

# An unsupervised method to increase film color restoration sustainability for small cinematheques

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## ABSTRACT

Digital film restoration plays a crucial role in preserving audiovisual heritage, offering a unique potential to enhance image quality and accessibility. However, it faces significant challenges in terms of technological and, even more critically, economic sustainability. This study proposes an automated, unsupervised method to optimize film restoration workflows, reducing costs and resource consumption, particularly for small cinematheques with limited budgets.

To illustrate this point, we present a comparison between two case studies. The first is the film “The Funerals of the Bombing of Piazza della Loggia in Brescia”, shot by Mario Bertoli in 1974 and currently preserved in the archive of the “Casa della Memoria” in Brescia. This historically significant document allows for a comparison of traditional and digital restoration techniques in terms of cost and quality. The second case study focuses on “La Lunga Calza Verde”, a 1960 animated short film directed by Roberto Gavioli and based on a script by Cesare Zavattini. Created for the centenary of Italy’s unification, it was entirely restored using the proposed automated digital process.

These examples demonstrate the feasibility and advantages of an unsupervised approach and highlight how it can enhance the sustainability of film restoration for small cinematheques.

**KEYWORDS** Film restoration, Color restoration, Sustainability, Film Digitization, Digital Restoration, Spatial color algorithms, Unsupervised restoration

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## 1. Introduction

Digital film restoration plays a fundamental role in preserving the audiovisual heritage and make them accessible to a wider public. However, current practices present important critical issues, especially in terms of technological and economic sustainability; these difficulties can be critical in the case of foundations, libraries and small film libraries with limited resources to deal with the costs and complexities of the restoration process.

Digital technologies applied to film restoration have generated a limited number of commercial software with which very complex operations can be performed. However, apart from the payment of a licence fee, the biggest cost is the work of personnel highly trained in their specific use: the effectiveness of operations such as dust and scratch removal and color correction are closely linked to the software chosen and the level of training of the operators. Moreover, these software intended for a professional niche, when not discontinued, pay for a certain slowness in their development due to their small user base, unlike widespread applications dedicated to graphics such as, for example, Adobe Photoshop®.

This study proposes the evaluation of the use of Spatial Color Algorithms (SCAs), based on automated and unsupervised methods, compared to a supervised digital restoration process. The aim is to consider them to optimize workflows in film restoration, reducing operational costs, while improving efficiency and technological accessibility.

In order to highlight the differences between the classic supervised digital restoration and the automated approach enabled by SCAs, we will analyze two case studies: the restorations of the 1974 documentary “The Funeral of the Piazza della Loggia bombing in Brescia” (Plutino et al. 2018) and the 1960 animated short film “La Lunga Calza Verde” (Berolo et al., 2012).

The examples given in this article show how the adoption of innovative technologies can improve the sustainability of restoration by making it, with a small loss in quality, more cost-effective.

## 2. The concept of sustainability in film conservation and restoration

The original concept of sustainability (Brundtland, 1987) has over time been stretched to include the economic, social, technological and cultural dimensions of all human activities.

In the audiovisual sector sustainability is relevant at all stages (Meilani, 2021) but in the context of film preservation and restoration it acquires a specific meaning. Here, sustainability concerns the optimization of resources (both material and energy), cost containment, and the preservation of historical and artistic value, while ensuring broad accessibility of restored works (Lopera-Mármol and Jiménez-Morales, 2021).

Preservation challenges differ between analogue and digital formats. Film materials are inevitably subject to chemical and physical degradation, which can only be slowed through strong controlled storage conditions (Harrison, 1997; Reilly, 1998; Plutino and Bellotti, 2022; RTI I. P., 2021). Digital archives, while avoiding physical decay, face other sustainability issues: planned obsolescence of storage media like RAID or LTO, continuous migration requirements, and the high energy demand of data centers (Antoniazzi, 2020). These factors make long-term digital preservation costly both financially and environmentally.

Film restoration is inherently expensive because all steps in the standard workflow require the use of high-quality hardware and software equipment and highly qualified personnel. In this sector, sustainability emerges not only as an environmental requirement, but also as an economic and cultural strategy, safeguarding the long-term accessibility of the audiovisual heritage.

## 3. The context of restoration

In sustainable film restoration, cost represents a decisive constraint, particularly for small cinematheques. As noted by The Film Foundation, expenses vary significantly according to a film’s condition, length, and technical requirements: black-and-white features with sound may cost between USD 50,000 and 250,000, while color features with sound typically range from USD 80,000 to 450,000 for photochemical processes, with even higher figures for 2K or 4K digital workflows (The Film Foundation, n.d.). Such figures illustrate the financial pressures faced by smaller institutions and underline the need for more sustainable, cost-efficient strategies.

Small archives are further challenged by limited resources, which often compel them to prioritize works with greater public or commercial appeal, leaving lesser-known yet culturally significant materials at risk of neglect. Dependence on expensive proprietary software and training, coupled with the absence of accessible open-source alternatives, undermines institutional autonomy and compromises long-term sustainability. While international initiatives promote collaboration and resource sharing, smaller cinematheques remain underrepresented due to scarce specialized personnel and the limited visibility of their collections.

To address these challenges, automated and unsupervised restoration algorithms - such as Spatial Color Algorithms (SCAs), designed to minimize manual intervention while preserving restoration quality (Rizzi et al., 2014) offer a promising solution. By reducing operator involvement, limiting training requirements, and mitigating reliance on proprietary tools, they help lower costs and processing times, enabling institutions to tackle a larger share of their holdings within existing constraints. Importantly, their open-source availability allows adoption without the financial and contractual limitations of commercial solutions.

Central to this approach are SCAs (Rizzi and McCann, 2007), which perform spatial analysis to detect and correct deviations in color and contrast while preserving image integrity. Their effectiveness depends on the state of the original material: since they do not perform scratch removal, in some cases they provide a complete restoration solution, while in others they serve as a preliminary stage within a traditional workflow, in both instances reducing the overall cost of the process.

The following section outlines the methodological framework of this approach, presenting the underlying algorithms, workflow configuration, and comparative performance against operator-driven methods. This provides the basis for a critical evaluation of its potential to reconcile cost-effectiveness, operational efficiency, and preservation quality.

## 4. Two case studies

### 4.1. The restoration of “The Funerals of the Bombing of Piazza della Loggia in Brescia” film (1974)

The first case study concerns the restoration of “The Funerals of the Bombing of Piazza della Loggia in Brescia”, as described by Plutino et al. 2018. The film constitutes a primary historical source, bearing witness to a pivotal moment in the political and civic history of Brescia (Italy).

The material presented heterogeneous preservation conditions: the footage of the explosion day was severely degraded, whereas the funeral scenes were comparatively well preserved, though the film overall exhibited common issues such as scratches, dust, and color fading.

The restoration was carried out at the I’ve Seen Things Research Lab following a structured workflow: historical and technical analysis; digital scanning; primary color correction; dust and scratch removal with frame stabilization; repair of damaged frames; secondary color correction and scene harmonization; and final editing (Plutino et al., 2018). Digitization alone required about 15 hours of automated acquisition, with operator supervision to ensure the film’s physical integrity. Primary color correction involved calibration of white balance, saturation, and contrast across 120 scenes, a task that demanded 62 hours of work and the expertise of senior editors for the most compromised sections.

The subsequent digital restoration phase - dust and scratch removal, stabilization, and replacement of irrecoverable frames - proved particularly labor-intensive, requiring approximately 88 hours. Operator expertise was decisive here, as incorrect parameter settings could compromise detail and overall image quality. Secondary color correction, essential for harmonizing individually processed scenes, required the direct involvement of the project supervisors. The final stage included editing and export in two formats: MPEG-4 AVC (H.264), optimized for distribution, and DPX, a lossless format suitable for long-term preservation but memory-intensive.



Fig. 1. On the left the original frames of the short film “The Funerals of the Bombing of Piazza della Loggia in Brescia” compared to the restored version on the right (LAB MIPS, 2020).

In total, the project lasted around two and a half months, amounting to roughly 200 hours of work and involving eight people - five students and three experienced editors. The case illustrates how film restoration combines automation with significant manual and expert intervention. While highly trained operators are indispensable for color correction and quality control, less specialized personnel play a crucial role in supervising automated processes and performing manual tasks such as dust and scratch removal, which remain essential to achieving reliable results (Plutino et al. 2018).

### 4.2. The restoration of “La Lunga Calza Verde” (1960)

The second case study concerns the restoration of the animated short film “La Lunga Calza Verde”, directed by Roberto Gavioli and produced by Gamma Film in 1960 (Berolo et al., 2012).

The intervention, carried out in 2012 by the MIPS Laboratory of the Giovanni degli Antoni Department of Computer Science at the University of Milan, represents a comprehensive example of an unsupervised restoration performed using SCAs.

SCAs, widely employed in photographic image enhancement, operate according to perceptual principles

inspired by the human visual system, focusing on the appearance of color rather than its physical measurement (Berolo et al., 2014).

While this approach is effective in correcting degradations such as fading or contrast loss, it requires careful supervision in the audiovisual field, since directors may have intentionally introduced

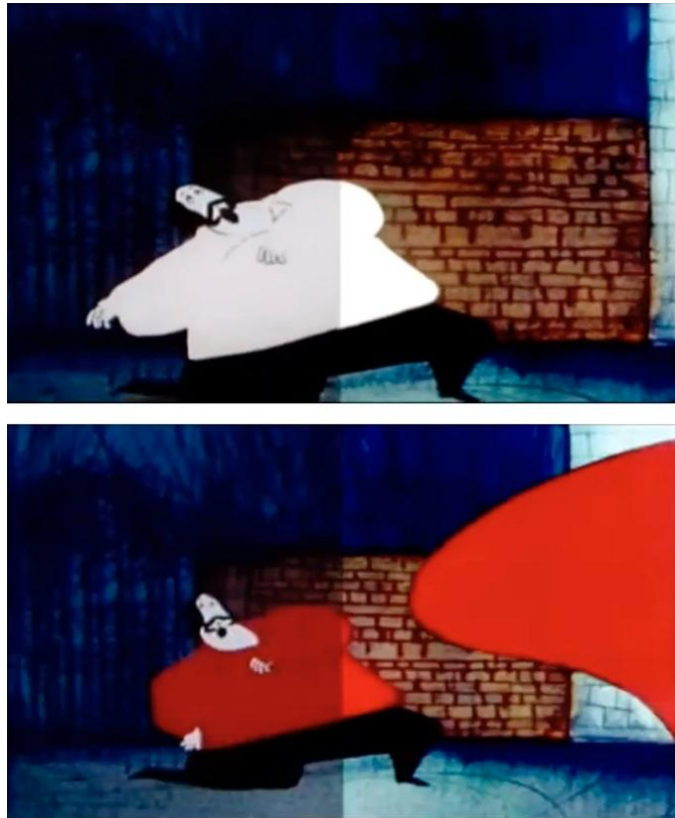
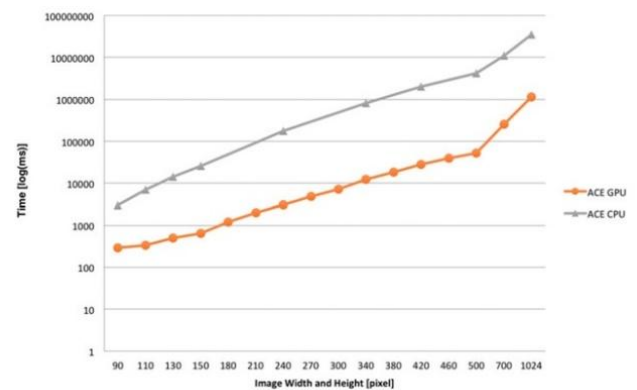


Fig. 2. Original frames (left) from “La Lunga Calza Verde” set against the restored version (right) (LAB MIPS, 2018).

Effects - such as color dominance or limited dynamic range - that must be preserved as part of the work’s aesthetic identity. SCAs are, in general, computationally expensive, with algorithmic complexity ranging from  $O(N \log N)$  to  $O(N^2)$ , where  $N$  is the number of pixels in the image. To address this limitation, two main strategies can be adopted: smarter software implementation and/or efficient parallel processing. One example of software optimization is the Local Linear Look Up Table (LLUT) (Gatta et al., 2006; Artusi et al., 2006), which significantly reduces computational time while introducing only a minor loss in filtering quality. Moreover, the computational structure of SCAs makes them particularly suitable for parallelization on many-core or multi-core architectures, such as modern GPUs. Implementations on GPUs are relatively straightforward when using high-level programming APIs like CUDA or OpenCL, although challenges remain in optimizing data transfer and memory access within the GPU hierarchy. As shown in Tab. 1, a comparison (in logarithmic scale) between CPU and GPU implementations of the ACE algorithm underscores these performance differences. The CPU version, written in C++

and executed in single-core mode on an Intel Xeon Quad Core E5-2609 2.40GHz running Windows 7, was compared with a GPU version implemented in OpenCL on an NVIDIA Quadro 4000 within the same workstation. Results showed that GPU computation delivered speed-up factors ranging from 10x to 80x, with an average improvement of 45x.

The combination of software-level optimization and parallel computing thus makes it possible to overcome the computational limitations of SCAs, opening the way to their use for high-resolution content and high frame-rate processing. The restoration of “La Lunga Calza Verde” was



Tab. 1. Comparison between computational performances of CPU and GPU implementations of ACE algorithm. The computational times (Y axis) are shown using a logarithmic scale, on the X axis are showed the images width in pixel. (Rizzi et al., 2014).

conducted on an Intel Xeon Quad Core E5-2609 2.40GHz, a processor introduced in 2012. For a meaningful comparison, its performance can be contrasted with that of a more recent Intel Core i9-13900K (2022).. On the Cinebench R15 benchmark, the i9-13900K achieves a single-core score of 330 compared with 73 for the Xeon, and a multi-core score of 6,141 versus 606, while requiring only about 40% more power consumption (CPU-Monkey, 2024). These figures suggest a performance increase of nearly an order of magnitude, illustrating the dramatic advances in processing power available to contemporary restoration workflows.

## 5. Comparative analysis of the two restoration approaches

### 5.1. Introduction to the Case Studies

The two case studies presented - the restoration of “The Funerals of the Bombing of Piazza della Loggia in Brescia” (1974) and “La Lunga Calza Verde” (1960) - highlight two fundamentally different approaches to film restoration: a manual, supervised, multi-step process one and a largely automated, unsupervised, algorithm-driven process. Both aim at preserving and enhancing the visual quality of historical audiovisual materials, yet they differ substantially

in workflow, resource requirements, technological reliance, and the role of human expertise.

### 5.2. Workflow and Methodology

The restoration of “The Funerals of the Bombing of Piazza della Loggia in Brescia” followed a classical sequence of steps: digitization, multiple stages of color correction, manual and semi-automated defect removal, and final editing. Every stage required careful human intervention, particularly for maintaining color fidelity and correcting scratches and dust.

Conversely, “La Lunga Calza Verde” employed SCAs, which, after initial parameter tuning and key frame selection, enabled fully automated enhancement across entire scenes. Human involvement was limited to verification and final adjustments, significantly reducing manual labor while maintaining control over key restoration decisions.

### 5.3. Human Resources and Expertise

The supervised restoration of “The Funerals of the Bombing of Piazza della in Brescia” required eight people, including three highly experienced professionals, over

approximately 200 hours. Skilled personnel were critical for accurate restoration, especially in color grading and handling severely degraded portions.

In contrast, the “La Lunga Calza Verde” restoration, while still needing expert input at key decisions, reduced manual labor significantly by leveraging SCAs, minimizing total time through parallel processing and algorithmic optimization.

The difference in resource allocation and efficiency is summarized in Tab. 2, comparing film durations, total work hours, and personnel. Although the films have almost identical durations, “The Funerals of the Bombing of Piazza della in Brescia” required more than twice the working hours of “La Lunga Calza Verde”. While the workload was distributed across eight people (≈25 hours each) for the former, the latter concentrated 90 hours on a single operator. Normalized by person-hour, “La Lunga Calza Verde” is ≈2.3 times more efficient, highlighting the impact of workflow design, algorithmic support, and personnel organization on restoration sustainability.

	<b>A) The Funerals of the Bombing of Piazza della Loggia in Brescia</b>	<b>B) La Lunga Calza Verde</b>
Film lenght	19' 50"	20' 22"
People involved	8	1
Total hours worked	200 hrs	90 hrs
<b>Hours worked per minute of film</b>	<b>10,10 hrs/min</b>	<b>4,4 hrs/min</b>
<b>Minutes of film for every hour of work</b>	<b>0,10 min/hr</b>	<b>0,233 min/hr</b>
<b>Hours per person</b> (if distributed evenly)	<b>25 hrs/prs</b>	<b>90 hrs/prs</b>
<b>Relative speed</b> (per capita productivity)	—	<b>≈ 2,33x faster than A</b>

Tab. 2. Comparative data on the restorations of “The Funerals of the Bombing of Piazza della Loggia in Brescia” (1974) and “La Lunga Calza Verde” (1960). The table summarizes film duration, total working hours, personnel involved, and derived indicators of productivity and efficiency (Elaboration made by the Authors).

### 5.4 Technological Requirements and Performance

Technologically, the “The Funerals of the Bombing of Piazza della Loggia in Brescia” restoration depended on specialized hardware (film scanner) and professional video editing and color correction software, but its efficiency was bounded by the speed of manual intervention.

“La Lunga Calza Verde” restoration, conversely, showcased the potential of computational acceleration: GPU-based SCAs implementations achieved performance gains of up to 80x compared to CPU-only execution, making high-resolution automated restoration feasible even on mid-range hardware of the time.

### 5.5 Aesthetic and Curatorial Considerations

The supervised workflow applied on “The Funerals of the Bombing of Piazza della Loggia in Brescia” allowed curators to make context-sensitive decisions throughout the process, an advantage when dealing with historically significant footage where visual authenticity must be preserved with the highest fidelity. The automated SCAs-based workflow, instead, while highly efficient, carries inherent risks of overcorrection or unintended alteration of artistic intent—risks that can be mitigated but not eliminated through careful parameter tuning and targeted human review.

### 5.6 Sustainability and Scalability

The automated approach demonstrates a model with reduced human labor and scalable computational solutions, making it feasible for smaller archives to process larger volumes of material at lower cost once the necessary infrastructure is available.

Nevertheless, for complex restorations of documents, with atypical visual characteristics, the labor-intensive supervised approach remains the most reliable option to ensure authenticity.

### **5.7 Towards Hybrid Workflows**

The comparison suggests that hybrid workflows - integrating the speed of automated SCAs with targeted expert oversight - could provide the optimal balance between efficiency, quality, and resource allocation, particularly for small and medium-sized archives facing both budgetary and preservation challenges.

## **6. Conclusions**

The comparative analysis of the two case studies shows that unsupervised digital restoration methods based on SCAs can improve the sustainability of film conservation, especially for small film libraries with limited resources. Traditional supervised restoration ensures high control over image quality but requires specialized personnel and long timeframes, generating significant economic and operational burdens. SCAs, by enabling automatic color correction with minimal intervention, reduce labor costs, accelerate workflows, and minimize technological and human resource consumption.

The restoration of "The Funeral of the Bombing of Piazza della Loggia in Brescia" illustrates the demands of traditional digital restoration, including extensive manual intervention and technical expertise. Conversely, the unsupervised restoration of "La Lunga Calza Verde" shows that SCAs can deliver high-quality results while simplifying workflows and reducing costs, allowing smaller institutions to preserve works otherwise inaccessible.

From a sustainability perspective, SCAs support economic, social, and technological sustainability: economically, by reducing reliance on costly software and specialists; socially, by enabling broader participation including students and emerging technicians; technologically, by offering open-source algorithms adaptable to institutional needs.

In conclusion, automated, unsupervised methods reconcile quality and sustainability in film restoration. While supervised methods remain essential for works of high aesthetic or technical complexity, SCAs provide an effective, cost-efficient, and environmentally friendly alternative. Their use demonstrates that operational speed can be combined with acceptable final quality.

## **7. Conflict of interest declaration**

All authors declare that they have no conflicts of interest.

## **8. Funding source declaration**

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**Alessandro Rizzi** - Alessandro Rizzi is a Full Professor at the University of Milan's Department of Computer Science, where he teaches multimedia, colorimetry, and film restoration. Head of the MIPS Laboratory, his research since 1990 has focused on digital imaging, particularly color, HDR, photography, and perceptual aspects of imaging, interfaces, and lighting.

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