The laser as a tool for the cleaning of Cultural Heritage

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Abstract. Laser ablation is one of the most important irradiation effect which can be induced
on optically absorbing materials. Laser cleaning is a particular case of laser ablation where a
specific substrate is uncovered through the removal of undesired layers. The idea of using
laser ablation for the selective removal of encrustations from the surface of artifacts dates back
to the 70s. However, only in the last years, thanks to studies on the ablative process and on the
development of dedicated laser systems, laser cleaning has become a daily routine in the world
of conservation. The development of brand new devices optimized for the cleaning of artworks
is here reported: the innovative machines exploit the versatility provided by the presence of
different pulse durations, which turned out to be a key parameter in the laser-target interaction.
In addition to the well-known laser cleaning of stones, novel applications are discussed such as
the cleaning of metals, wall paintings, and the novel use of the Er:YAG laser for the removal of
aged varnishes from easel paintings. The growing flexibility and versatility of the new laser
systems dedicated to the cleaning of artworks enlarge the panorama of successful application
of this cleaning method.

1. Introduction
The properties of monochromaticity, collimation, and coherence of laser light and the associated
interaction features have favoured the development of a variety of laser applications in several fields,
such as for examples industrial, biomedical, and cultural heritage.

Laser cleaning is a particular case of laser ablation where a specific substrate is uncovered through
the removal of undesired layers.

The application of laser cleaning in the conservation of artworks was proposed by J.F. Asmus and
L. Lazzerini since the beginning of 1970s [1, 2, 3] through a set of practical tests carried out in Venice
on encrusted stone artefacts: the novel approach, though, did not overcome the experimental stage for
several years mainly because of the technological limits of the pulsed laser sources available at that
time. During the 1990s several research centres, conservation institutions, and restoration enterprises
started constructive synergies aimed at developing tailored laser systems and methodologies to face
different classes of materials and deterioration problems.

The gradual acceptance within the scientific and conservation communities of laser cleaning as a
restoration tool is documented by the high number of studies published in various applied physics,
applied chemistry, and interdisciplinary journals and by the spread of dedicated conferences such as
LACONA (Laser in the Conservation of Artworks) which has become a fundamental reference for the
development and dissemination of the laser techniques in the conservation field.
In Italy, where laser cleaning is nowadays a common practice in restoration, the conference APLAR (Applicazioni Laser nel Restauro – Laser applications in conservation) is also a very interesting discussion forum and meeting point for restorers who daily use laser as a cleaning tool.

2. Laser cleaning features
Laser ablation occurs when the laser irradiation fluence (pulse energy per unit area) overcomes a critical threshold, which is an intrinsic property of the material structures under irradiation.

Laser ablation process involves optical, photothermal and photomechanical phenomena depending on the laser parameters and material properties. The main important parameters in laser cleaning are: wavelength, pulse duration and pulse energy.

The process of laser cleaning can be explained in a simplified way by evaporation (photo thermal ablation mechanism) and ablation/spallation (photo mechanical and photo chemical ablation mechanism) effects. The simplest case is a white stone covered by a black dark crust. The laser action causes the complete evaporation/ablation of the black crust; as the laser beam interacts with the white surface of the stone there is no more dark material absorbing the laser light and the laser will be reflected away without producing any damage on the white stone (see figure 1).

![Figure 1](image)

**Figure 1**: (a) the laser beam interacting with the black crust causes the ejection of particles, (b) as the black layer is removed the laser beam does not interact with the reflecting surface and it is diffused away.

However, in reality such clear simple cases are rare due to the extreme variety of substrates and encrustations found in Cultural Heritage conservation, therefore the process of laser cleaning is actually much more complex. A fundamental parameter of the laser cleaning process is the pulse duration. The material removal, indeed, follows different “channels of ablation” depending on the pulse duration and on the pulse energy: spallation, thermal explosion, fast or slow vaporisation are just some of this channels. Only pulsed lasers are actually used in the cleaning of art and historical objects. Up to a few years ago, the most employed systems in stone cleaning were Q-Switched (QS) Nd:YAG lasers emitting at the fundamental harmonic (1064 nm) with pulses of typical duration of 8-20 ns. Usually, also the Free Running (FR) regime is available on these commercial laser systems providing pulse durations of 200-500 µs. QS systems could cause photomechanical stress on the target, whereas FR laser can cause photothermal damages on the substrate: to avoid these problems a novel class of Intermediate Pulse Duration Nd:YAG lasers was proposed. These systems are based on Short Free Running (SFR) [4] and Long Q-Switching (LQS) [5] regimes providing pulse duration of 100ns and 30-120 µs, respectively, intermediate between the QS and the FR regimes, reducing hence both the thermal- and mechanical damages to the substrate [6, 7].

3. The evolution of laser cleaning in Cultural Heritage field

3.1. Laser cleaning of stones
Since the second half of the 1980s laser cleaning was widely applied in stone artefacts restoration in Italy, France [8, 9], England [10, 11] and other countries, mainly for the removal of black crusts produced by environmental pollution but also for the removal of intentional dark layers applied in the past. Laser cleaning was applied massively on restoration of stone reliefs, historical façades [12, 13], ancient archaeological artworks such as the West Frieze of the Parthenon [14] and famous Renaissance masterpieces such as Profeta Abacuc, San Marco and Pulpito by Donatello, the capitals of the leaning Tower in Pisa, panels of the Giotto’s tower of the Florence Cathedral by Andrea Pisano [15].

In the last years the laser has been used also in the cleaning of the St. John Baptistery in Florence to remove the crust from the very fragile friezes of the windows and from some capitals where chemical and mechanical traditional methods proved to be too aggressive. Still in Florence, the laser has been lately used for the cleaning of the worldwide known statue of Neptune by Ammannati in Piazza della Signoria for the removal of the thick calcareous crust covering the artwork (see figure 2).

![Figure 2](image)

**Figure 2**: (a) cleaning of a capital of the St.John’s Baptistery, (b) detail of some laser cleaning trials on the Neptune’s statue by Ammannati (courtesy of R.A.M. restauri).

In the last years, the use of laser cleaning overcame the European borders to land in Asia and the USA where important stone conservation works has been performed by laser such as at the Agra Temples in India, the Venus Temple in Balbeek (Lebanon), the Metropolitan Museum Cloisters in New York (USA).

This extensive application of laser cleaning was accompanied by basic studies on the phenomenological characterization of irradiation effects, diagnostic of the material removal and physical modelling which allowed the definition of operative fluence ranges ensuring discrimination between encrustation to be removed and the substrate to be preserved [16, 17] and solving the well-known problem of yellowing [18, 19, 20]. The first case can be addressed by using SFR [4, 20] and double wavelength QS [21, 22] lasers which permit the control of the chromatic hue of the stone surface. Laser ablation of stone surfaces provides many advantages with respect to mechanical and chemical methods in terms of gradualness, self-termination, selectivity, environmental impact and safeguard of the so-called “age patina”.

**3.2. Laser cleaning of metals**

The application of laser cleaning on metals concretely started with the case study of the gilded bronze panels of the Porta del Paradiso by Lorenzo Ghiberti: a careful optimization of laser parameters was performed and led to the introduction of the already mentioned Long Q-switching laser system [23]. The effectiveness and safety of the new temporal regime for the cleaning of mercury amalgam gilding, gold laminas, silver and related alloys was proved during the years. After this first successful study laser cleaning was in fact applied to other gilded artworks such as the Amore Attis and the David by
Donatello [24, 25], and the North Door of the Baptistery in Florence by Lorenzo Ghiberti. The South Door of the Baptistery, the oldest one of the three, manufactured by Andrea Pisano in 1330 is currently under restoration at the Opificio delle Pietre Dure in Florence and the laser is, once again, widely used for the cleaning of gilded parts.

**Figure 3:** (a) laser cleaning of the North Door of the Baptistery of Florence, (b) cleaning of the David by Donatello. Both artworks are made of gilded bronze: the North Door is amalgam gilding and the David is gold leaf.

The restoration of silver included the underwater cleaning of a Roman Treasure (around 300 silver alloy Roman coins) [26] and the application of laser ablation to solve the problem of silver tarnishing [27]. A step forward was represented by the cleaning of oil gilding decorations by using the SFR laser: the restoration of the David by Verrocchio [28] and of the Santi Quattro Coronati by Nanni di Banco [29] demonstrated the effectiveness of the SFR laser to safely uncover gold leaf decorations.

Large bronze sculptures were also lately laser cleaned such as the Etruscan statue “Arringatore” or the sculptural group “Decollazione del Battista” by Vincenzo Danti [30] from the Baptistery of Florence. Moreover, a more recent statue as the bronze Napoleon as Mars the Peacemaker [31] by Antonia Canova (1811) in the courtyard of the Brera Palace in Milan has been cleaned thanks to the LQS laser in combination with more traditional mechanical methods.

### 3.3. Laser cleaning of wall paintings

The application of laser cleaning on wall paintings concretely started with the case study of the frescoed walls of the Old Sacristy and the Chapel of the Mantle in Santa Maria della Scala, Siena [32,20]. The painted walls and the vaults of the Old Sacristy and of the Chapel of Mantle were coated with layers of whitewashing and lime applied in the past.

Preliminary cleaning tests were carried out with SFR and LQS lasers. These two intermediate-pulse systems proved to be extremely effective and safe; used together or one by one, they resulted in the successful removal of the whitewashing, revealing the frescoes resting underneath (figure 4).
**Figure 4** – Uncleaned (left) and laser-cleaned (right) fresco’s detail in the Old Sacristy in Siena.

After these successful results in Siena, the laser started to be used also on extreme environments such as catacombs. One interesting example is the cleaning of the wall paintings in the “Portico dei Fornari” in the Domitilla’s catacombs in Rome [33]. During the last twenty years, the removal of the dark film covering the vaults has been carried out mostly manually but the results obtained with this method were unsatisfactory as they did not end up in the complete cleaning of the surface. Thanks to the laser the dark film was completely removed from all the shades of colours (white, green, ochre, etc) and the wall paintings were completely uncovered by the black layer that concealed them.

Another example of successful laser cleaning in hypogean environment is the cleaning of the decorated stuccoes of the vault of the Pythagorean Basilica of Porta Maggiore in Rome. The stuccoes in the vault were covered by a thick and strong layer of calcium carbonate whereas the decorations on the walls were covered by earthy residues. A powerful QS laser was used to safely remove the encrustations bringing back to light the delicate decorative motifs.

**Figure 5** - (a) laser cleaning of a detail of a fresco in the Domitilla’s catacomb and (b) removal of thick calcareous crust from the decorated plaster of the Basilica of Santa Maria Maggiore (courtesy of R. Mancinelli – C.S.R. Restauri).

In some particularly complicated cases the combined use of different laser systems is required. One of these cases is the restoration of the Carracci Gallery in Palazzo Farnese, Rome. The laser has allowed the recovery of inscriptions and drawings in sanguine and charcoal, made between the late ’600 and 800 by artists who visited and studied the Gallery. The drawings were concealed by a thick layer of lime and, only thanks to the synergistic action of laser systems with different operating modes, it was possible to remove the lime and bring to light the beautiful sketches that were hidden under it. The restorers, depending on the thickness of the crust and on the nature of the underlying drawing, employed both the Er:YAG laser than the Nd:YAG LQS and SFR systems.

A set of different lasers is currently being employed also in the Sforzesco Castle in Milan at the Sala delle Asse on the walls painted by Leonardo Da Vinci. The decoration is based on a dense interweaving of branches and foliage, which develops in a sort of pergola and ideally breaks through the wall of the closed hall, transforming it into a piece of open-air landscape. Particularly interesting is the fragment on the east wall, brought to light in 1954, covered by a black-white monochromatic preparatory drawing, where large roots can be seen penetrating some rocky stratifications: this is the base of the tree stem, from which originally departed all the green leaves that cover the vault of the room. On the east wall the laser beam is used to remove the layers of whitewash in search of the original preparatory drawings, while on the vaults the laser helps the restorers to look for the authentic colours of Leonardo below the different repaintings. In this conservation project the restorers are using Nd:YAG systems with QS, LQS and SFR pulse durations.
3.4. Laser cleaning of easel paintings

The cleaning of easel paintings i.e. the removal of thin films of varnishes, resins, repaintings or deposits from the pictorial layer, represents the main challenge of laser cleaning.

Recently, the interest turned to the Er: YAG laser systems with a wavelength of 2940nm which proved to be particularly effective in the removal of repaintings and aged, yellowish varnishes from paintings on canvas and board [34, 35]. The wavelength of 2940nm is highly absorbed by OH bonds therefore, the efficiency of the laser ablation is directly proportional to the amount of OH groups present in the materials. When these OH bonds are not present on the original material, they can be obtained by the addition of hydroxylated liquids, which can also help to limit the heat penetration. The application of Er:YAG laser cleaning to easel painting is the newest frontier of this technique. There are quite few case studies reported in literature [36] and a scientific, rigorous approach is still at its initial stage but the interest has enormously increased in the last period thanks to some successful cleaning results obtained on the removal of mastic and dammar varnishes, linseed oil/ sandarac varnishes, Paraloid B72 and animal glue.

Restorers, conservators and scientists are working together to fully exploit the huge potential of this brand new approach that will surely bring a new important tool in the restorer’s toolbox: the laser.

Figure 6 - The laser acting on a drawing in the Carracci Gallery in Palazzo Farnese in Rome (courtesy of Paolo Pastorello-CRC Restauri).

Figure 7 - Duke University professor Adele De Cruz using the Er:YAG laser for the removal of aged varnish from a Borrasa’s Panel Painting (15th Century).
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