Bayes’ theorem-based binary algorithm for fast reference-less calibration of a multimode fiber

TIANRUI ZHAO, 1 LIANG DENG, 1 WEN WANG, 1 DANIEL S. ELSON, 2 AND LEI SU 1,*

1School of Engineering and Materials Science, Queen Mary University of London, London E1 4NS, UK
2Department of Surgery and Cancer, Imperial College London, London SW7 2AZ, UK
*lsu@qmul.ac.uk

Abstract: In this paper, we present a Bayes’ theorem-based high-speed algorithm to measure the binary transmission matrix of a multimode fiber using a digital micromirror device in a reference-less multimode fiber imaging system. Based on conditional probability, we define a preset threshold to locate those digital-micromirror-device pixels that can be switched ‘ON’ to form a focused spot at the output. This leads to a binary transmission matrix consisting of ‘0’ and ‘1’ elements. High-enhancement-factor light focusing and raster-scanning at the distal end of the fiber are demonstrated experimentally. The key advantage of our algorithm is its capability for fast calibration of a MMF to form a tightly focused spot. In our experiment, for 5000 input-output pairs, we only need 0.26 s to calibrate one row of the transmission matrix to achieve a focused spot with an enhancement factor of 28. This is more than 10 times faster than the prVBEM algorithm. The proposed Bayes’ theorem-based binary algorithm can be applied not only in multimode optical fiber focusing but also to other disordered media. Particularly, it will be valuable in fast multimode fiber calibration for endoscopic imaging.

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1. Introduction

Focusing light through a multimode fiber (MMF) and raster-scanning the focusing spot at the fiber distal end holds promise in developing ultrathin endoscopes for biomedical imaging. Controlling light through multimode optical fibers (MMF) has been a great challenge due to the strong mode coupling in the fiber. Typically, a series of modes with different phase velocities are excited and coupled with each other during light propagation, which results in noise-like speckle patterns at the fiber end facet [1]. Recently, spatial light modulation achieved control of the transmitted light field through scattering media [2–7] and MMFs [8–18]. Vellekoop et al. pioneered light focusing through scattering media using a liquid-crystal-based spatial light modulator (SLM), by shaping the incident light wavefront to compensate the scattering effect of the medium [2]. By decomposing and modulating the phase and amplitude of incident light field into SLM pixels, the transmitted field at the output can form desirable images or patterns such as a tightly focused spot.
There are a number of approaches to calibrate disordered media when using SLM, including digital optical phase conjugation [13-14,19], iterative algorithms [2,3,9,20] and transmission matrix (TM) measurements [10-12,21,22]. Digital optical phase conjugation requires a prior focused light spot at the target position in the output plane. Subsequently, a camera records both amplitudes and phases of the transmitted light field holographically. By projecting the reversed amplitudes and phases onto an SLM placed in the same optical plane, the same focused spot can be achieved. The digital optical phase conjugation method has been demonstrated in fluorescence imaging [13] and photoacoustic imaging [14]. In contrast, a prior focused spot is not needed for iterative algorithms and TM methods. Iterative algorithms sequentially change the phase delay at each SLM pixel and select the phase that leads to the desirable pattern at the MMF distal end. By recording the optimized phase masks for light focusing at each output location and projecting the masks for desired output patterns, Čižmár et al. achieved micro-particle manipulation and image transmission through MMFs [8,9,23]. The measurement of a TM decomposes both input and output fields into pixels, linking input and output pixels with a complex amplitude. Based on the measured TM of the disordered medium, the optimal input field or the target output can be determined if one of these fields is known. Popoff et al. measured the TM of diffuse media using a ‘four phase’ approach [21,22], which was also applied to a MMF [12]. Choi et al. calibrated the TM of a MMF by measuring both the input and output light fields and achieved image reconstruction through a single MMF [10].

Recently, digital micromirror devices (DMD) operating at frequencies over 20 kHz, were used as fast alternatives to SLMs [3,10,24,25]. As a binary amplitude modulator, each DMD pixel provides two states, ‘ON’ or ‘OFF’. Turning ‘ON’ a DMD pixel allows projecting light from this pixel to the medium. DMDs have been used in iterative methods [3] and TM measurements [10] as well as being used as a phase modulator based on Lee holograms [26] and in super-pixel methods [27]. Additionally, binary TM measurements [28] and millisecond digital optical phase conjugations [29] were achieved, by dividing DMD pixels into two categories according to whether the DMD pixel leads to constructive or destructive interference with reference beams. Recently, DMDs were used with phase retrieval algorithms for reference-less TM measurements, leading to a simplified experimental configuration [30,31].

In this work, we develop a high-speed algorithm based on Bayes’ theorem using conditional probability, to measure the binary TM for a reference-less DMD-based MMF imaging system. We note that with the measured complex elements (t
\text{in}) in a row of a complex TM, turning ‘ON’ only those DMD pixels corresponding to Re(t
\text{in}) > 0 or Re(t
\text{in}) < 0 respectively, leads to light focusing at the corresponding output location. When focusing light through a disordered medium with a binary DMD, a complex TM that requires extra computing time may not be necessary. In our algorithm, we use conditional probability to find a group of DMD pixels that can form a sharp focus at a certain output location when being switched ‘ON’, leading to a binary TM We show that iteration optimization is unnecessary in our binary calculation, and therefore high-speed MMF calibration is achieved. We experimentally demonstrate light focusing through a MMF and raster-scan the focused spot across the fiber distal end. The enhancement factor and the computing time of our algorithm are compared to those provided the prVBEM algorithm, and our algorithm is more than 10 times faster to achieve the same enhancement factor.

2. Binary transmission matrix algorithm

2.1 Binary amplitude modulation

When a DMD fills the entrance pupil of a MMF, the transmitted field measured by a camera at the MMF output is a linear superposition of the output fields from all input DMD pixels. Here we define a DMD pixel as an ‘input’ pixel (the total number is N) and a camera pixel as
an ‘output’ pixel (the total number is $M$). For the $m$th output pixel, the field $E_m$ is the superposition of all input fields $E_n$ multiplied by their corresponding TM elements $t_{mn}$:

$$E_m = \sum_{n=1}^{\infty} t_{mn} E_n$$  \hspace{1cm} (1)

where $t_{mn}$ is the complex TM element that links the $m$th output pixel and the $n$th input pixel, the number of elements in a TM row is the same as the number of input pixels $N$, and $E_n$ is the field at the $n$th input pixel. Due to the binary DMD modulation turning ‘ON’ a DMD pixel can be considered as setting the corresponding input pixel to 1, while ‘OFF’ is 0. Assuming uniform illumination over the DMD, without loss of generality, we can set $E_n$ to 1. Therefore, the complex amplitude at the target output position can be considered as a superposition of different $t_{mn}$ corresponding to ‘ON’ DMD pixels. Since all the complex TM elements $t_{mn}$ statistically accord with a circular Gaussian distribution to first approximation [2], $\text{Re}(t_{mn})>0$ is applicable for approximately half of the elements $t_{mn}$. The superposition of $t_{mn}$ with the same real-part sign in the $m$th TM row results in constructive interference, leading to a focused spot at the $m$th output pixel. Note that the superposition of $t_{mn}$ with negative or positive real parts, or generally any half of the complex plane, leads to the same effect. By dividing $t_{mn}$ into two categories according to the sign of its real part, the focusing task is simplified to turning ‘ON’ all DMD pixels having the same real-part sign (Fig. 1).

![Schematic explanation of the binary amplitude modulation by DMD for light focusing through a disordered medium. Complex TM elements of the disordered medium are shown as vectors in the complex plane. Red vectors refer to elements with positive real parts while black vectors refer to negative real parts. Green vectors refer to the superposition of complex numbers. (a) When all DMD pixels are turned ‘ON’ (indicated by 1), all TM elements in the corresponding row are ‘activated’ and superpose at the output position. (b) When turning ‘OFF’ DMD pixels corresponding to black vectors (marked by 0), only red vectors superpose at the target position, resulting in constructive interference, and shown as a focusing spot on the camera.](image)

2.2 **Binary algorithm based on Bayes’ theorem**

As mentioned above, in binary TM calibration, all TM elements are distinguished into two categories according to their real part sign. Usually this is achieved by having a reference beam [27,28]. In our reference-less system we resort to Bayes’ theorem to calculate the probability for each TM element contributing to a constructive or destructive interference state.

According to Bayes’ theorem, the probability for an event $B$ to happen, based on prior knowledge of a condition $A$ associated with the event, can be expressed as:

$$P(B \mid A) = \frac{P(A \mid B)}{P(A)} = \frac{P(A \mid B) P(A)}{P(A \mid B) + P(A \mid B^c)}$$  \hspace{1cm} (2)

where $B^c$ is the complement of the set $B$ and $P(A \cap B)$ is equivalent to $P(A \mid B) \times P(B)$. 
In our case, the probability for a TM element $t_{mn}$ that leads to higher output intensity as a result of constructive interference is expressed as:

$$P(C|T)_{mn} = \frac{P(T|C)_{mn} \times P(C)_m}{P(T|C)_{mn} \times P(C)_m + P(T|D)_{mn} \times P(D)_m} \quad (3)$$

Assuming the total number of measured input-output pairs is $K$, for the $m$th output pixel, there are $K$ intensity values. We define a preset intensity threshold $H_m$ for the $m$th output pixel, to separate its $K$ measured intensity values into two categories: a higher-intensity category (C) with $K_c$ intensity values greater than $H_m$ and a lower-intensity category (D) with $K_d$ intensity values smaller than $H_m$. $P(C)_m = K_c/K$ and $P(D)_m = K_d/K$ are the fractions of higher and lower-intensity categories for the $m$th output pixel, respectively. We assume the $n$th DMD pixel is in the ‘ON’ state $k_c$ times for the $K_c$ higher-intensity outputs, and is in the ‘ON’ state $k_d$ times for the $K_d$ destructive outputs. $P(T|C)_{mn} = k_c/K_c$ is the fraction of times the $n$th DMD pixel is ‘ON’ for the $K_c$ higher-intensity values of the $m$th output camera pixel. Similarly $P(T|D)_{mn} = k_d/K_d$ is the fraction of times the $n$th DMD pixel is ‘ON’ for the $K_d$ lower-intensity values of the $m$th output camera pixel. $P(C|T)_{mn}$ is the probability for the $n$th DMD pixel corresponding to the higher-intensity category (C) at the $m$th output pixel when it is ‘ON’ (T).

The preset threshold $H_m$ is specific to the $m$th output pixel and can be determined by analyzing the $K$ measured intensity values. We found in our experiment that the 80th percentile of the $K$ measured intensity values for the $m$th output pixel is the most efficient when being used as the threshold to generate a sharp focused spot (Fig. 4(a) in Section 4.1). We therefore used the 80th percentile of $K$ measured intensity values for the $m$th output pixel as the preset threshold $H_m$ in the following calculations unless stated otherwise.

Similarly, the probability for a TM element $t_{mn}$ belonging to the lower-intensity category is expressed as:

$$P(D|T)_{mn} = \frac{P(T|D)_{mn} \times P(D)_m}{P(T|D)_{mn} \times P(D)_m + P(T|C)_{mn} \times P(C)_m} \quad (4)$$

where $P(D|T)_{mn}$ is the probability for the $n$th DMD pixels corresponding to the lower-intensity category (D) at the $m$th output pixel when it is ‘ON’ (T).

For the $m$th output camera pixel determined by the $m$th row of the TM, we have obtained two probabilities $P(C|T)_{mn}$ and $P(D|T)_{mn}$ for the $n$th input DMD pixel. Here we use these two probabilities to determine a group of DMD pixels ($G_m$) that need to be turned ‘ON’ to form a focused spot at the $m$th output pixel. The asymmetric feature of a real fiber results in slight deviations of the probabilities from their ideal values and this forms the basis of our approach. We consider the $n$th DMD pixel belongs to $G_m$, if $P(C|T)_{mn}$ is greater than the median of all $P(C|T)_{mn}$, and $P(D|T)_{mn}$ is less than the median of all $P(D|T)_{mn}$. The reason we choose the medians of probability groups, namely $P(D|T)_m$ and $P(C|T)_m$, to determine $G_m$ is because the TM elements in one row obey an approximately circular Gaussian distribution [2], i.e. roughly half of elements have positive real parts. This choice is also proved experimentally in Fig. 4(b) in Section 4.2. By turning ‘ON’ all DMD pixels of the above-determined DMD pixel group $G_m$, the resulting output fields from all input pixels lead to a sharp focused spot at the $m$th output pixel. The $m$th row of the binary TM is obtained by setting $t_{mn}$ corresponding to $G_m$ as ‘1’ and the rest as ‘0’. By evaluating the probabilities for all output camera pixels using Eqs. (3) and (4), a binary TM can be obtained row by row.

Note that our probability-based approach described above cannot precisely determine the real-part signs of the TM elements, or the constructive elements. However, our method ensures that only a small fraction of TM elements with opposite signs are included in $G_m$, and the probability calculation in our approach is to minimize this fraction. This is verified in Fig.
4(a) in Section 4.1, as we show a higher enhancement on the intensity of the focused spot by increasing the total input-output pairs.

Our binary algorithm is suitable for multi-spot focusing, in which the K measured intensity values of each target output pixel are compared with the preset threshold. When the intensities at all target locations are higher than the preset threshold, the corresponding input is considered to be in the constructive category.

To briefly sum up the principle, our binary algorithm using the conditional probabilities [Eqs. (3) and (4)] to estimate whether an input DMD pixel should be turned “ON” or “OFF” in order to form a sharp focus at a certain output location at the MMF distal end.

3. Experimental methods

The experimental setup is shown in Fig. 2. A He-Ne laser (632.8 nm, 17.0 mW, 25-LHP-925-230, Melles Griot) was used as the light source. A DMD with 1024 × 768 micro-mirrors (Discovery 1100, Texas Instruments) driven by an interface board (ALP-1, ViALUX) was used for binary amplitude modulation. The modulated fields were coupled into a MMF (50-μm-core, 0.22 NA, 300-mm-long, FG050UGA, Thorlabs) using a tube lens (AC254-200-A-ML, Thorlabs) and a microscope objective (Nikon CFI Plan Achro 40 ×, 0.65 NA, 0.56 mm WD, tube lens focal length: 200 mm), with the transmitted light magnified with a microscope objective (Olympus 20 × Plan Achro, 0.4 NA, 1.2 mm WD, tube lens focal length: 180 mm) and another tube lens (AC254-100-A-ML, Thorlabs) before captured by a CMOS camera (C1140-22CU, Hamamatsu). 2 × 2 micro-mirrors were combined as a single macro-pixel to enhance the difference between an ‘ON’ pixel and an ‘OFF’ pixel. We used N = 1296 macro-pixels for the input basis and M = 9216 pixels for the output in this case.

Different numbers (K) of random DMD inputs were generated by MATLAB at an ‘ON’-‘OFF’ ratio of 50:50. This led to K input-output pairs, and we used K = 5000, 7500, 10000, 12500, 15000, 17500 and 20000 in our experiment for binary TM calibration. The mth row of the binary TM was then used as the DMD input mask to generate a focusing spot at the mth output pixel. We compared the binary algorithm with the prVBEM algorithm [30, 32]. Stability of our experimental system was monitored during binary TM measurement, and a high correlation above 98% was obtained for two outputs with the same input mask projected at the beginning and the end of the calibration (approximately 1 hour). Intensity enhancement factors were measured for quantitatively estimating the focusing effect. The focusing region is defined as the area with intensity higher than FWHM intensity around the target pixel (3 × 3 pixels in our case). The intensity contrast between the focusing region and the background is defined as the enhancement factor:

$$\eta = \frac{I_{loc}}{I_{back}}$$  (5)

where $I_{loc}$ is the average intensity inside the focusing region and $I_{back}$ is the average background intensity (including the focusing region).
4. Results

4.1 Single-spot focusing

The binary TM of the MMF was calibrated by using our Bayes’ Theorem-based fast binary TM algorithm as described in Section 2. Using the binary TM and turning ‘ON’ corresponding DMD pixels, we achieved focusing and raster-scanning of the focused spot across the fiber distal end. The experimental results for 9 focused spots at different output locations are shown in Fig. 3. The simulated outputs for 3 focused spots were also calculated with the binary TM by switching ‘ON’ all DMD pixels in the corresponding Gm. The FWHM of the focused spots in both experimental and simulation results is 3 pixels (approximately 1.7 μm).
Fig. 3. Examples of light focusing through the MMF using the binary TM algorithm at (a) the 2328th, (b) 4632th, (c) 6936th, (e) 2352th, (f) 4656th, (g) 6960th, (i) 2376th, (j) 4680th and (k) 6984th output camera pixels. (d), (h) and (l) are the simulated focused spots at the same positions as (c), (g) and (k). The number of input-output measurements $K = 20000$. The colorbar for experimental results spans the camera pixel output intensity values; the colorbar for simulation results spans arbitrary intensity values calculated using Eq. (1).

The enhancement factor as a function of the intensity threshold $H_m$ is shown in Fig. 4(a). For the $m$th output pixel, we vary $H_m$ by using different percentiles of all measured intensity values and calculated the enhancement factor $\eta_m$. In Fig. 4(a), we show the enhancement factor distribution for 100 randomly chosen output pixels. The results suggest that the 80th percentile intensity value is the most efficient threshold to achieve the highest enhancement factor for the focused spot in this system.

We can also demonstrate that the choice of using the probability median as the threshold to determine the input DMD pixel group $G_m$ that needs to be turned ‘ON’ optimizes the focused spot at the $m$th output pixel. The enhancement-factor distribution for 100 randomly chosen output pixels for different probability thresholds is shown in Fig. 4(b). The probability thresholds, i.e. the x axis in Fig. 4(b), are the different percentiles of all the calculated probability groups, $P(C|T)_m$ and $P(D|T)_m$, respectively. It can be seen that the higher enhancement factors are achieved when the probability median (50th percentile) is used.

The enhancement factors for different numbers of input-output pairs $K$ are shown in Fig. 4(c) using boxplot. Figure 4(c) shows that the enhancement factor increases with the increase of the input-output-pair measurement number $K$. Approximately 10% of the output pixels could not form a sharp focused spot due to he inherent properties of the MMF, which also results in the varying focusing strength at the different output locations (depicted by the large error bars in Fig. 4(a)-(c)). These are comparable to the results achieved using prVBEM algorithm [30, 32].

The computing time is another important consideration for the performance of the algorithm. We used the binary algorithm in MATLAB to measure a TM row with a Macbook Pro (2.3 GHz Intel Core i5), and calculated the average computing time for 100 different rows. As shown in Fig. 4(c), the calculation time for our binary algorithm was 0.26 s for 5000 measurements. We also used prVBEM algorithm to obtain the same row in TM for light
focusing using the same experimental system and PC. In order to obtain the same enhancement factor of 28 for 5000 measurements, 300 iterations were needed in prVBEM, which required approximately 8.1 s. And for 20000 measurements, 27.3 s of computing time was required in prVBEM while the binary algorithm only needed 1.5 s to achieve the same enhancement factor.

![Graphs showing enhancement factors and computing times](image)

**Fig. 4.** Boxplots (100 randomly chosen output pixels and \( K = 5000 \)) of (a) the enhancement-factor distribution as a function of different intensity thresholds \( H_m \). The median values of boxes are 43.7, 46.8, 54.0, 54.3 and 51.4 from left to right and (b) the enhancement-factor distribution at different probability thresholds. The median values of the boxes are 52.1, 54.0, 54.3, 54.0, 52.2, 45.5 and 36.2 from left to right. (c) The enhancement factor as a function of \( K \). The median values of boxes are 54.3, 69.2, 77.0, 84.4, 88.4, 92.3 and 96.7 from left to right. (d) Comparison on the average computing time between our binary algorithm and prVBEM at various \( K \) values.

4.2 Two-spot focusing

The binary TM algorithm was tested for two-spot focusing. We first separate the DMD pixels into the higher-intensity and the lower intensity categories for two targeting pixels, namely the 4656th and 6960th output pixels, using our Bayes’ theorem-based binary algorithm. We then switched ‘ON’ all DMD pixels in the higher-intensity category to achieve a similar level of intensity at the 4656th and 6960th output pixels. Both experimental and simulation results using binary TM are shown in Fig. 5. The FWHM of the focused spots in simulation results are 3 camera pixels (approximately 1.7 μm). In the experimental image, the FWHM of the focused spot is 3.1 μm at 4656th pixel and is 1.7 μm at the 6960th pixel. In two-spot focusing, the thresholds \( H_m \) need to be calculated for two output pixels, and this additional computing time is negligible compared to single-spot focusing. The difference between the experimental and simulation results for two-spots focusing shown in Fig. 5 is due to the binary TM. Two focused spots can be obtained at desired positions.
5. Discussion

The fast algorithm based on Bayes’ theorem presented in this paper for MMF binary TM measurement will be applicable for other disordered media to achieve a tight focus and raster-scanning. In binary TM measurements, the key aim is to distinguish the complex TM elements into two categories according to the sign of its phase. While the binary method has been studied using interference with a reference beam [28,29], the algorithm developed in this work is significant in terms of the reference-less system, which simplifies the system, and could lead to compact and low-cost devices. Compared to previous reference-less algorithms using iterative optimization [30–32], the binary algorithm is highly efficient as only simple conditional probability is calculated and hence allows high-speed operation which is, to the best of our knowledge, the first time a statistical approach was used for TM calibration. To calibrate the TM using data from 5000 measurements, our binary algorithm needs only approximately 0.26 s, and using a high-performance computer could further reduce the computation time. In comparison, to achieve the same enhancement factor using the prVBEM algorithm [30, 32] the computing time required is 10 times longer. In addition, the experimentally measured enhancement factor using our binary algorithm demonstrates the strong light focusing ability through a MMF by binary amplitude modulation. The reference-less configuration, high-speed calibration and strong light focusing capability of our method make it particularly promising in medical imaging application such as endoscopic imaging. It is worth noting that real-time calibration of single MMF at the proximal end is highly desirable. Although this is still a technical challenge, there are theoretical proposals of calibrating the MMF from the proximal end [33].

It is worth noting that our binary TM algorithm only provides information for binary amplitude modulation, while prVBEM describes the TM with both amplitude and phase information and is more suitable for applications where a complex TM is required, such as image transmission [10,11,14] and microparticle manipulation [8].

There are factors that influence the enhancement factor of the focused spot. Since the binary algorithm is based on a statistical method, using a large amount of data will certainly achieve higher enhancement factors. This is consistent with the increase of the enhancement factor with the rising number of measurements (Fig. 4(c)). In a recent study, ultrahigh enhancement through a diffuser was achieved through modulating the incident light by a large number of DMD pixels [34]. This may be applicable to MMF-based system, too. However, the increase of the number of measurement or input pixels requires extra computation time, as shown in Fig. 4(d)...

For practical use, the number of measurements can be determined according to the requirements on the computing time and enhancement factor. We also showed experimentally that changing the thresholds can be effective in enhancing the focusing effect, further analysis is needed to understand the optimized threshold.
6. Conclusion

In summary, we developed a high-speed binary TM calibration algorithm based on Bayes’ theorem, to achieve raster scanning of a high-contrast focal spot via a MMF, eliminating the needs of phase retrieval and a reference beam. To the best of our knowledge, it is the first time a conditional probability theory was used for TM measurement. This work is also the first to present a binary TM in a reference-less MMF imaging system and our algorithm is promising for light focusing and raster-scanning through other disordered media. The high-speed and simplicity offered in both calibration and measurements hold promise for single MMF based endoscopic imaging.

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