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Abstract: the "BHAI - Artificial Intelligence applied to Byzantine Sigillography" interdisciplinary project (Projet-ANR-21-CE38-0001) is presented; it aims at proposing protocols and software solutions based on Artificial Intelligence and Machine Learning techniques, mathematical modelling and knowledge engineering, in order to facilitate the interpretation of Byzantine seals for both beginners and experts.

Keywords: sigillography; Artificial Intelligence; spatial relationships; image and text detection and understanding; Digital Humanities; Cultural Heritage

Introduction

This article analyses the benefits and challenges of applying Artificial Intelligence methods to Byzantine sigillography and presents the first steps of an innovative approach at the intersection of these two domains. Our research combines computer vision, knowledge engineering and mathematical modelling of spatial relationships to help with the interpretation of Byzantine seals (iconography and writings).

Fig. 1. A well-preserved example: the seal of Tatianos *hypatos*.(Collection Yavuz Tatiş; Cheynet 2019, n. 5.57, p. 225.)

Since Byzantine seals (Fig. 1) are mostly made of lead, they suffer from corrosion and are often damaged. The historians' interpretation work becomes a challenge when seals have been crushed or shattered, making their inscriptions difficult or impossible to read. However, considering their intrinsic properties, such as recurring iconographic models and textual formulae, as well as similarities between different seals (e.g., belonging to the same person over their career), historians can make hypotheses on the missing parts.

In this article we present the BHAI project (Projet-ANR-21-CE38-0001) and some preliminary results considering the spatial reasoning for image understanding. The goal of the BHAI project is to (i) work on the recognition of writings on seals, (ii) analyse iconographic scenes and (iii) propose solutions based on hybrid Artificial Intelligence (AI) and Machine Learning (ML) techniques to interpret damaged areas based on spatial relations and spatial reasoning for image understanding.

The Artificial Intelligence applied to Byzantine Sigillography (BHAI) project

The BHAI project (Projet-ANR-21-CE38-0001) is an interdisciplinary Digital Humanities project that proposes an innovative approach to Artificial Intelligence applied to Byzantine sigillography. The project has four principal objectives, each of which is based on state-of-the-art artificial intelligence methods applied to Byzantine sigillography:

- ***Objective1: To create a curated, interoperable, and annotated dataset of seals***
- ***Objective2: To help domain experts in the interpretation and annotation of seals***
- ***Objective3: To estimate the inception date of Byzantine seals***
- ***Objective4: To explore hybrid AI approaches to "augment" the historical content of damaged or missing parts of seals.***

Objective1: To create a curated, interoperable, and annotated dataset of Byzantine seals

Byzantine seals enclose essential knowledge about the Byzantine administration, aristocracy, and religion. Their importance derives from both the scarcity of surviving Byzantine documents and the large number of extant seals. Although there are around 100 000 seals scattered worldwide, there is no unified knowledge database regarding Byzantine sigillography. The first objective is to create a curated, interoperable, and annotated dataset of images of Byzantine seals from referenced sources. We work on published seals. This project already has support from the French National Library (BNF). The datasets are manually curated and annotated to build ground-truth datasets by Byzantine experts.

Objective2: To help domain experts in the interpretation and annotation of Byzantine seals

We started by detecting objects on Byzantine seals, such as crosses, staffs, swords, sceptres, crowns, or imperial clothes. Then, we identified figures by recognizing imperial objects in the hands of emperors and empresses, as well as the specific crowns or clothing they wore.

Objective3: To estimate the inception date of Byzantine seals

Domain experts determine the inception date of seals by comparing the new seals with those for which the creation date is already known, and by experience. Dating Byzantine seals is a complex task that only experts with considerable background experience can accomplish. Our goal is to use computers to create a chronological ranking of seals according to the date difference between seals, with the help of already dated seals and sigillographers' estimations for published seals. This action may subsequently be complemented by all or part of the associated annotations. Grouping seals in temporal series may help the experts to refine the proposed dating. In return, this feedback could improve our algorithms.

The study of the similarities and differences among the resulting clusters of seals may improve the hypotheses formulated by historians, not only concerning the Byzantine prosopography, but also about the changes in the administration or the administrative geography or the iconographic motifs retained. Therefore, allowing progress in history. Nowadays, there is no tool to initiate students into this dating process and this database could also help students in dating seals.

Objective4: To explore hybrid AI approaches to "augment" the historical content of damaged or missing parts of seals.

Seals were used to authenticate letters and documents. Most Byzantine seals were made of lead, which is prone to corrosion, especially when in contact with air but also with wood. Many seals currently preserved are damaged or partially corroded. When seals have been kept in wooden boxes or shelves for many years, their corrosion speeds up. Even seals more recently discovered can be damaged by the passing of time. Therefore, a question arises: Would it be possible to imagine the missing parts from a partially broken or corroded seal?

The objective is to propose a hybrid approach combining the strengths of Computer Vision algorithms (object and character recognition) and mathematical modelling of spatial relations to allow for interpretations of iconographical scenes and presumptions on the missing. Feeding the computer with indices of proper names (personal and geographical) and dignities, it could make suggestions of possible characters for the damaged or missing parts of the seal. It is important to notice that the objective is not to propose a tool to "invent" missing parts of seals, but instead, to use existing data analysed from multiple channels (graphical, spatial, and semantic relations within and between seals) to generate insight and make suggestions about what "could" be in the missing parts.

State of the art

Byzantine seals are studied from a cultural heritage perspective based on state-of-the-art research in artificial intelligence. This section details state-of-the-art approaches for spatial reasoning for image understanding, character and handwritten text recognition on historical documents, and domain adaptation and knowledge graph embeddings.

Spatial reasoning for image understanding

Knowledge about space, particularly spatial relations, is vital for image understanding.[1] Indeed, human beings intensively use spatial relations for describing, detecting, and recognizing objects. Ambiguities between objects of similar shape or appearance can be solved based on their spatial arrangement since spatial relations are often more stable than other objects' characteristics. For example, a rectangular-shaped object at the bottom of a seal is more likely to be a surmount than a crown (most likely found at the top around a character's head).

Spatial reasoning has raised much attention in computer vision and pattern recognition, artificial intelligence, cognitive sciences, mobile robotics, and geographical information systems.[2]

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[1] Bloch 2005.

[2] See e.g., Aiello et al. 2007 for an overview of different approaches.

According to the semantic hierarchy proposed by Kuipers,[3] spatial relations can be grouped into topological and metrical relations. Among the metrical relations, directional and distance relations can be distinguished, as well as more complex relations such as "between" or "along".

In the domain of qualitative spatial reasoning, most representation models are symbolic, often relying on logical formalisms, and mainly deal with topological or cardinal (directional) relations. For instance, region connection calculus was used to identify objects based on their mere topological relations.[4]

Several works aim at learning meaningful spatial relations from images. New approaches emerged to provide descriptions as whole sentences, i.e., automatic image captioning. This refers to the typical "show and tell" approaches that benefit from recent advances in machine learning (convolutional networks and deep learning), or use mostly clustering and probabilistic approaches.[5] Such approaches are also used to model queries in image retrieval.[6] Fuzzy approaches have been developed as well.[7] Such descriptions can also be seen as means to explain the result of the object or image recognition.[8]

To the best of our knowledge, none of these approaches have been used to analyse Byzantine seals, nor in the more general domain of digital humanities. The majority of seals have two sides carrying information. One side generally carries text, and the other carries text or an image with ornaments around it (such as a border of dots). The spatial organisation of these objects and their arrangement in relation to each other could guide identification algorithms.

Character and handwritten text recognition in epigraphy and historical documents[9]

Recognizing the inscriptions on the seals is essential. However, in contrast to modern documents, ancient documents need heavy pre-processing. Reading becomes difficult due to the missing or broken parts or to the presence of defects. When dealing with stone monument images,[10] characters are engraved. The lighting creates shadows that make character recognition difficult. When dealing with seal images, characters are embossed. Localising and recognizing characters is a challenge due to the low contrast between background and characters, and uneven illumination.

Among existing projects, Kuronet has been developed for reading images of ancient Japanese texts written on wooden tablets.[11] Accessing the content of their digitised documents is also essential for digital palaeography projects (Greek,[12] Hebrew,[13] Latin[14]). The project BESSARION,[15] pursued by a team of researchers of the University of Ioannina (Greece), is an

[3] Kuipers 1978.
[4] Landini et al. 2019; LeBer et al. 2002.
[5] LeCun et al. 2015; Vinyals et al. 2015.
[6] See e.g., the reviews by Goodrum 2000; Smeulders et al. 2000.
[7] E.g., Castillo-Ortega et al. 2010.
[8] Pierrard et al. 2021.
[9] For a general survey, see Nabu, Soumya 2019.
[10] Morita et al. 2021.
[11] Clanuwat et al. 2019.
[12] Cilia et al. 2021.
[13] Dhali et al. 2017.
[14] Kestemont et al. 2017.
[15] https://bessarion.gr/ (last accessed 25/07/2022).

attempt at character recognition on Greek donor inscriptions. This project started in 2020 and is funded by the EU through the Hellenic Foundation for Research and Innovation.

Deep learning approaches are currently widely used for a large scope of computer vision tasks, such as character recognition tasks, i.e., recognizing words or character strings from document images. Results are impressive and rely on large training databases. Architectures based on Recurrent Neural networks are the more popular ones since they consider the sequential aspect of writing.[16]

Domain adaptation and Knowledge graph embeddings

Transfer Learning[17] is the field of artificial intelligence that focuses on improving a model's performance on a challenging target domain by leveraging data from a well-known source domain. In particular, Domain Adaptation is a sub-field of Transfer Learning that aims to minimise the domain gap between the source and target domains, reducing the required data to train a neural network. This idea has become a common practice in cases where retraining a neural network from scratch would be considered too computationally heavy. Instead, the use of a pre-trained model based on a large data set is preferred, with only the last layers being retrained. This strategy improves the models' performance drastically.

Knowledge Graphs played a significant role in preserving cultural heritage and modelling human expert knowledge. In the last ten years, hundreds of semantic data models, vocabularies, and knowledge graphs have been developed for digital humanities, such as MusicKG,[18] Sampo,[19] NOnt,[20] or CLARIAH.[21] Knowledge graphs provide rich semantic context about the images' content that is useful to extract class-informative embeddings. The idea is to add information gathered in knowledge graphs when training neural networks with sparse and heterogeneous image datasets, which is the case of cultural heritage data.

Knowledge graph embedding methods aim at mapping a component of a knowledge graph (KG), including nodes, entities, and relationships between them, into a continuous vector space using algorithms such as Node2Vec. Machine learning models, mainly neural networks, can use the resulting vectors since this structure is simpler than a graph structure while preserving the inherent information and structure of the graph.[22] These techniques have gained popularity due to their wide utility for downstream applications such as KG completion and relation extraction, Recommender Systems, Question Answering, and Relation Extraction from texts.

Knowledge graph embeddings[23] are considered low-dimensional representations of the nodes and relations in a knowledge graph. Knowledge graph embeddings are mappings on different parts of the knowledge graph into a vector space that satisfies specific properties and maintains the information that exists in the graph. Each method defines a score function that measures the distance of two nodes relative to their relation in the mapped embedding space.

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16 Chammas 2018; Morillot 2013.
17 Pan, Yang 2010; Bekkouch et al. 2021.
18 Eyharabide et al. 2019.
19 Hyvonen 2020.
20 Meghini 2021.
21 Meroño-Peñuela, De Boer 2020.
22 Wang et al. 2017.
23 Ristoski et al. 2016; Cochez et al. 2017.

The goal of these score functions can be summarised as keeping the nodes connected in the graph close in the mapped dimension and those that are not connected far from each other. The most famous score functions are TransE, TransR, RESCAL, DistMult, ComplEx, and RotatE.[24]

All the approaches and techniques detailed above are included at various steps of the research; in this paper, we will expose the preliminary results of the application of spatial reasoning methods to the analysis of images of Byzantine seals.

Spatial relations reasoning for interpreting Byzantine seals

The project started in 2021 and we have been working on image recognition, on character recognition and on spatial relations modelling. We can present here some preliminary results for interpreting Byzantine seals using spatial relations modelling. In particular, we show some examples of spatial relationships between objects in images taken from the photographic archive of Jean-Claude Cheynet who has edited many catalogues of Byzantine seals[25].

Before calculating the spatial relations between objects, the first step is to identify the objects depicted on the seals and then manually annotate those objects in the seals' images. After consulting Byzantine sigillographers, we decided to annotate: a) the personages (such as Christ, Virgin Mary, Archangel Michel, etc.), b) the objects in the personages' hands (such as globe, sword, book), c) the body's parts (head, hands, wings), d) the crosses (including tendrils, steps, and ornaments), and e) the clothes, nimbus, and crowns.

The second step is to mark the objects in the images of seals by defining their borders. Therefore, our experts manually annotated the image dataset using Supervisely[26], a collaborative online tool for image annotation to create bounding boxes. Later, the experts associate a label (Theotokos, Patriarchal_Cross, Monogram, Sword, Suppedion, etc.) to each object mask. Figure 2 shows an example of manual annotation of a monogram in the Seyrig collection.

Fig. 2: An example of manual annotation of a monogram, Seyrig collection (Cheynet, Morrisson, Seibt 1991, cat. n° 19, inv. 355).

[24] Wang et al. 2017.

[25] Cheynet, Morrisson, Seibt 1991 ; Campagnolo-Pothitou, Cheynet 2016. List of publications at http://www.cfeb.org/curiculum/mb_cheynet.pdf

[26] https://supervise.ly/

We wish to explain the proposed approach through an example. A few objects have been annotated (overlayed in colour) in Figure 3. The figure on the right illustrates the spatial relation "the nostril is to the right of the cross". To calculate this relation, the cross was taken as a reference object R, and for each point x of the image, the degree *d*(x, R)[27] (in [0.1]) to which the relation "to the right of R" is satisfied at point x was computed (the higher the degree, the brighter the intensity in the representation). This figure shows that the nostril fits well in the right region, i.e., for each point y of the nostril, the satisfaction degree *d*(y, R) is high. A global assessment of the relation can then be derived using an aggregation function applied to the values d(y, R) for all points y of the fleuron. For instance, in this example, the relation's average degree of satisfaction equals 0.89. Applying this procedure to all the objects detected in the seal and several relations, a description of the spatial arrangements can be provided to interpret the seal.

Fig. 3. Example of spatial relationships reasoning for seals understanding. (Cheynet 2019, cat. n. 6.26, inv. n° Tatiş 2706)

Left relation: the labarum is on the emperor's left

In Figure 4, we present the reverse of one seal from the seals' collection at the Musée d'art et d'histoire in Geneva (gift of J. Zacos)[28]. First, we detect an emperor (person with a crown) in the middle. Then, we compare each object present on the seal (labarum, crown, hands, etc.) to the head of that personage. In the example, we present the results when comparing the labarum and the emperor's head for the four basic relations: left (Fig. 4.c), right (Fig. 4.d), top (Fig. 4.e), and bottom (Fig. 4.b). The emperor's head being the object of reference, we want to know if the labarum is to its right, left, above, or below. Consider Figure 4.c and imagine that we place a lamp on the emperor's head that projects light to the left. Does that light illuminate the labarum? It does, the labarum is almost entirely visible and the degree to which the relation is satisfied is 0.97.

Now consider Fig. 4.d, imagine the same lamp but projecting its light to the right. Is there an intersection between the light and the labarum? No, the Fig. 4.d is all black and its degree is zero. We continue in the same way to calculate the values for the relations top and bottom. As shown in the figure, the left relation is the one that obtains the highest value, which is 0.97.

[27] Bloch 1999.

[28] Campagnolo-Pothitou, Cheynet 2016, cat. n. 8, inv. n. CdN 2004-537, https://collections.geneve.ch/mah/oeuvre/bulle-dor-de-5-solidi/cdn-2004-0537 (last accessed 27/07/2022).

Therefore, we can conclude that the labarum is on the emperor's left. Since the labarum is an object, we can imagine that the emperor is holding this object with his right hand. This result can be confirmed visually when regarding the image and also when reading the description made by the experts: *"Reverse: the emperor, portrayed half-length, facing front, wearing a short beard, crowned with the crucifer stemma featuring pendants with trifold termination... In the right hand, he holds the labarum, and in the left hand the akakia against his chest."*

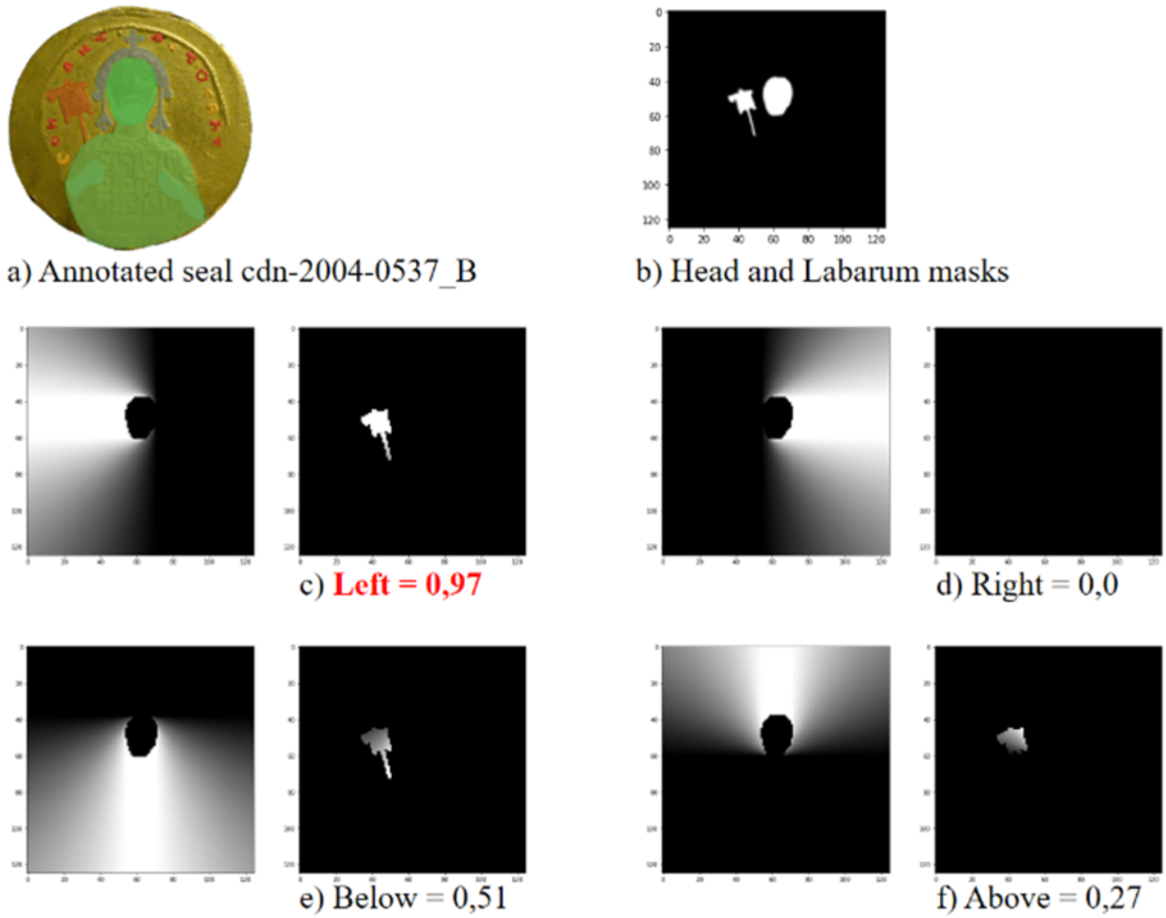

Fig. 4. Relations' calculation example: being the emperor's head the object of reference, is the labarum to its right, to its left, above or below?

Right relation: The Christ Child is on the Theotokos' right

Figure 5 presents the obverse of another seal "cdn-2004-0274" also part of the seals collection of the Musée d'art et d'histoire in Geneva (gift of J. Zacos)[29]. In this seal, two figures have been annotated: the Christ Child and the Theotokos. The latter occupies the biggest area. Therefore, we calculated the four relations between the two figures heads. We can conclude that the Child is on his mother's right; thus, the Theotokos is holding the Child with her left arm. The description of this seal details: "*Obverse: in a circle of dots, the Virgin Hodigitria, standing on a souppedion, turned three-quarters towards the Child, whom she carries on her left arm…*"

[29]Campagnolo-Pothitou, Cheynet 2016, cat. n. 240A, CdN 2004-274, https://collections.geneve.ch/mah/oeuvre/sceau-patriarcal/cdn-2004-0274 (last accessed 27/07/2022).

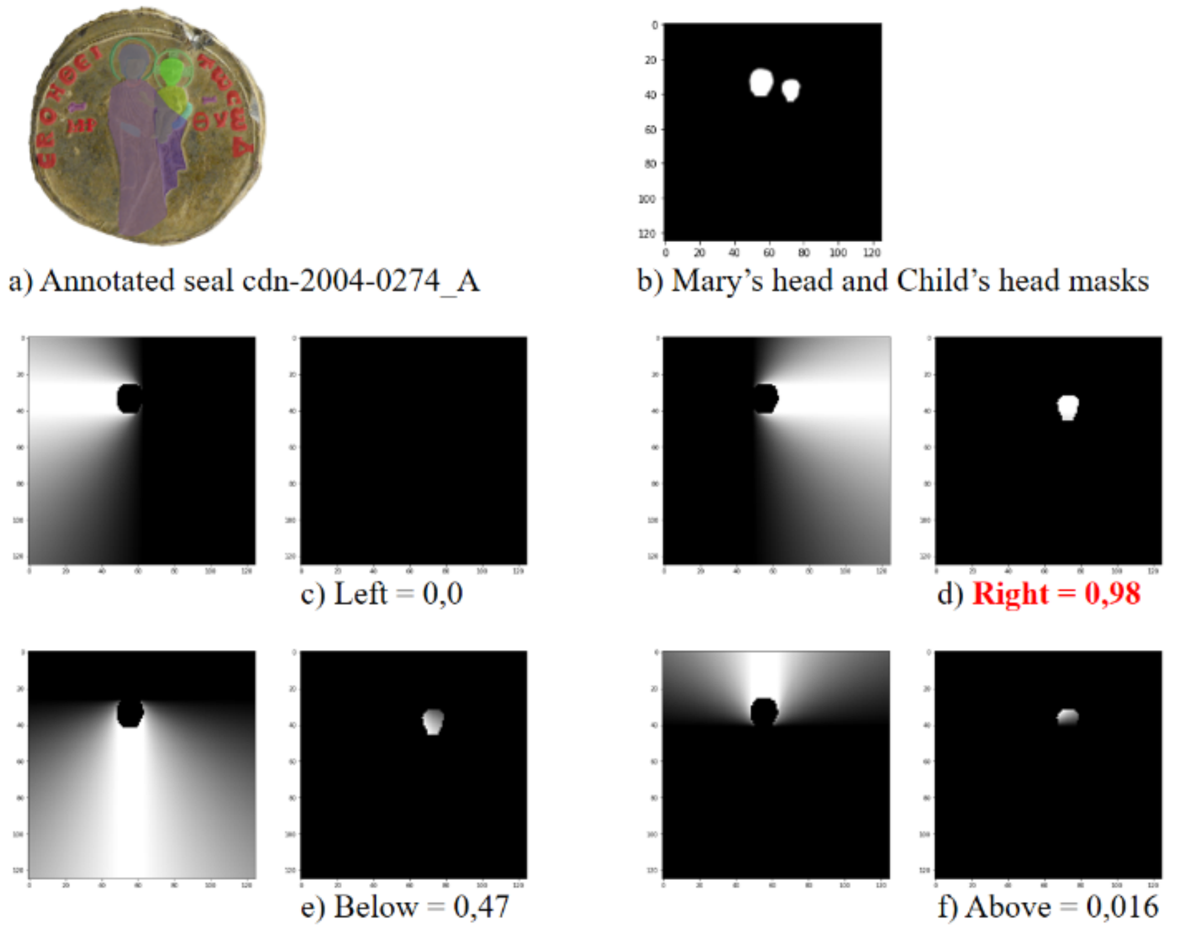

Fig. 5 Example of spatial relation calculation between the Christ Child and his mother. We obtain mathematical evidence that the Theotokos is carrying the Christ Child on her left arm.

Right-bottom relation: The Christ and the Bible

Sometimes, several relations can be found between two objects. That is the case in Figure 6, depicting the obverse of the seal "cdn-2004-0539" in the seals collection of the Musée d'art et d'histoire in Geneva[30]. When calculating the relations between the Bible and Christ, the "bottom" relation is the one that obtains the highest value with 0.96. However, the value for "right" relation is also high, with 0.82. Therefore, we can conclude that the Bible is in the right-bottom part of the seal. The description of this seal details: "*Obverse: In a circle of dots, bust of Christ, face, beardless (?), ..., he blesses with his right hand, and holds the Gospels in his left hand.*"

[30] https://collections.geneve.ch/mah/oeuvre/bulle-dor-de-2-solidi/cdn-2004-0539

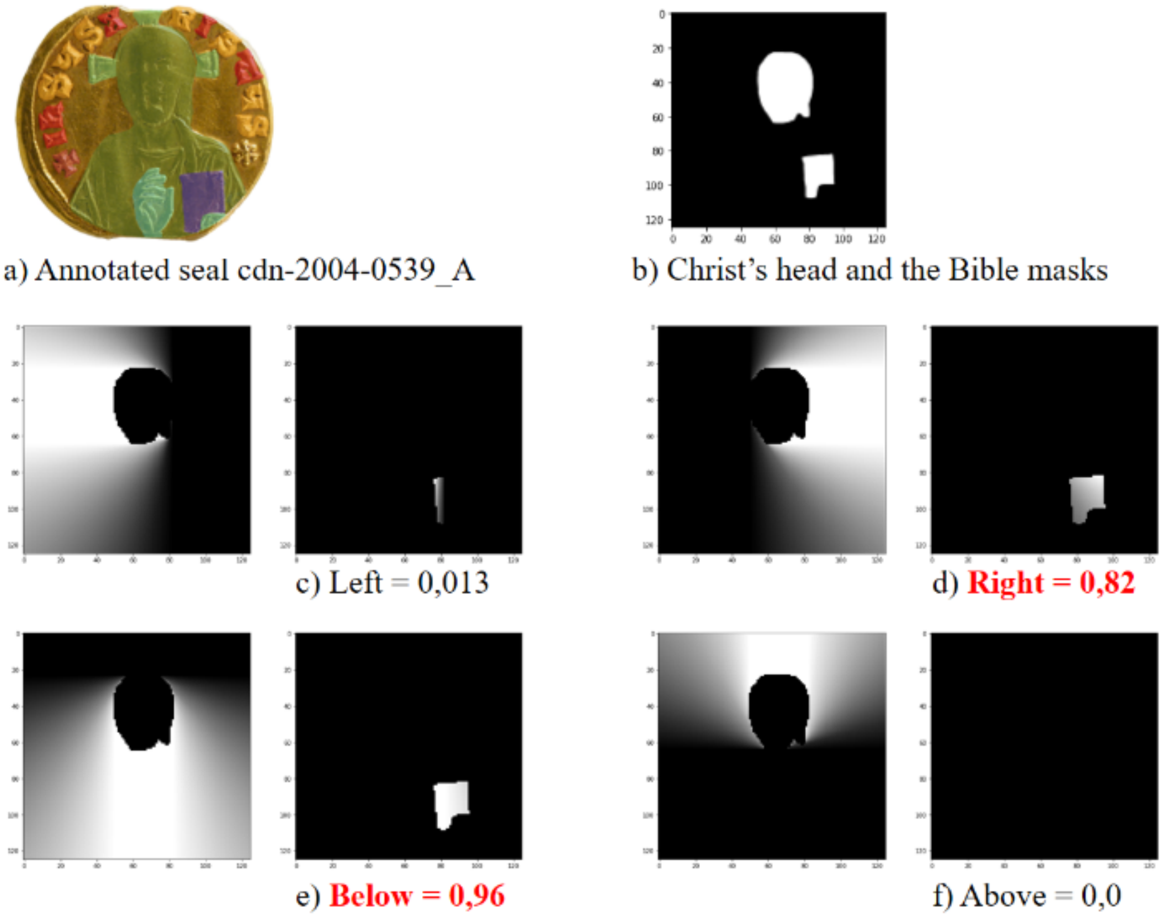

Fig. 6 Example of a seal in which the Bible is placed on Christ's right-bottom

Conclusions and future research

The results of the spatial relation reasoning techniques are highly promising, also on less readable samples, and are a solid base in order to develop more refined recognition instruments, capable of detecting more complex ensembles of objects on the seals.

We plan to develop a useful image recognition and character recognition tool on Byzantine seals. The choice of seals to implement artificial intelligence programs is possible because we have a large series of these objects, making it possible to train neural networks. Later, the method could be adapted to any object inscribed with Greek letters, starting with coins and other objects such as lapidary or painted inscriptions.

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Illustration Captions

Fig. 1. A well-preserved example: the seal of Tatianos *hypatos* (Cheynet 2019, N. 5.57, p. 225).

Fig. 2: An example of manual annotation of a monogram, Seyrig collection (Cheynet, Morrisson, Seibt 1991, cat. n° 19, inv. 355).

Fig. 3. Example of spatial relationships reasoning for seals understanding (Cheynet 2019, cat. n. 6.26, inv. n° Tatiş 2706).

Fig. 4. Relations’ calculation example: being the emperor’s head the object of reference, is the labarum to its right, to its left, above or below?

Fig. 5 Example of spatial relation calculation between the Christ Child and his mother. We obtain mathematical evidence that the Theotokos is carrying the Christ Child on her left arm.

Fig. 6 Example of a seal in which the Bible is placed on Christ’s right-bottom.

Illustrations

Fig. 1

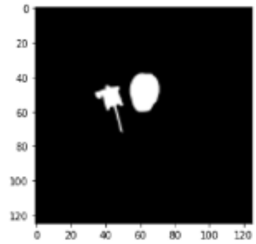
Fig. 2


Seyrig 019_A.jpg
Collections › Seyrig
07_century_4/4
08_century_1/4
TypeOfPrayer: Vir...

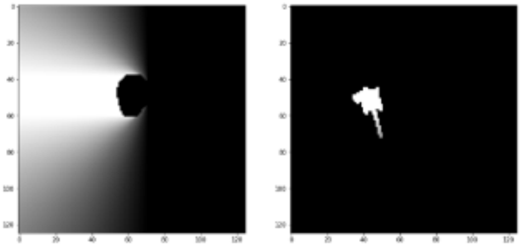
Fig. 3

Fig. 4

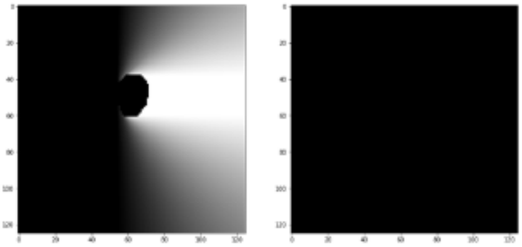
a) Annotated seal cdn-2004-0537_B



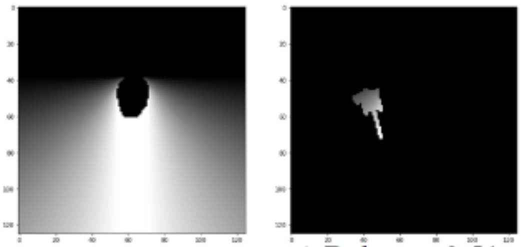
b) Head and Labarum masks



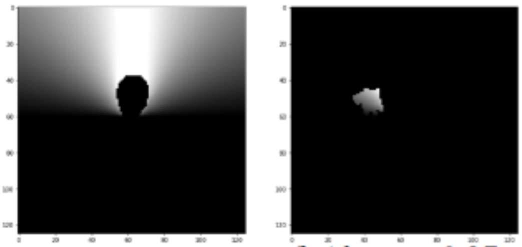
c) Left = 0,97



d) Right = 0,0



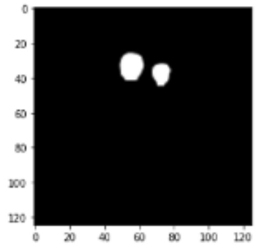
e) Below = 0,51



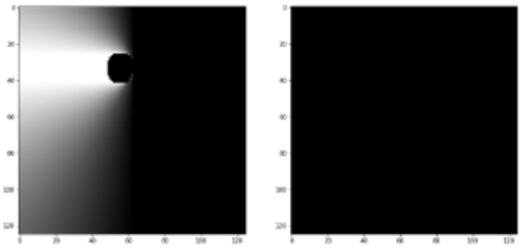
f) Above = 0,27

Fig. 5

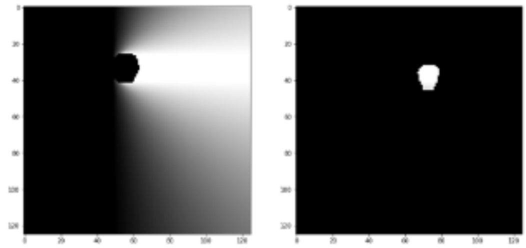
a) Annotated seal cdn-2004-0274_A



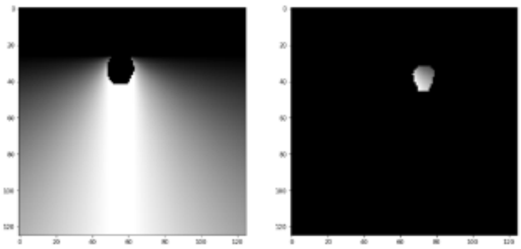
b) Mary's head and Child's head masks



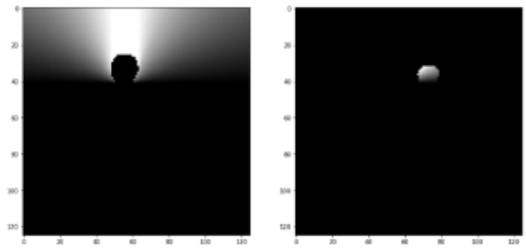
c) Left = 0,0



d) **Right = 0,98**



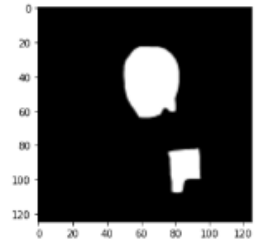
e) Below = 0,47



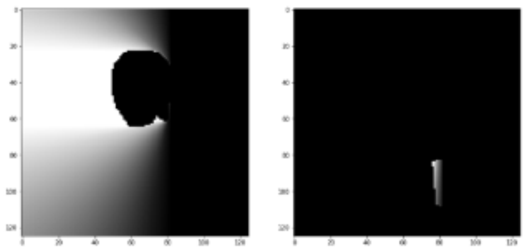
f) Above = 0,016

Fig. 6

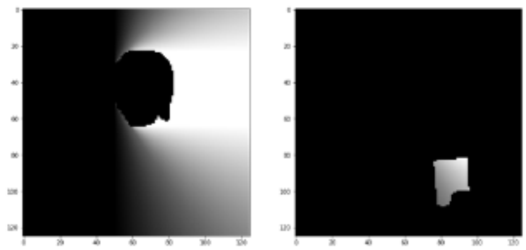
a) Annotated seal cdn-2004-0539_A



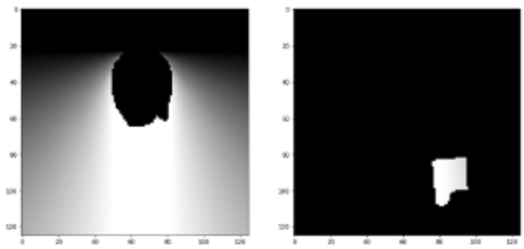
b) Christ's head and the Bible masks



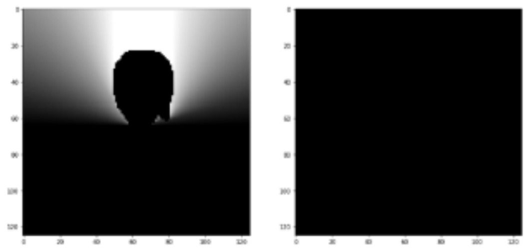
c) Left = 0,013



d) **Right = 0,82**



e) **Below = 0,96**



f) Above = 0,0