)$ 3 times, go to step 2 and generate the neighbourhood solutions by moving another parameter of i randomly.
7. Repeat steps 2-6 until the criteria for stopping the search is met.

As a result, TG is finished after 1,154 iterations, taking 16 seconds running on Pentium III 600 MHz 512-M computer. The results of search are shown in the following table.

	R_1	R_2	α_1 (nm)	α_2 (nm)	λ_{B1} (nm)	λ_{B2} (nm)
True value	0.8	0.5	0.2	0.2	1530	1530.1
Estimated by TG	0.78	0.51	0.19	0.18	1529.9961	1530.1027

The detection error for the Bragg wavelength of FBG1 and FBG2 are 3.9 pm and 2.7pm respectively. We repeat the tabu-gradient search 8 times from different initial solutions, and the measurement error is shown in Fig. 4. The root mean square (RMS) values for Bragg wavelength detection error for FBG1 and FBG 2 are 3.027 and 2.26 pm respectively, and the average processing time is 19 seconds.

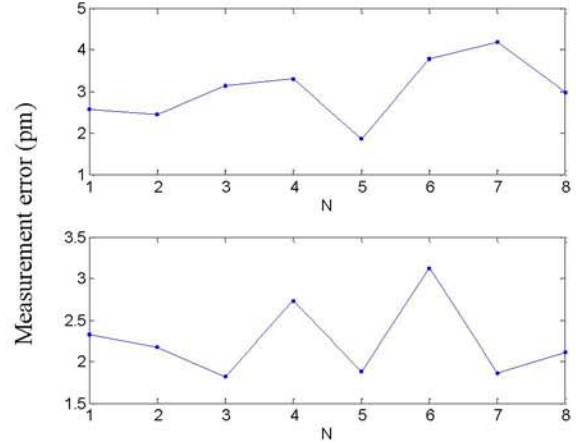


Fig.4 Bragg wavelength detection error for FBG1 (upper diagram) and FBG2 (lower diagram) using TG algorithm

V. CONCLUSION

The global optimization algorithm TG has been applied on an IWDM based FBG sensing system. The simulation results indicate that by using TG algorithm we can accurately and quickly detect Bragg wavelengths even when the original spectrums of FBG sensors can not be pre-determined.

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