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A combined approach for the attribution of handwriting: the case of Antonio Stradivari's manuscripts

Giusj Valentina Fichera[1] · Piercarlo Dondi[1] · Maurizio Licchelli[1,2] · Luca Lombardi[3] · Stefano Ridolfi[4] · Marco Malagodi[1,5]

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Abstract Numerous artefacts from Antonio Stradivari's workshop are currently preserved in the "Museo del Violino" (Museum of the Violin) in Cremona, Italy. A large number of them are paper models containing instructions and technical notes by the great violin maker. After his death, this collection has had several owners, while new annotations added to the original ones, sometimes imitating Stradivari's handwriting, caused problems of authenticity. The attribution of these relics is a complex task and, until now, only a small part of them has been examined by palaeographers. This paper introduces a multi-analytical approach able to facilitate the study of handwriting in manuscripts with the combined use of image processing and X-ray fluorescence spectroscopy: the former provides a fast and automatic screening of documents; the latter allows to analyse the chemical composition of inks. For our tests, 17 paper relics, dated between 1684 and 1729, were chosen. Palaeographic analysis was used as reference. The results obtained showed the validity of the combined approach proposed herein: the two techniques proved to be complementary and useful to clarify the attribution of different pieces of handwriting.

✉ Giusj Valentina Fichera
giusj.fichera@unipv.it

1 Arvedi Laboratory of Non-Invasive Diagnostics, University of Pavia, Via Bell'Aspa 3, 26100 Cremona, Italy

2 Department of Chemistry, University of Pavia, Via Taramelli 12, 27100 Pavia, Italy

3 Department of Electrical, Computer and Biomedical Engineering, University of Pavia, Via Ferrata 5, 27100 Pavia, Italy

4 Ars Mensurae, Via Comparini 101, 00188 Rome, Italy

5 Department of Musicology and Cultural Heritage, University of Pavia, Corso Garibaldi 178, 26100 Cremona, Italy

1 Introduction

A considerable number of pieces of Antonio Stradivari's handwriting, one of the most important and popular violin makers in the world, consist of paper manuscripts containing instructions, drawings, information and technical notes important to the design and construction of musical instruments. Currently, a collection of more than 1300 relics (which includes paper and wooden moulds, drawings, annotations and tools) is preserved at "Museo del Violino" (Museum of the Violin) in Cremona, Italy. Many of these have annotations (a few letters and words or longer text lines) written by one or, sometimes, two or even more hands [1].

In fact, these relics had a very troubled history, and the authenticity of some of them is still uncertain. After Antonio Stradivari's death (first half of the eighteenth century), the collection has had several owners over the years, and new annotations and pieces of handwriting have been added to the original ones, often imitating Stradivari's handwriting [2] itself.

Today, this complex and unclear situation represents an exciting challenge for curators, restorers and conservation scientists who want to study and catalogue all the relics and to ascribe the different pieces of handwriting to their original authors. Until now, attributions have been made on the basis of (1) palaeographic examination, which requires a high level of research experience [1]; (2) historic analysis, with in-depth sessions of study and research of sources [3]. For all these reasons, this kind of study takes a lot of time and also requires, in this particular case, a deep knowledge of the main features of Stradivari's handwriting.

Nowadays, palaeographic study has been conducted on 125 pieces of handwriting, by comparing them with letter references definitely attributed to Antonio Stradivari [1]. The examination was performed in two different steps: (1) description of the stroke of the single letters and of the most characteristic features of Stradivari's writing; (2) palaeographic comparison of the different pieces of handwriting. Among the relics already examined, we selected 17 paper relics (Table 1; Fig. 1) that included pieces of handwriting attributed to Stradivari, pieces of handwriting attributed to other hands, and no imitators of Stradivari's style. Our goal was to define a procedure to clearly distinguish Stradivari's handwriting from the handwriting of others. This work introduced a non-invasive multi-analytical approach that combines image elaboration and X-ray fluorescence (XRF) spectroscopic analysis: the former provides a fast and automatic screening of documents; the latter analyses the chemical composition of inks. Handwriting recognition and identification is a well-known task in image processing [4], but it is less frequently used in the field of historical documents. In the current case, palaeographic studies have already identified key graphic elements (graphemes) characteristic of Stradivari's handwriting [1]. Starting from this sample set, we chose some of the most frequent graphemes as reference to develop a recognition algorithm based on a variation of a classic template matching. This procedure segments pieces of writing with a specific thresholding, normalizes the data with respect to scale, and selects the regions that are most similar to the models. The proposed method is fast and can provide a rapid classification of paper relics, but at the same time it can produce false-negative or false-positive detections, for example due to discoloured or damaged pieces of writing, or letters casually similar to Stradivari's. For this reason, X-ray fluorescence (XRF) spectroscopy was chosen as support to image analysis, with the aim of (1) characterizing chemical elements present in the inks, (2) providing statistical data by performing appropriate analytical experiments.

From historic sources, it is known that iron-gall ink was extensively used in the second half of the seventeenth century and that also Antonio Stradivari could have used it for his writing [3]. This kind of ink mainly contains iron, with traces of metal ions, which can be important parameters to assess the composition of an ink, as well as copper, zinc or nickel [5–9]. Due to the variety of recipes and the

Table 1 List of paper relics ordered by inventory code and comparison between palaeographic and automatic attribution

Relic code	Date (if present on the relic)	Palaeographic attribution (ground truth)	Automatic attribution
MS_210	1690	Stradivari	Stradivari
MS_213	–	Stradivari	Unclassified
MS_214	1690	Stradivari	Stradivari
MS_222	1727	Not Stradivari	Not Stradivari
MS_234	1690	Stradivari	Stradivari
MS_238	1690	Stradivari	Stradivari
MS_250	1684	Stradivari	Stradivari
MS_251	1684	Stradivari	Stradivari
MS_252	–	Not Stradivari	Not Stradivari
MS_255	1684	Stradivari	Stradivari
MS_257	1684	Stradivari	Stradivari
MS_272			
Recto	–	Stradivari	Unclassified
Verso	–	Not Stradivari	Not Stradivari
MS_323	1701	Stradivari	Stradivari
MS_324			
Recto	1701	Stradivari	Stradivari
Verso	–	Stradivari	Stradivari
MS_601 BIS	1708	Stradivari	Stradivari
MS_601			
List	1698	Not Stradivari	Unclassified
Signature	–	Stradivari	Stradivari[a]
Stradivari's last will	1729	Stradivari	Stradivari

[a] Casual correct attribution due to a false positive

Fig. 1 Some of the relics analysed: **a** Stradivari's last will; **b** model of the neck and the head of the viola da gamba 1684; **c** model of the neck and the head of the viola 1690; **d** neck measure of a viola da gamba (attributed to an other hand)

natural origin of different materials, there is a wide range of components and impurities in historical iron-gall inks [10, 11], and the ratios between iron and other metals (Cu, Zn, Ni or Pb) could be used as "fingerprint information" to identify a specific ink [12]. Several pieces of handwriting were analysed by XRF spectroscopy, and several inks belonging to pieces of handwriting certainly attributed to Stradivari were used as reference. Moreover, a lot of those relics were dated and a chronological assignment of the inks was performed. The results obtained show the validity of the combined approach proposed herein.

2 Analytical methods

The proposed combined approach was applied to 17 paper relics, all previously examined by palaeographers. When a relic was written on both sides (recto and verso), the two parts of handwriting were considered separately, for a total of 20 pieces of handwriting on 17 relics. For all of them, we proceeded in the same way: first, the automatic classification by image processing procedure was performed, and thereafter the results were refined by combining them with the XRF analysis data. The palaeographic attribution was used as reference (ground truth).

2.1 Morphological study of the inks: photographic and stereomicroscopic examination

High-resolution images of the paper relics were acquired by using a Nikon D4 full-frame digital camera (50 mm, f.1.4 Nikkor objective, f/11 as focal ratio, ISO 100). The same conditions were used for all pictures and all paper relics. In order to reduce perspective distortions of the objects, the image plane of the camera was placed parallel to the surface of the relics. To limit accidental oscillations, the camera was mounted on a horizontal telescopic arm (fixed to the ground by a tripod) and controlled by remote. Two softbox LED panels ($T = 5400$ K) provided a uniform illumination. The images were saved in RAW format and then converted into TIFF. An XRite ColorChecker passport was used for colour calibration and white balancing.

Preliminary microscopy observations were performed by means of a stereo microscope Olympus SZX10, which allowed to observe the inks used in handwriting of Stradivari's relics at high magnification (from 9.45× to 94.5×). The microscope was connected to a digital camera (Olympus DP73), which allowed to acquire high-resolution images; Stream Essentials software was used to create maps and perform micrometre measurements of lengths and areas.

2.2 Image-based identification: automatic palaeographic system

Handwriting recognition and identification is a complex task in the field of image processing. Different approaches are available in literature, mostly related to forensic document analysis. For instance, Khalifa et al. [13] used a codebook approach, which, however, needs a very large database of samples; Newell and Griffin [14] presented a method for writer identification that exploits texture-based encoding. Other solutions for writer identification involve the use of texture and allographic features [15], the extraction of local features and graphemes [16], or the combined use of small redundant patterns and significant writing characteristics, such as orientation or curvature [17]. Complete surveys of handwriting identification methods have also been published in the last decades [18, 19]. In the field of cultural heritage, handwriting recognition techniques are widely used for facilitating the digitalization of writing on ancient paper [20] or stone relics [21]. Methods for palaeographic analysis of ancient documents are less frequent and are mainly focused on mediaeval manuscripts [22–24]. There are only few studies about more recent historical manuscripts, such as Eglin et al. [25] which applied Hermite and Gabor transforms for the classification of handwritten pages form the eighteenth centuries.

Our scenario is particularly complex, as the cursive writing used in the seventeenth–eighteenth century is irregular and very different from the geometric letters used in mediaeval texts. Moreover, the majority of Stradivari's relics contain short work notes (a couple of lines or a few words). Among the 1300 relics held in the museum, there are only two long documents surely written by Stradivari (a letter and his last will). This is particularly critical, since the major part of writer identification algorithms need long texts to work efficiently. Even forensic methods for signature identification that operate on few words are trained with large databases.

However, the results of the recent palaeographic study performed by D'Agostino [1] can be used as a starting point. In fact, this analysis identified different graphic elements or graphemes (such as numbers, single letters or couples of letters) typical of Stradivari's handwriting. Among them, the most characteristic ones are certainly the following 11 graphemes: "8, a, Ad, D, F, G, l, p, tt, q, zz". Our idea was to imitate the normal palaeographic approach: to acquire a sample set of key graphemes and then find occurrences of each of them in the writing. Due to the limited number of the relics considered, not all the 11 key graphemes had the same probability to appear. After a first screening, four of them with a very low occurrence ("Ad, F, q, zz") were excluded. For each of the remaining ones ("8, a, D, G, l, p, tt") 3–4 samples were extracted, in order to consider the distinctive pattern variations typical of the handwriting. In fact, slight differences are always possible due to many unpredictable factors, i.e. the pressure of the hand, the mood of the writer, the writer's posture in writing, or even the writer's age. For a complete covering of all the most frequent variations in Stradivari's handwriting, we would need a larger number of samples for each grapheme. However, considering the limited number of paper relics available for this work, increasing the sample set would mean using almost all the key graphemes in the text.

Figure 2 shows an overview of the main phases of our method. As a preliminary step, each sample key grapheme was rescaled at different dimensions (from a minimum of 35 × 35 pixels to a maximum of 120 × 120), in order to increase our limited sample set and to consider the possible different dimensions of the writing. Rotations were not considered, because they can be critical in the proposed scenario. For example, the letter "l" is characteristic of Stradivari's handwriting not only for its shape but also for its inclination, thus a rotation loses this important information.

The next step is the normalization of the sample key graphemes and of the input paper relics. Due to their age and the composition of the inks, paper relics can have different colours or blots on their surface, and the text can be discoloured. A thresholding process can extract and highlight the writing, while excluding other irrelevant parts. For this purpose, Otsu's method was applied, followed by a morphological filtering [26] to close the gaps.

The last step is the template matching. After testing different possible methods, we chose the matching based on normalized cross-correlation, the one that gives the best results. The program performs comparisons and accepts as valid only the matches with the highest percentage of

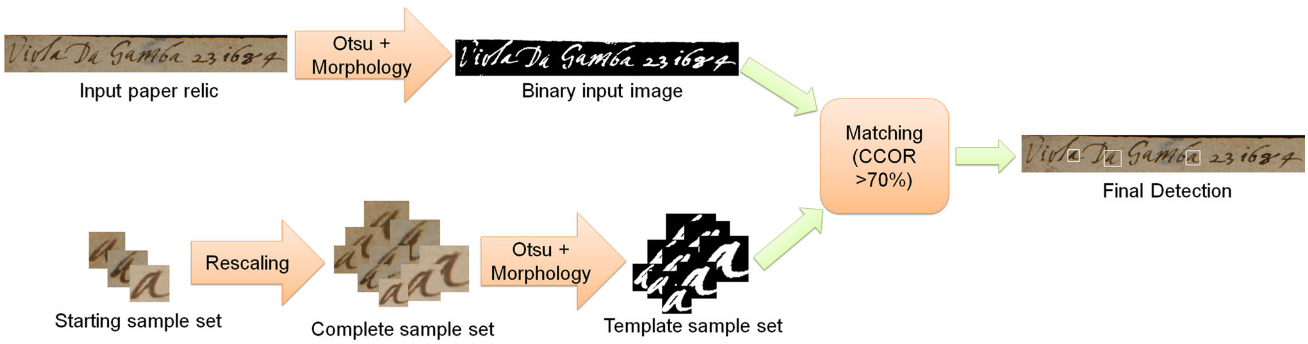

Fig. 2 Overview of matching procedure with one letter

similarity (Fig. 3). Different thresholds of acceptance were set, depending on the type of key grapheme and the dimension. More strict thresholds were adopted with small ones, because they can be confused with generic "blobs" (e.g. a very small "a" could be confused with a blot).

It is important to notice that we do not need to find all the occurrences of a key grapheme in a paper relic; the similarity thresholds are maintained high, because we are interested in finding only those that have the highest resemblance with the chosen models. In this way, false negatives can increase, but false positives are hugely reduced. This compromise is acceptable, as our aim is to provide very sure attributions. It is better to classify as unsure a piece of Stradivari's writing rather than to classify as made by Stradivari a piece written by a coeval author. However, some false positives can occasionally occur (especially with small pieces of writing). Possible error sources are mainly three: (1) faded writing confuses the program (Fig. 4a); (2) totally different letters with a shape casually similar to one of the models (Fig. 4b); (3) key graphemes written by another author in the same (or at least very similar) manner as Stradivari's (Fig. 4c).

According to the proposed procedure, a piece of writing is attributed to Stradivari if at least three different types of key graphemes are found. This minimum threshold is a reasonable compromise: it is difficult to find a relic with all seven key graphemes, because the pieces of writing are almost always very short, with only some notable exceptions, such as Stradivari's last will; on the other hand, the detection of only one or two key graphemes could be accidental, due to false positives. The final output is a high-level classification in three macro categories: very likely Stradivari (three or more different graphemes found); very likely not Stradivari (no graphemes found); unsure/unclassified (only one or two different graphemes found). In order to work correctly, our program needs at least one or two words; thus, relics with only few uppercase letters cannot be analysed.

With this system, it is possible to perform a fast screening of a large amount of paper relics in a few minutes, while a normal palaeographic analysis would take hours or days. The resulting classification is the first step of our combined method, but it is also meaningful as itself for palaeographers and researchers, who can use it to speed up their work (e.g. they can analyse only the unsure cases instead of the entire set of documents).

2.3 Elemental characterization of the inks: X-ray fluorescence spectroscopy

Elemental composition was obtained using X-ray fluorescence spectroscopy. Different zones of each considered relic were analysed, including the paper, and several ink areas. The measurements were performed operating at 40 kV, 60 µA, and, for each of them, the acquisition time was varied to allow a reliable comparison among data trends. XRF spectra were acquired by means of a portable XRF spectrometer ELIO produced by XGLab srl (Milan, Italy). This system was constituted by a Large area Silicon Drift Detector (25 mm^2) and good throughput capability, thanks to a new complementary metal-oxide semiconductor (CMOS) Silicon Drift Detector readout

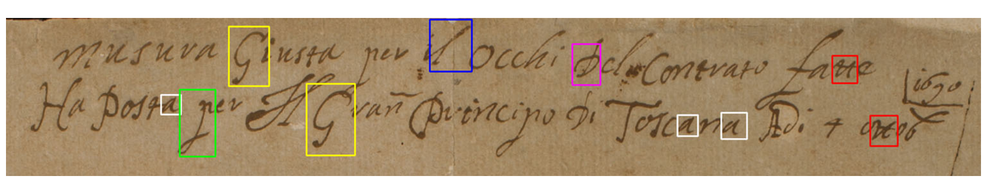

Fig. 3 Example of detection on relic MS_210: six different types of key graphemes with a high similarity with the chosen samples are retrieved (*different colours mark* different key graphemes)

Fig. 4 Examples of different types of false positive: **a** wrong detection of a “tt” on a faded writing; **b** a “q” confused for a “G” due to partial similar shape; **c** a correct detection of a “l” on a writing surely attributed to an author different to Stradivari

(CUBE). The excitation source worked with an Rh anode, and the beam was collimated to a spot diameter on the sample surface of about 1.2 mm. The head of the XRF was attached on a tripod allowing flexible positioning during the analysis sessions. The relics were analysed by laying sheets on a holed plate, and they were positioned in such way that the analysed area was on the hole [27]. All the analyses were performed keeping the sample-to-probe distance constant, to correctly compare the element distribution in the ink samples. Ten points for each piece of handwriting were analysed, in order to obtain statistically valid data. A spectrum of the paper was also taken for each sample (under the same experimental conditions) at a point of the paper near the ink and subsequently was subtracted this value to the spectrum taken on the ink. The thickness and homogeneity of the two points of the neighbouring paper can be assumed equal. The differences between the two spectra are therefore attributable only to the ink.

Although a full quantitative analysis was not possible, the use of the same geometry, voltage, and current conditions for different specimens allowed reasonable comparisons. Relative content of the detected elements were evaluated by integrating the corresponding Kα peaks. The integration of the peaks is calculated with a component due to the background determined with a fitting on the whole spectrum (global parameter) and a component due to a gaussian fitting of the specific section of the spectrum (locale parameter) where the peak is located. The results obtained from XRF analyses were compared with those concerning palaeographic studies.

3 Results and discussion

Stereoscopic examination of the inks highlighted the presence of several morphologic features. Figure 5 shows some examples. Most of the inks examined showed a cracking on the surface with distinguishable patterns and a shift in colour or gloss from that of the overall ink (Fig. 5a, b). In some cases, a golden or orange colour, together with a pale surface haze, was observed (Fig. 5c, d).

The result of our automatic classification system was compared to ground truth attribution (the palaeographic analysis of D’Agostino [1]). We achieved a good level of precision (Table 1): 17 cases out of 20 were correct, while the other three were identified only as unclassified. There were no cases of completely wrong attribution (e.g. a piece of not-Stradivari handwriting recognized as very likely written by Stradivari). The program also proved to be computationally efficient: tested on an entry-level PC equipped with an Intel Core2 Quad Q9300 @2.50Ghz and 4 GB RAM, it completed the analysis on our set of paper relics in about 4 min, going from a minimum of 0.8 s for relics with short text (only a few words) to a maximum of 64 s for the last will.

X-ray fluorescence analysis performed on the handwriting revealed the presence of both typical elements of iron-inks and paper, i.e. Si, S, K, Ca, Ti, Mn, Fe, Cu, Zn, with lower amounts of Hg and Pb [28]. As far as Hg and Pb are concerned, these two elements may come from additional colouring in the ink or the treatment, or they can be present as impurities [28]. However, Hg and Pb, together with Si, Ti and Mn, were not considered in the discussion, due to the lower and variable intensity of their emission peaks. Also S, K, and Ca elements were not discussed in this paragraph, because their contribution could come from different materials and not only from the ink. In fact, the presence of S and K could be related to the use of alum as a sizing agent during the processes of papermaking [29, 30] and the calcium detected in the ink could be due to the vegetal components (i.e. gum Arabic) used as binder [11, 31]. Moreover, the S element in the ink has not been taken into account, because the amount of sulphur decreases over time due to ageing or to interaction processes with the paper [12]. For all these reasons, only Fe, Cu and Zn were taken into consideration as elements directly correlated to the inks [32], and their relative amounts were compared in the different pieces of handwriting. As reported in literature, the Fe/Cu, Fe/Zn and Cu/Zn ratios can be considered the key factors to distinguish the inks of different documents [5, 12, 27, 33]. The average values of the elemental ratios obtained by analysing different ink spots of the examined relics are listed in Table 2.

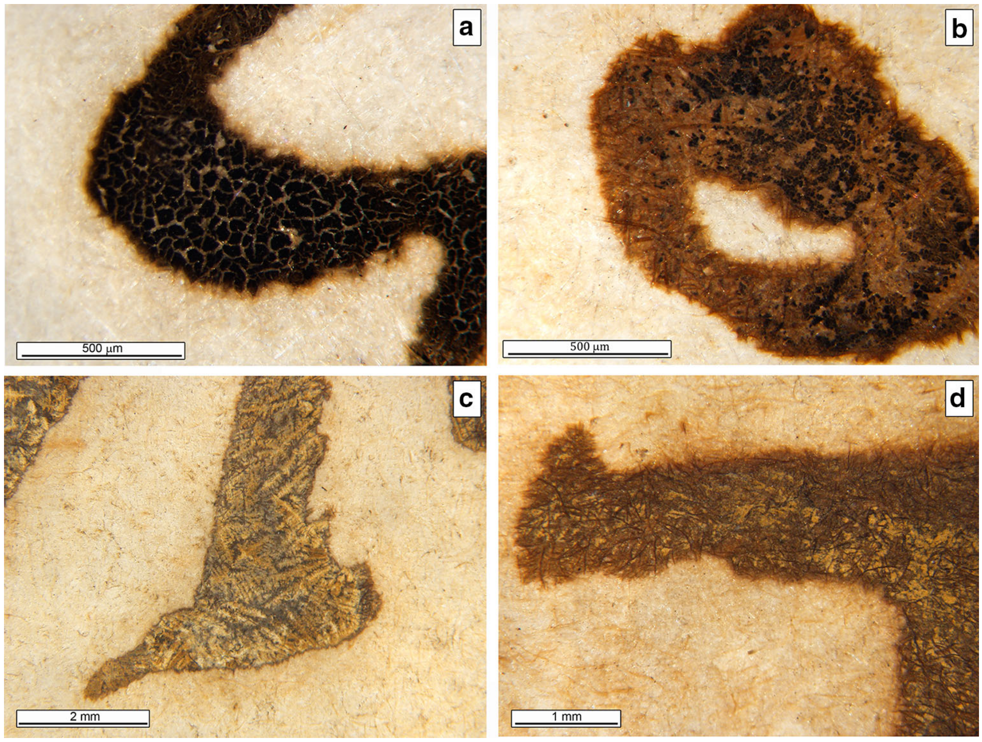

Fig. 5 Stereomicroscopic images of some details of the iron-gall ink crystallization observed in handwritings: **a** Stradivari's last will; **b** model for the neck heel of a viola da gamba; **c** scroll drawing of a viola; **d** body drawing of a viola

The relics were grouped according to their age and to their attribution to a particular set, which was made on the basis of historical information [1]. The investigation on the elemental composition showed that relics with the same date or belonging to the same set are not always characterized by the same type of ink.

An elemental comparison of all inks of the pieces of handwriting attributed to Stradivari by palaeographers was carried out. All data obtained from XRF analyses were reported in the binary diagram in Fig. 6. The graph shows the presence of several groups, and each of them defines a specific type of ink ascribable to a specific date. In general, the groups were well defined and only in a few cases (MS_272_recto, MS_323, MS_324_verso, MS_601_signature, and MS_601_BIS) a greater degree of dispersion could be observed. In particular, it was possible to detect 10 types of iron-gall inks in the time span considered (from 1684 to 1729) (Fig. 6; Table 3).

The results obtained on each relic are described below, with particular focus on the most interesting cases, where the combined use the two analytical techniques allowed us to obtain information that cannot be obtained by using only one of them.

At first, the combined analytical approach was applied to SET_I, which consisted of four paper models dated 1684 and attributed to Stradivari and just one (MS_252) attributed to another hand. The inks observed at higher magnifications showed similar morphological features, including a cracked surface and a colour that varies from intense black (abundant ink) to light brown (low amount of ink). The presence of an evident and wide halo was observed only in the ink of relic MS_250. This halo did not cause any problems to the handwriting identification system, which was able to detect three key graphemes ("8", "a" and "l"), which was sufficient to attribute the relic to Stradivari. The other relics did not show particular problems, as the automatic procedure classified all of them as made by Stradivari. In particular, MS_251 was one of the more clear samples, with six out of seven types of key graphemes found. Although MS_255 and MS_257 consisted of short pieces of writing, three different key graphemes were correctly identified ("G", "a", "8" on the first; "a", "D", "8" on the second). As far as relic MS_252 was concerned, the program did not find any key graphemes typical of Stradivari's handwriting. XRF analyses performed on relics belonging to SET_1 revealed the presence of inks with different compositions (Fig. 6; Table 2). The inks of relics MS_251, MS_255 and MS_257, all attributed to Stradivari, had very similar values, suggesting that the same ink was used for all of them. On the contrary, the values of the elemental ratios determined for MS_250 and MS_252 were different from the other relics, suggesting the presence in the set of different inks. The handwriting on the MS_250 model was definitely

Table 2 Average values of the elemental ratios (net area counts) of the inks obtained by XRF analyses

Paper relics	Fe/Cu	Fe/Zn	Cu/Zn
SET I (1684)			
MS_250	18.6	32.8	1.77
MS_251	3.67	5.20	1.42
MS_255	3.57	5.28	1.48
MS_257	3.75	5.06	1.35
MS_252	10.9	12.1	1.13
SET II (1690)			
MS_210	11.0	10.7	0.98
MS_213	8.03	5.54	0.69
MS_214	7.53	5.09	0.68
MS_234	11.2	10.8	0.97
MS_238	7.44	4.88	0.66
1698			
MS_601			
List	18.1	61.5	3.40
Signature	26.0	70.2	2.70
SET III (1701)			
MS_323	26.7	59.4	2.23
MS_324			
Recto	17.4	18.9	1.09
Verso	25.5	58.5	2.30
1708			
MS_601 BIS	20.7	38.4	1.85
1709			
MS_272			
Recto	91.2	66.2	0.76
Verso	22.8	23.2	1.06
1727			
MS_222	9.96	3.78	0.38
1729			
Stradivari's last will	10.3	21.5	2.10

attributed to Stradivari, both by palaeographic and automatic analysis; therefore, the presence of a different ink supports our hypothesis that Stradivari used two types of ink within the same year. Relic MS_252 was attributed to a different hand by palaeographic as well as automatic examination, and the elemental composition of the ink definitely confirmed that it was not made by Stradivari.

SET_II concerned relics used for the construction of two violas (tenor and alto) dated 1690. Stereoscopic examination of the inks highlighted different morphological features if compared to SET_I. In particular, three models (MS_214, MS_238 and MS_213) showed a golden or orange colour together with a pale surface haze, while the handwriting on the models MS_210 and MS_234 showed a lower amount of ink. The image processing tool classified the four dated pieces of handwriting as written by Stradivari. In particular, on MS_214 and MS_238, three key graphemes ("p", "l", "tt") were found, while six out of seven key graphemes were retrieved on MS_210 and MS_234. Instead, relic MS_213, which did not display any date and was attributed to this group only on the basis of historical sources, resulted unclassified. XRF analyses performed on this group of relics highlighted the first subdivision made on the basis of the morphology of the inks, showing the presence of two different types of inks, as shown in Fig. 6. The first type (MS_214 and MS_238) regarded two pieces of handwriting in drawings on the scroll of the tenor and alto viola. This ink was characterized by a very constant distribution of the ratio values. On the contrary, the second type (MS_210 and MS_234), which concerned the annotations written in the body models of the violas, had a more scattered distribution. Relic MS_213 showed ratio values comparable with those of the first type of inks found in this set (Table 2), with the same distribution. Thus, even though the result of the automatic identification was unclear, the elemental analysis seemed to confirm the affinity of this relic to this original set.

SET_III consisted of only two relics (MS_323 and MS_324 with handwriting on recto and verso) belonging to the set for the construction of a "viola da gamba". Models MS_323 and MS_324_recto reported the date 1701, while MS_324_verso did not display any date. The inks in the handwriting showed the same morphological features. All of them showed a light brown colour and a few areas characterized by cracking of the ink. The automatic attribution system identified the two paper relics as written by Stradivari: four key graphemes were found on MS_323 ("8", "a", "D", "l") and MS_324_recto ("8", "a", "l", "tt") and three on MS_324_verso ("a", "l", "p"). XRF analyses refined these results. As shown in Fig. 6, two different types of inks were detected: one ink (ascribable to relic MS_324_recto) was characterized by a more constant distribution of the elements, while the other one (ascribable to relics MS_323 and MS_324_verso) showed a more scattered trend. The correspondence between the ink compositions of the handwriting on MS_323 and MS_324_verso allowed us to hypothesize that they were written at the same time, helping us to date (1701) also the annotation written on the verso of model MS_324.

The case of MS_601, shown in Fig. 7, represents a good example of the efficiency of the proposed integrated approach. This document contains a list of expenses for the funeral of Stradivari's first wife and shows the date 1698. According to the palaeographic examination, the first section of the document (herein referred to as *list*) had a no definite attribution, while the last two lines (herein referred to as *signature*) were attributed to Stradivari. The observations at

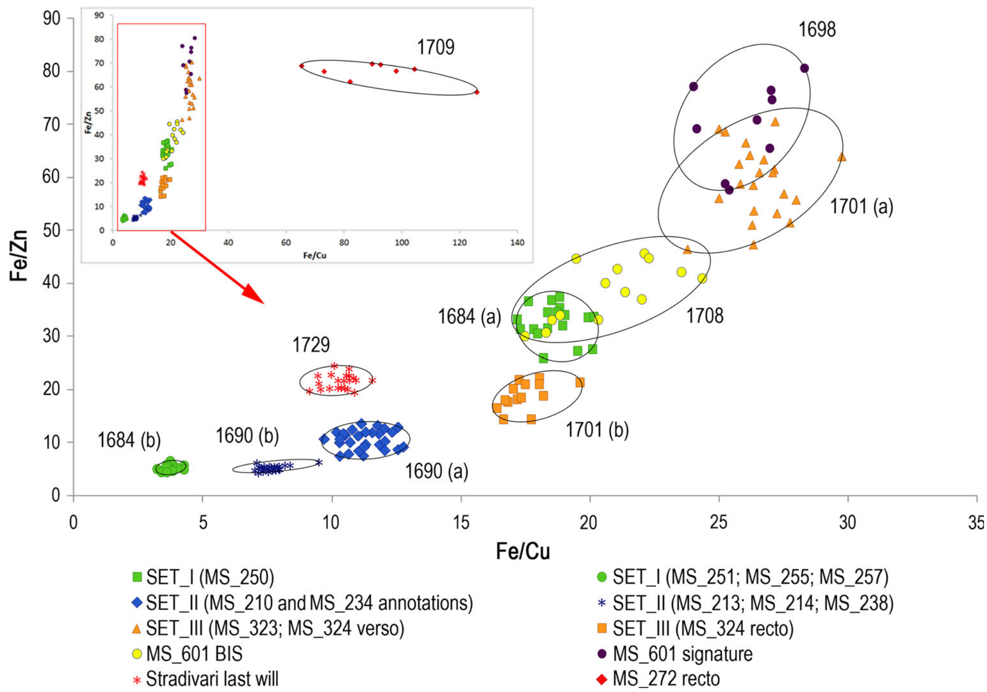

Fig. 6 Binary diagram of the discriminant elemental ratios of inks in the Stradivari relics from 1684 to 1729; "*a*" and "*b*" letters indicate different inks of the same year

Table 3 List of different types of inks determined with XRF analysis

Stradivari inks (determined by XRF analysis)	Historical period	Relic
I	1684 (a)	MS_250
II	1684 (b)	MS_251
		MS_255
		MS_257
III	1690 (a)	MS_210 annotation
		MS_234 annotation
IV	1690 (b)	MS_213
		MS_214
		MS_238
V	1698	MS_601 signature
VI	1701 (a)	MS_323
		MS_324_verso
VII	1701 (b)	MS_324_recto
VIII	1708	MS_601BIS
IX	1709	MS_272_recto
X	1729	Stradivari's last will

high magnification showed that the ink had a light brown colour, a cracked surface and an evident and wide halo. Moreover, in the signature, some letters were partially mixed, confused and, in some case, faded. These particular features made the automatic examination more difficult. In the list, the program found occurrences of two false-positive key graphemes ("l" and "G"); thus, the document was wrongly classified as uncertain. The signature was problematic, too: although it was correctly attributed to Stradivari, this result was only due to a casual false positive. In fact, the program correctly identified an "l" and an "8", but it also found a "tt" in the middle of the name "Stradivari" near the "v". The XRF analyses allowed us to clarify the results of the automatic attribution system: the elemental ratios of the iron-gall inks were different near the list and the signature (Fig. 7). Therefore, we can confirm the hypothesis of two different hands, solving the uncertainties of the automatic detection. We can assume that probably the list was written earlier and then, at a later date, Stradivari signed the document.

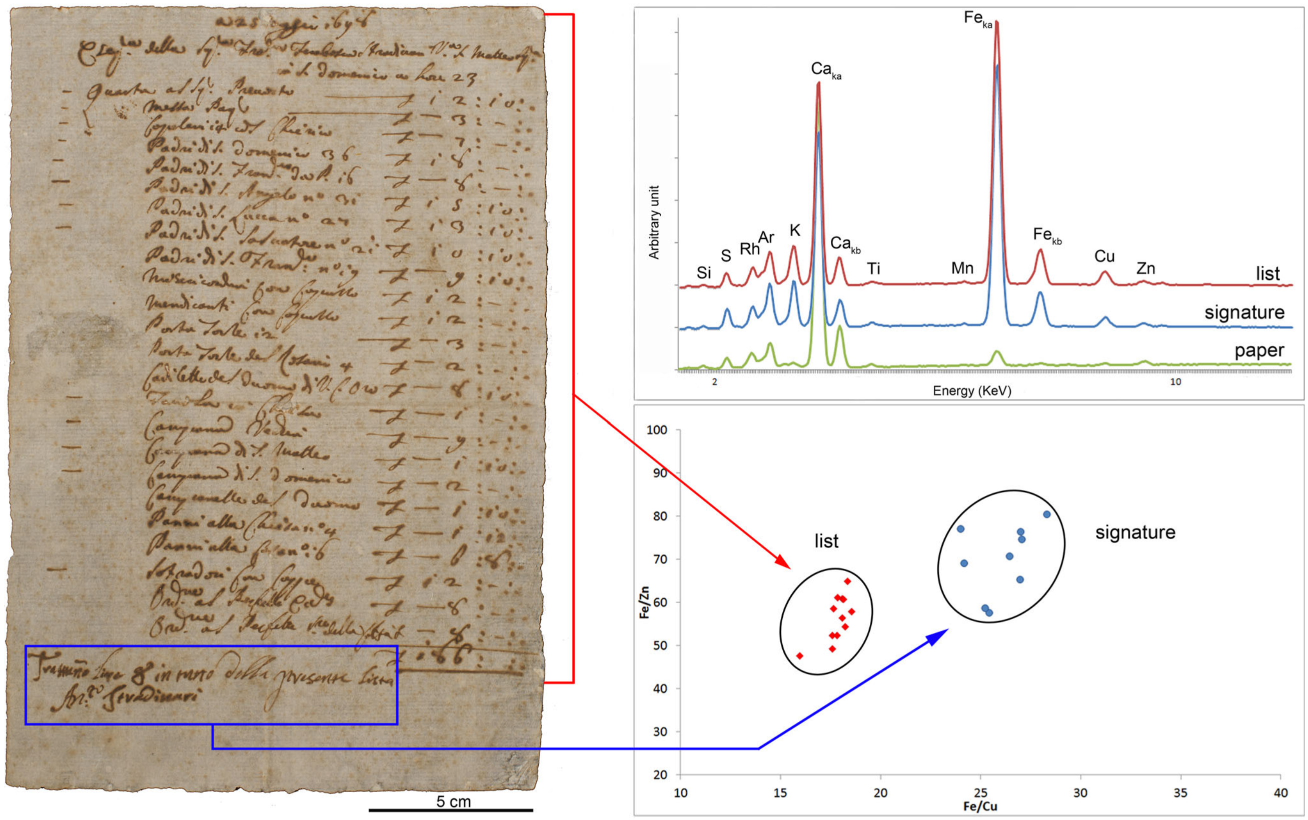

Fig. 7 Photo of the relic MS_601; *right top*: representative XRF spectra of the iron-gall ink (list and signature) and of paper; *right bottom*: Fe/Cu versus Fe/Zn ratios of iron-gall ink in different areas of the document

Each of the four remaining relics considered (MS_601_BIS, Stradivari's last will, MS_272, MS_222) was written in a different year (Table 1). The automatic attribution system indicated that both the autograph manuscript (MS_601_BIS) and Stradivari's last will were written by Stradivari, in accordance with results from palaeography. Multiple correct occurrences of six out of seven key graphemes (all except for "8" not present in the pieces of writing) were retrieved. Inks in the handwriting show a cracked surface in distinguishable patterns and different colours (brownish and blackish for MS_601_BIS and Stradivari's last will, respectively). XRF analyses performed on ink spots provided elemental ratios that were different from those determined in the other inks used by Stradivari.

Relic MS_272, which was part of the set for the construction of the cello dated 1709, represented an interesting case of study: the handwriting on the recto was attributed by palaeographers to Stradivari, while the one on the verso to another hand. As expected, the verso handwriting was classified as not made by Stradivari by the automatic attribution (no key graphemes found) and the XRF analysis coherently showed a chemical composition different from all the other inks used by Stradivari. Instead, the results of recto handwriting were in contrast with the palaeographic examination: the automatic program retrieved only one key letter ("p"), not sufficient for a clear attribution; the ink composition showed a high Fe/Cu ratio (up to 120), very different from the values found in other inks used by Stradivari (usually in the range 4–30, see Table 2; Fig. 6). We consider this case very important, because the combined approach proposed in this work calls into question the attribution performed by palaeographers, and new examinations are under way to better understand this outcome.

Finally, the combined analytical approach was applied to relic MS_222, the handwriting on which was attributed to another hand from historic sources and palaeographic studies. The attribution to a different hand was confirmed by both the automatic identification system (no key grapheme found) and the chemical characterization of the inks (ratios different from the inks used by Stradivari).

4 Conclusions

This work represents a multi-disciplinary approach for the study, characterization and attribution of Antonio Stradivari's handwriting. The combined use of an automatic palaeographic system and XRF analysis provided good results. The image processing proved to be a quick palaeographic support, with a good level of precision despite the limited sample set available (among 20 handwritings present on the relics, 17 were correctly attributed, 3 were unclassified and no one was wrongly attributed). The ink characterization of Stradivari's relics allowed us to date a scale of inks and to use it as reference for the studies of the handwriting of the great violin maker. In particular, through the determination of key parameters (e.g. ratios between characteristic elements), it was possible to identify ten types of inks in the paper relics, used between 1684 and 1729. The evaluation of these elemental ratios, in combination with the automatic attribution, allowed us to highlight the presence of different ink compositions in the same year. No correspondence between the inks on relics written by other hands and those written by Stradivari was found. The XRF analysis allowed also to solve those cases in which our automatic classification gave an uncertain attribution. During this research, three important results were obtained: (1) the assignment of a relic with uncertain date to its original set, (2) the attribution of the original date to a relic, (3) the ability to distinguish texts written in different periods on the same relic. Moreover, in one case, the proposed combined approach was able to call into question the attribution to Stradivari previously made by a palaeographer. New examinations are currently under way to understand this result.

Further enhancements of the automatic handwriting identification are currently ongoing. First of all, as the set of samples increases, we can increase the number of samples for each key grapheme and add the four ones currently excluded. In this way, we could achieve a better covering of the variations of Stradivari's writing style. We are also considering a refinement of the binarization process to make the faded writing clearer, and the integration of other feature detection algorithms to increase the precision of the detection. After these improvements, new tests on a larger set of hundreds of papers and wooden relics are planned.

The results of this work can be used as reference for analysing paper relics not yet examined by palaeographers. If a sufficient number of key graphemes in combination with one of the inks detected in this work are present on a piece of handwriting, there is a high probability that it was made by Stradivari.

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