

Image Inpainting

By *Guillermo Sapiro*

Inpainting, a set of techniques for making undetectable modifications to images, is as ancient as art itself. Applications of image inpainting range from the removal of an object from a scene to the retouching of a damaged painting or photograph. For photography and film, inpainting can be used to reverse deterioration (e.g., cracks in photographs, scratches and dust spots in film), or to add or remove elements (e.g., stamped dates, “red-eye,” and, infamously, political enemies) from photographs. In each case, the goal is to produce a modified image in which the inpainted region is merged into the image so seamlessly that a typical viewer is not aware that any modification has occurred.

Traditionally, inpainting has been done by professional artists (see Figure 1). Recently, motivated in part by work of Nitzberg–Mumford and Masnou–Morel, my research group and collaborators (M. Bertalmio, C. Ballester, A. Bertozzi, V. Caselles, S. Rane, J. Verdera, and I, in various combinations) have developed algorithms for automatic digital inpainting. The first step, with Bertalmio, Ballester, and Caselles, was the formulation of a partial differential equation that propagates information (the Laplacian of the image) in the direction of the isophotes (edges). The proposed algorithm shows that both the gradient direction (geometry) and the gray-scale values (photometry) of the image should be propagated inside the region to be filled in, making clear the need for high-order PDEs in image processing. In general, our algorithms imitate the basic approaches used by professional restorers, which we learned about by consulting with the Minneapolis Institute of Art.

Our algorithm propagates the necessary information by numerically solving the PDE

$$\frac{\partial I}{\partial t} = \nabla^\perp I \cdot \nabla \Delta I \quad (1)$$

for the image intensity I inside the hole—the region to be inpainted. Here, ∇^\perp denotes the perpendicular gradient ($-\partial_y, \partial_x$), and Δ the Laplace operator. The numerics are based on techniques developed by Osher and colleagues. The goal is to evolve this equation to a steady-state solution, where

$$\nabla^\perp I \cdot \nabla \Delta I = 0, \quad (2)$$

thereby ensuring that the information is constant in the direction of the isophotes. With Bertalmio and Bertozzi, we have shown a relation between this approach and the Navier–Stokes equations, an intriguing link between fluid dynamics and image processing.

Ballester, Bertalmio, Caselles, Verdera, and I have investigated the use of a formal variational formulation for the simultaneous propagation of edges and gray-scale values. A number of theoretical results and advanced numerical implementations have been developed for this model. This approach, like those of Nitzberg–Mumford and Masnou–Morel, is connected to Euler’s elastica—another connection between classical mathematics and modern image processing.

More recent work, with Bertalmio and Rane, involves the combination of our work on image inpainting with results of Efros and Leung on texture synthesis; our goal was the filling-in of missing blocks in wireless image transmission, and the techniques developed are fully compatible with the JPEG and JPEG 2000 standards.

Examples of all these techniques can be found in Figure 2. Interested readers can find additional information at the Web site mountains.ece.umn.edu/guille/inpainting.htm, which includes numerous images for a wide variety of applications and pointers to other resources, in particular to the pioneering PhD dissertations of M. Bertalmio, S. Masnou, M. Nitzberg, and J. Verdera.

The work mentioned here only begins to address the challenges of image inpainting. Even for still images, many questions—like the PDE-based simultaneous filling-in of textured and structured regions—are still open. Especially intriguing for many of us is video inpainting, our current direction. Video provides some advantages (a lot more data), but some challenges as well, like the need to smooth temporal, and not just spatial, inpainting. Kokoram et al. and Geman et al., among others, have made some progress in this direction, although, again, much remains to be done. We expect many more results to come in this exciting combination of art with engineering and mathematics.

Further Reading

- [1] C. Ballester, M. Bertalmio, V. Caselles, G. Sapiro, and J. Verdera, *Filling-in by joint interpolation of vector fields and gray levels*, *IEEE Trans. Image Process.*, 10 (2001), 1200–1211.
- [2] M. Bertalmio, G. Sapiro, C. Ballester and V. Caselles, *Image inpainting*, *Computer Graphics, SIGGRAPH 2000*, July 2000, 417–424.



Figure 1. *Inpainting as performed by artists. Top, detail from “Cornelia, Mother of the Gracci,” by Suvee, from G. Emile-Male, The Restorer’s Handbook of Easel Painting. Bottom, from D. King, “The Commissar Vanishes.”*

Figure 2. Original images (top row) after inpainting (bottom row) for, respectively, the restoration of damaged photographs, restoration of scratched film, text removal, object removal for special effects, and block reconstruction in wireless transmission.



[3] C. Braverman, *Photoshop Retouching Handbook*. IDG Books Worldwide, 1998.
 [4] A. Efros and T. Leung, *Texture synthesis by non-parametric sampling*, Proceedings of the IEEE International Conference on Computer Vision, Corfu, Greece, September 1999, 1033–1038.
 [5] G. Emile-Male, *The Restorer's Handbook of Easel Painting*, Van Nostrand Reinhold, New York, 1976.
 [6] D. King, *The Commissar Vanishes*, Henry Holt and Company, 1997.
 [7] S. Masnou and J.M. Morel, *Level-lines based disocclusion*, 5th IEEE International Conference on Image Processing, Chicago, IL, Oct 4–7, 1998.
 [8] M. Nitzberg, D. Mumford, and T. Shiota, *Filtering, Segmentation, and Depth*, Springer-Verlag, Berlin, 1993.
 [9] S. Walden, *The Ravished Image*, St. Martin's Press, New York, 1985.

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