JOIPO (Joint Optics/Image Processing Optimization) 光学処理と画像処理の融合を図る新しい設計方法

JOIPO (Joint Optics/Image Processing Optimization): A New Method for Designing Electro-Optical Systems

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要 旨

JOIPO（Joint Optics/Image Processing Optimizationの略）と呼んでいるデジタルカメラ，スキャナー，光学センサーあるいはプロジェクターなどの光学-電子機器のための新しい設計方法を紹介する．従来の設計方法は次に述べるような形で順に行うものであった．すなわち，まず光学技術者が最も高画質の画像がセンサー上に結像するように光学系を設計（その特徴量として点像分布関数が用いられる）し，その後に，画像処理技術者がセンサーで得た画像がより良くなるように適切なデジタルフィルターを設計する．これに対し，我々が研究開発しているJOIPOメソッドでは，光学設計上のパラメータと画像処理上のパラメータを全体として最適なパフォーマンスが得られるように同時に調整する．その結果センサー上に結ばれる中間像は必ずしも高画質ではなくなるのが特徴である．我々はこのJOIPOメソッドによって従来の設計方法に比べて，より低コストに製作可能なシステムや，より高画質な最終画像が得られる可能性を示した．また組み付け公差等が緩くなり，モノづくりにおいて歩留まり向上などで貢献できる可能性も示した．このような形で，今後JOIPOメソッドが光学-電子システムを含む工業製品に広く適用されていくことを期待している．

ABSTRACT

We introduce JOIPO (Joint Optics/Image Processing Optimization), a new method for designing electro-optical systems such as digital cameras, digital scanners, sensors, and optical projectors. Traditional design methods are sequential: first optical engineers design the optics to provide high-quality image (characterized by small point spread function) and then image processing engineers design digital filtering to improve the sensed image. In our novel JOIPO method the optical and the image processing parameters are adjusted simultaneously to ensure the best overall performance, even though this often means that the intermediate optical image is of low quality. We have shown that the JOIPO method leads to designs that are less expensive and yield higher quality images than those designed using traditionals (sequential) methods. We have also shown that JOIPO methods can compensate for manufacturing errors better than can traditional compensation methods. In this way, JOIPO may increase the manufacturing production yield of electro-optical systems.

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1. Introduction

Electro-optical imaging is central to many Ricoh products, from scanners and MFPs to digital cameras and CD/RW pickups. Traditionally, Ricoh and nearly all other imaging companies design electro-optical imaging systems in two stages: First, optical designers design the optical subsystem to give the highest quality optical image (under cost, size, or other constraints); second, image processing engineers design the algorithms to reduce the residual errors or aberrations appearing in the sensed image.

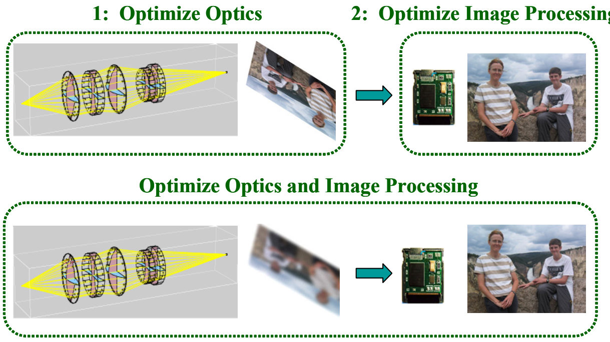

Fig.1 In the traditional electro-optical imaging design method, the optical subsystem and the image processing subsystem are designed and optimized one after the other. This gives a possibly complex optical system and a high-quality optical image (top). Through Ricoh's new JOIPO system design method, the entire electro-optical system is optimized at the same time. JOIPO gives a lower-quality optical image, but complex image processing, and thus the final digital image is of equal or superior quality to that produced by the traditional method (bottom).

Ricoh's new design method is called JOIPO—Joint Optics/Image Processing Optimization. In JOIPO, the entire electro-optical imaging system is considered and optimized as a whole (Fig. 1). That is, during design, the parameters of both the optical subsystem (lens placement, curvatures, etc.) and the image processing subsystem (digital filter coefficients) are adjusted so as to produce the best final digital image[1), 2)]. Note that in this method it is not necessary that the intermediate optical image be of high quality. After all, noone will see that image. In short, JOIPO produces an optical image for the computer—not for a human.

In this paper, we present some of the assumptions, results and future directions for JOIPO research within Ricoh.

2. Core Technology

In traditional optical design, the optical designer uses sophisticated optical design software, for instance CODE V or Zemax, and enters general properties of the desired design (e.g., number of lens elements, types of glass, placement of aperture stops, ...) as well as spatial or other constraints. Then the software adjusts the free parameters, such as the curvature of lens surfaces, separation of lens elements, and so on, all in order to optimize some optical merit function of the image produced. Typically, the merit function is based on the size of the point spread function (PSF)—the smaller the PSF the sharper, and hence better, the image.

The next step in traditional design methodology is for image processing engineers to develop software to process the digitally sensed image. Such processing will generally involve gamma correction, color space transformations, linear spatial convolution, and possibly thresholding (for binary images), even high-level processing such as segmentation. The desired output often depends upon the application, including making an image merely "look good."

Up to now, there has been very little research using a single metric or merit function applied to both the optical and the image processing domains. In JOIPO, we use a merit function based on the root mean-sum-squared error (RMSE), that is, the sum of the squared differences between the final digital image and the ideal image that would be produced by a diffractionless pinhole, i.e., in the absense of optical aberrations. This merit function has a number of useful properties, both in theory and in practice. First, it is general purpose. Second, it is non-negative, and zero only when the actual image is the same as the ideal image. Third, and most importantly for JOIPO, the RMSE metric allows us to compute the Weiner filter[3)], the digital filter that will best correct (in a RMSE metric) the optical deficiencies, that is yield the RMSE.

3. Software tools

No commercial software system integrates optical design and image processing design that is the core of the JOIPO method, and thus we developed our own software. We use Zemax commercial optical design software and wrote our own image processing and optimization algorithms in Matlab.

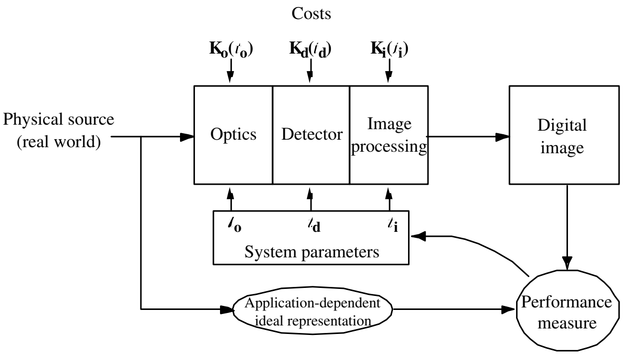

Fig.2 JOIPO flowchart. The top line shows the data path, where light from the physical world passes through the optic, is detected by a digital sensor and then processed to yield a digital image. During design, this image is compared with an "ideal representation," for instance an ideal pinhole image in the absence of diffraction. Our JOIPO software adjusts the imaging system parameters of the optics and the detector and the image processing algorithms in order to reduce the error of the digital image, for example the RMSE error with respect to the ideal image.

4. Results

We designed two simple singlet (one lens) document scanners to test if JOIPO gave superior images. The first scanner was designed through traditional methods (top row, Fig.1). That is, first the optical system was design to give the highest quality optical image (minimum point spread function), then the optimal linear digital convolution filter. We designed the second scanner using our new JOIPO methods (bottom row, Fig.1).

Figure 3 shows our results. The top figure shows the ideal image, a scanned binary image of the word "experimental." The optical image produced by a system designed in the traditional method has an RMSE error of 58.1 gray levels, somewhat better than the image produced through JOIPO methods. However no one sees this image. It is the final, digital image that matters.

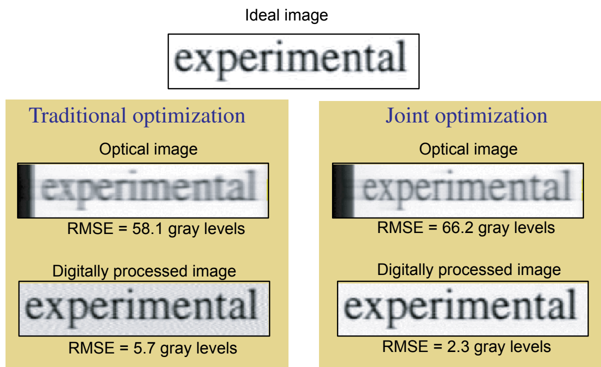

Fig.3 Design results. The top rectangle shows the ideal image from a digital scanner. The left half shows the optical image and final digital image for a system designed by traditional (sequential) optimization; the right half the JOIPO (joint) optimization. The final JOIPO image has lower error than the final traditional image, even though the JOIPO intermediate (optical) image is inferior.

The final image produced by the system designed by traditional methods has an RMSE of 5.7 gray levels, while the one designed by JOIPO method has an RMSE of 2.3. Indeed, we get better images (smaller error) for electro-optical systems designed through the JOIPO method. We have found that JOIPO outperforms traditional methods in a wide range of simple optical systems.

Our simulations and analyses reveal that JOIPO finds overall system designs that are rarely, if ever, found by traditional methods. Some optical aberrations are more easily corrected by image processing than other aberrations. In imaging systems designed by the JOIPO method, the balance of optical aberrations differs somewhat from traditional systems. JOIPO finds the optimal balance to reduce the final RMSE.

In related research, we have applied the JOIPO method to the problem of *compensation*, that is, fixing slight manufacturing errors. We have found that JOIPO designs can correct for a wider range of manufacturing errors than traditional designs. Thus JOIPO may improve the production yield of optical factories and thereby lower the cost of optical components and devices. We have also used JOIPO to design optical systems for multi-frame integration, or super-resolution. Here too, our JOIPO designs yield images that are of higher quality than those produced by traditional methods. Conversely, JOIPO produces equivalent images but with fewer optical elements (lenses) than traditional systems, i.e., JOIPO systems are less expensive.

5. Future Research and Applications

We are extending the theoretical foundations of the JOIPO method and seeking to understand deeply how optical aberrations are "fixed" by image processing. This theory will help us build practical optical imaging systems. We are extending JOIPO to apply to optical *projection* systems as well, though this is more difficult than *imaging* systems.

Finally, we are collaborating with colleagues in Japan on some of the first products based on the JOIPO method.

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