UniqueMark - A method to create and authenticate a unique mark in precious metal artefacts

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ABSTRACT

The project UniqueMark aims at creating a system to provide a precious metal artefact with a unique, unclonable and irreproducible mark, and at building a system for the validation of authenticity of it. The project defined two different modes for these marks. Firstly, the unique mark can be created by punching a dispersion of diamond particles on the artefact surface which is, in practice, irreproducible since the disposition of the particles results from a random chaotic process. Secondly, an alternative process for creating an irreproducible mark can be achieved by marking the artefact with a laser in a deterministic path described by a proper mathematical function whose effects on the metal are so that the accurate reproduction will be easily distinguished from the original one, thus creating a unique laser mark. The UniqueMark system also includes a system to verify the mark authenticity using a microscope, or a smartphone camera with attached macro lens. This validation check is based on a minutiae descriptor which is stored for each mark. UniqueMark (2 patents pending) might then be used by assay offices, producers, customer, and authorities to protect items from counterfeit as well as to trace objects over their life time.

KEYWORDS

hallmarking; unique marks; unclonable marks; irreproducible marks; punching with diamond particles; validate a mark; authenticate a mark

1. Introduction

Jewels, particularly those made from precious metals, and many times enriched by gems, are high-valued objects that for long have been exhibited by humans

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as a demonstration of power. Long ago sovereignty has identified the necessity to secure the value of precious metal artefacts in general, particularly of jewels. This necessity arose centuries ago due to a tremendous pressure on the veracity validation of these objects. In Portugal, the Assay Office, which is part of the Portuguese Mint and Official Printing Office, started its hallmarking activity about 125 years ago, being one the oldest all over the world. Typically, the hallmarking depends on the specific rules determined by the Law of each country, that specifies which objects and which precious metals should be marked, and with which hallmark design. The two most important physical processes are the punching, more traditional, and the laser marking, more recent. In Portugal, for instance, each object, before arriving at the front shop, must be added two hallmarks: the official mark, which states the metal (one of these: gold, silver, platinum, or palladium), and the manufacturers mark, that identifies where the object was produced.

Despite all the efforts to secure precious objects, the counterfeiting has been such a quite serious problem nowadays, and poses significant challenges to assay offices, producers and retailers in the global market. Organised crime groups play an increasingly important role in these activities and benefit significantly from counterfeiting and piracy. The trade in fake goods is booming and hitting the sales and profits of the affected organisations. It impacts governments, business in general, and consumers by cutting revenues and reducing economic well-being, health, safety and security. Worldwide the crime allegedly represents 2,5% of the world trade, USD 461 billion, and 5% of the EU imports Europol (2018).

Particularly, for the jewellery market, illegal activities of counterfeiting burke parallel markets of illegal precious metals, or even introduce objects made of metals with lower levels of purity than those that are announced. Consequently, traditional centennial hallmarks are no longer the solution for this problem since forgers are more and more technologically sophisticated, as well as able to produce fake markings with very high quality. The ideal solution is to provide the object itself with a unique unclonable identifier.

In this paper we present the UniqueMark that consists of a system to provide an object with a unique unclonable mark that may be applied not only to precious metal artefacts, but a variety of products in order to secure their authenticity. This UniqueMark validation system was developed by the Portuguese Assay Office in the scope of an R&D project with the University of Coimbra.

The produced marks are not only unique, since they are resultant of a random chaotic process, but unclonable, so as to it is virtually impossible to reproduce them. These two characteristics are critical to improve the security of the marks, once they together guarantee that there are no two identical marks.

The markings applied to jewels can use one of the two most important technologies, punching or laser. The former punches a random dispersion of diamond particles to guarantee the incrustation of these particles on the metal. As the diamond particles generate a random pattern, resultant from a chaotic process, and the punching will disseminate them in an unpredictable way, this physical process is impracticable to reproduce. The later one uses laser markings. In this case, the design of the laser beam path is deterministic, not random. However, the path itself is designed by a mathematical function so that the resultant pattern is unique. These marks are still impracticable to reproduce since the response of the metal during the laser marking, when the metal is in melt phase, are unpredictable and are determined by several uncontrollable and non-observable variables.

Thus, by either punching a random dispersion of diamond particles on the metal surface or by marking a precious metal artefact with a laser beam through a deterministic path in the melt phase of the metal, the UniqueMark system is able to provide an object with a unique mark.

For the validation of the uniqueness of these marks, their images are employed to validate it. Depending on the security level, the system contains a database to store a photo of the mark, and a minutiae vector produced by a known, yet private, algorithm, or both the photo and the minutiae. This validation must be quick and reliable enough so that the system can have real applicability to databases of millions of objects. The UniqueMark system can validate the marks produced by using a digital off-the-shelf microscope, or even using a smartphone with a simple commercial macro lens.

This validation process, simple and accessible not only to producers or in laboratory at forensic exams, but also to retailers and customers, is a major advantage of such a system. By using their smartphone, the customer is able to previously check the product and be more confident about the quality and authenticity of the object. Furthermore, the retailers themselves might provide simple digital microscopes to their customers and clients at their shops and boutiques.

At the logical level, the system validates the marks by processing the image of the mark itself. We developed an algorithm to detect, rectify and reconstruct the dispersion of particles or the salient characteristics of the laser marking using deep learning algorithms and computer vision methodologies. In general, the algorithms used to perform the matching pattern are designed to perform verification (1-to-1) as well as identification (1-to-many).

The rest of this paper is organised as follows: section 2 we present the literature review and the related work. Section 3 presents the marking process in both punching and laser marking. In section 4 we discuss the results and the options of the UniqueMark system and finally in section 5 we briefly conclude this work.

2. Literature review

It is difficult to find research works in the literature that are related to this new way of providing an object with a unique and unclonable mark.

A field of computer science that much resembles the problem we are dealing with is the field of human identification through biometrics, namely through the iris analysis field, fingerprint, or face recognition. Additionally, there is another related field which is the case of authentication of products, where the pattern to be identified and validated is often not intrinsic to object, as the fingerprint or iris pattern are from human beings. Usually, in those cases, there is a non-internal, possibly industrial process, that adds this unique and unclonable mark to the object (*1*).

Once biometric information is usually collected as images, the use of matching techniques such as correlation measures, would be an ordinary choice (*2*). However, the application of such techniques is quite limited due to the need to compare every entries in the database with the query patterns. The same can be said for feature point matching algorithms, like SIFT (*3*) and SURF (*4*). Despite the fact that these algorithms usually perform well in matching tasks like verification, its application on identification tasks is impractical with large databases. Moreover, not all feature point matching algorithms are invariant to scale, rotation and non-linear deformations. Both Ru Zhou (*5*) and Badrinath (*6*) applied such algorithms to fingerprint and Finger-knuckle-print matching, respectively, with good results. Yet, the number of unique identities in the databases of both works was of a few hundreds. The resilience to scale, rotation, translation, and non-linear deformation, cloud be achieved with the application of cloud point matching algorithms, like ICP (*7*) and CPD (*8*). These algorithms attempt to iteratively align two sets of points in space. Once aligned, a measure of similarity could be calculated and used to reason about the identity of a pattern. Nevertheless, such algorithms can not avoid the need to evaluate a large part of the database, and are highly dependent on the initial conditions. To avoid the analysis of a major part of a database, several approaches were taken where the identification task was handled as a multiclass classification problem. In those, each pattern (identity) is treated as a class. Yi Sun et al. (*9*, *10*), used a convolutional neural network to identify approximately 10.000 individuals through face recognition , with promising results. A naive pattern identification system would just compare the given pattern with all entries in the database. However, modern database contain a large number of patterns, consequently it needs a long time response which may not be desirable (*11*). In order to speed up the search on databases with large amounts of data, alternative methodologies have been proposed to the classic brute-force. For example, the implementation of parallel architectures is one of the tools used to improve the throughput of such systems.

High-performance computing has been a demanding key tool in modern science, which allows to solve problems that were unsolvable few years ago. Real-time data processing and concretely image processing have been taking advantage of more capable hardware and powerful computing architectures, especially those focused on parallel computing (*12*).

By using computational structures capable to process the information present on databases in parallel, it is possible to speed up the matching time of a query. However, such systems are usually affected by the law of diminishing returns (*13*), and they are not a genuine alternative to brute force matching for patterns identification. Such technique was tested by Peralta et al. (*12*), who achieved good performances and speeds up the matching process up to 127 times by parallelising the database search. More often than in the biometrics field, and specifically in human identification, the algorithms are based on the detection and characterisation of minutiae (*2*). Real alternatives to avoid brute force search are the space partitioning, and indexing methodologies.

Space partitioning approaches aim to reduce the number of candidate patterns. Doing so, it allows to reduce the number of one-to-one comparisons, and consequently the amount of time a query takes to be resolved. The partitioning of the search space can be performed by clustering algorithms, exclusive or not, like k-means, c-means, fuzzy clustering, etc. Each query is first evaluated and assigned to a cluster and only then the matching task is performed. Alternatively, to the creation of clusters algorithms like Locality-sensitive hashing and Kd-trees can partition the search space. By using such indexation techniques, Vandana Dixit K et. al. (*11*) were able to reduce the original space search to 15%, thus reducing the database searching time. Additionally, pure indexing approaches are also found in the current literature, mainly when the pattern description is based on minutiae detection. These proposals usually create indexes of characteristics, mapping a local descriptor to an entity (individuals/pattern). Such characteristics are often based on distances or angle metrics of pairs or triplet of minutiae (*2*). When a query is performed in the retrieving stage, the number of correspondences between the indices of the query and the stored patterns is computed, resulting in a list of candidate patterns (*14*). This approach was applied to the work of Khodadoust (*15*), Muoz-Briseo (*14*), and among others.

In 1996, D. Brzakovic and N. Vujovic (*16*), published a work where they used an identification system based on random patterns authentication to verify the authenticity of paper documents. It was deposited short fibres on the paper surface during the fabrication process. The authors presented a robust system of identification of such patterns to rotation and resilience to missing parts. The implemented matching system tries to find an entry of 3 points, per each quadrant of the document, on both the query document and the database document. Once it was found those combinations of points, the match was confirmed. The process of data exploration is based on the 3-points entry search. The authors report accuracy of 100% in a 10.000 patterns database, introducing rotation, translation (of the whole document), and fibre removal.

3. The marking process

In this chapter, we thoroughly present the UniqueMark system and split its phases and options. We start by presenting the physical layer, and then the logical one.

3.1. *The UniqueMark solution overview*

The present project aims at the development of a unique hallmarking, targeting the creation of a single brand by object that allows, not only to confirm the authenticity of the marked object, but also to track the artefact along its life path. For this reason, there are three main technical-scientific objectives, as follows:

- Creation of a single pattern based on the incorporation of particles into the surface layer of an ordinary metal object, or a precious metal artefact in particular, to be marked using the mechanical punching, or laser punching technique.
- Develop a highly mechanical resistance solution for the unique mark of the hallmarking that will resist for a period of time as long as possible, taking into account the high life time of the marked objects, keeping its unique pattern.
- Develop an easy solution to verify the authenticity of the object by com-

paring the mark with an image of the unique pattern previously generated and recorded in the database during the marking process. Additionally, this solution should also enable automatic verification of the authenticity of the marked object through a high ubiquity optical device (for professionals), but also a mobile device, or even a smartphone (for consumers).

The registration and validation processes of the UniqueMark solution are presented in Figure 1.

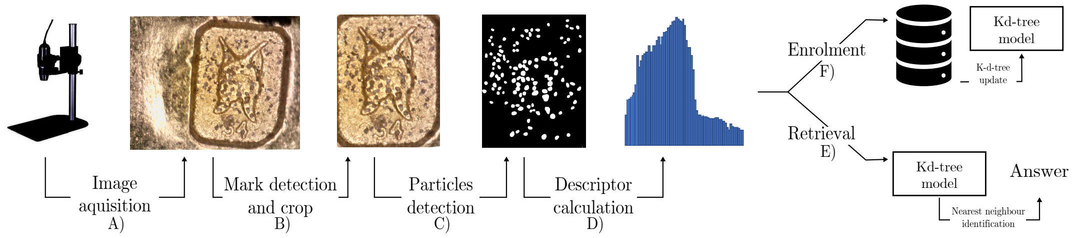


Figure 1. Registration and Validation processes for a new UniqueMark by using a punch hit upon a dispersion of diamond particles in gold. The process has the following phases: (A) image acquisition, (B) mark detection and crop, (C) detection of all diamond particles, (D) computation of the descriptor of the random dispersion, (E) for **validation** search on the database using a kd-tree model or (F) for **registration**, also called **enrolment**, to add a mark to the database.

The mark registration is made to be stored in a database that contains the unique characteristics of the hallmarking. A geometric descriptor of the pattern minutiae is created by using a mathematical algorithm.

The validation of the object is made by either a verification (1-to-1) or identification (1-to-many) process. The verification process is simpler and faster, but it is only possible if there is an ID claimed for validity. The general case, however, where the system does not have any hint on the identity of the object, is more time consuming, and the scale-up of this search motor poses serious challenges on performance and accuracy. This validation is made by acquiring a photo of the pattern and by processing its minutiae descriptor, which searches for it on the database, by either comparing a claimed identity and the stored data for that identity, or by systematically searching a query minutiae with all the stored identities (that can easily reach orders of magnitude of 10^6 till 10^8 items).

3.2. *Punching*

The process of punching a precious metal artefact is a traditional centennial procedure. In the UniqueMark, we added a previous step to it. A deposition of diamond particles is powdered before the punching, then it is applied to the area with the particles. The punching is applied with enough strength to force the particles to enter within the metal surface and create a random, permanent, pattern of dispersed particles.

As for the particles, the most adequate ones are the diamond particles. We tested several materials for the dispersion composition. Minerals were chosen instead of metal ones since one of the most important characteristics is that they need to be easily identified in a pattern image. Furthermore, mineral particles do not fuse themselves with the metal or constitute alloys. For the minerals, we tested, amongst others, diamond and alumina. The latter was not suitable for this process since it disintegrated itself while receiving the punch impact. Although it also creates a random dispersion of material, it is not suitable for the logical layer since its images are considerably more difficult to segment. Figure 2 presents some examples of dispersion created by pushing over a dispersion of alumina powder particles.

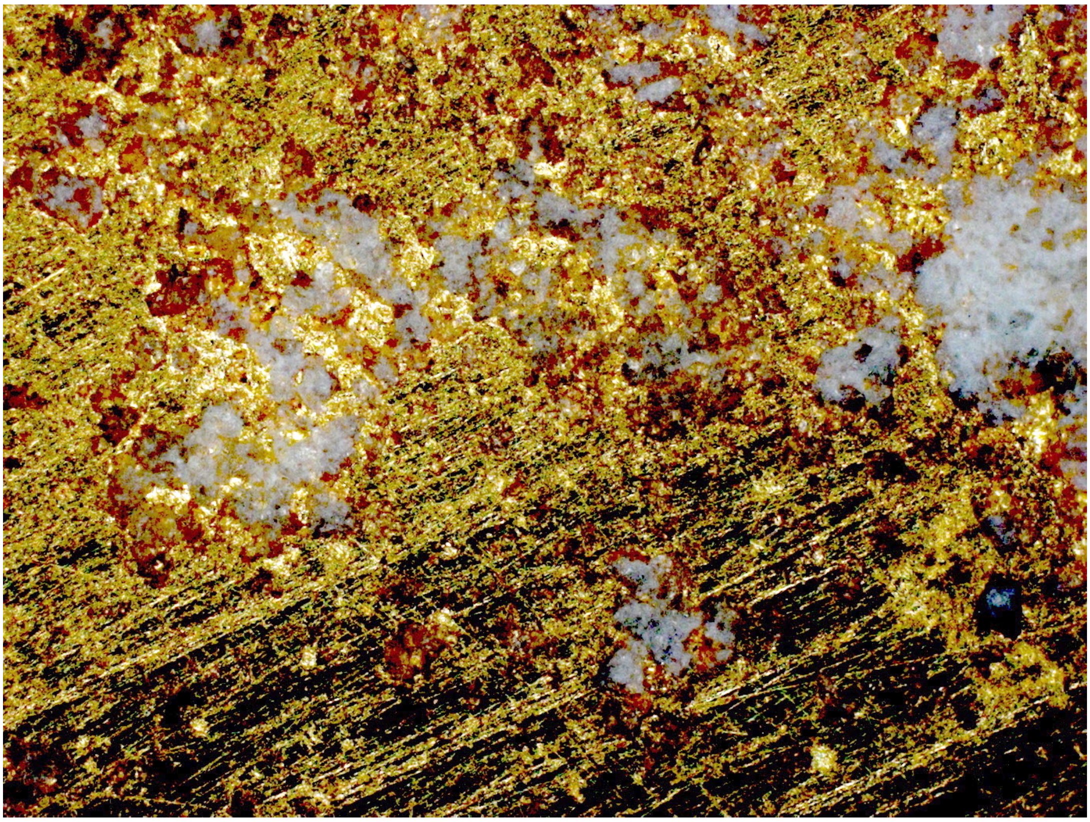


Figure 2. The effect of punching alumina particles over a metallic surface. It can be observed that the particles smash on the surface which difficult the process of identification of the mark.

Extensive experiments made with diamond particles showed that they are perfectly suitable for the punching process. Diamond powder particles have the necessary strength to accommodate the punch impact without disintegration, and they are relatively easy and cheap to obtain, making them the best mineral option to create the random dispersion on a given precious metal artefact surface.

It is noteworthy that precious metals, particularly gold, are ductile enough to receive and accommodate the particles, producing a permanent incrustation.

Figure 3 shows some examples of incrustations created by punching over a diamond powder particles dispersion.

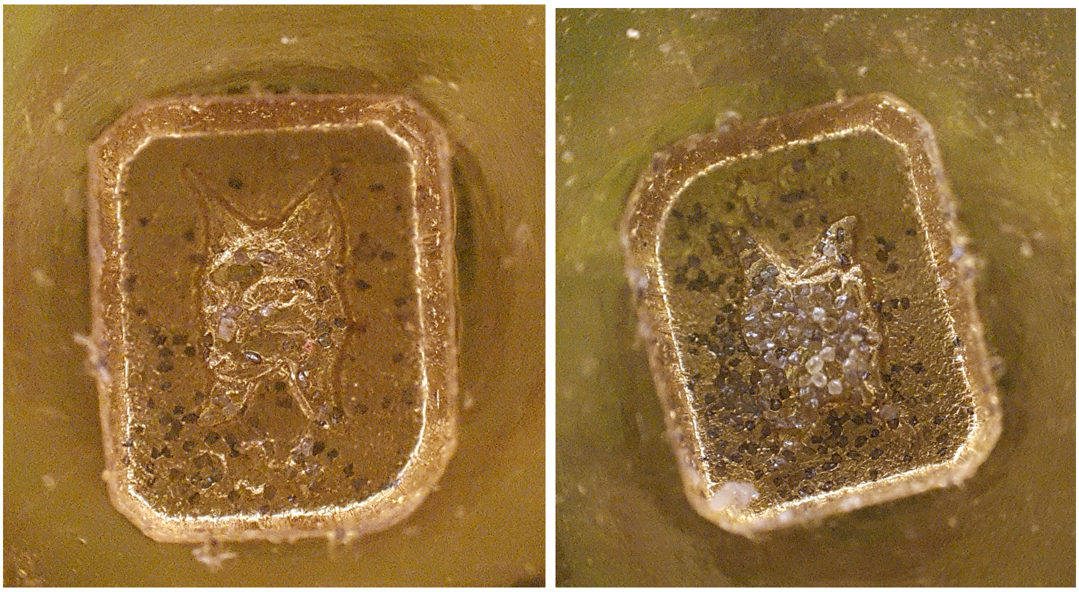


Figure 3. The effect of punching diamond powder particles over a gold object. It can be observed that the particles are very well defined in the image, and incrusted, which help considerably the detection process and the descriptor ability to discriminate between marks.

Regarding the dispersion process itself, it is important to mention that the powder particles, irrespective of the material they are, tend to agglomerate, which is undesirable since it might difficult the detection and segmentation of the particles individually. We found that it should be added a small vibration effect to the particles before the deposition. We built a dispersant tool to depose a small amount of powder particles on the metal surface before the punching. Figure 4 presents one dispersant.

As for the dimension of the hallmarking, we opted to maintain the usual dimensions for official hallmarks which is approximately $1mm^2$.

In order to define the adequate density of powder particles, one must consider the area (around $1mm^2$ in our markings) and also the desired number of particles, although only a part of the deposited particles is effectively incrusted on the material. The number of particles must also depend on a suitable density since, on the one hand, by increasing the number of particles, one has more possibilities, and the number of possible distinct patterns becomes significantly high. On the other hand, if the number of particles is excessive, the probability of having agglomerations of particles turns higher, thus reducing the straightforwardness

Figure 4. Dispersant tool (prototype version) used to deposit a certain amount of diamond particles on the metal surface. New automatic and more practical dispersant tools were designed and are being produced.

of the detection and segmentation processes. Figure 5 shows some examples of very different patterns created by a range of dispersion parameters, where it is possible to verify the easiness of the detection and segmentation processes.

Finally, it is also important to state the dimension of each powder particle. In our experiments we tried several dimensions of the diameter of the particles. Again, this parameter is also the result of an engineering trade-off decision. One the one hand, the particles should be as big as possible to simplify the detection. On the other hand, big particles will get incrustation process difficult, and even more important, raise the risk of deficient and ineffective incrustation by helping bigger particles to be released from the surface. After extensive experiments, we decided to use particles of diameter between 40 and 100 microns.

As described in this section, the punching over a small dispersion of diamond powder particles will produce a random, unique and irreproducible hallmarking on the surface of metals, which provides the artefact with a unique identity.

3.3. *Laser marking*

Lasers are today more and more reliable and cost-effective and, consequently, they have been increasing its importance in hallmarking. They are particularly important for fragile artefacts that are unable to propagate the punch impact and thus may be damaged by it. Lasers also have a very high precision on their markings.

Providing an object with a laser marking that shall be unique and irreproducible it is not simple to accomplish, and is more challenging than just use a punch over a dispersion of particles once it is not easy to guarantee the necessary randomness, so that it can be considered a chaotic process.

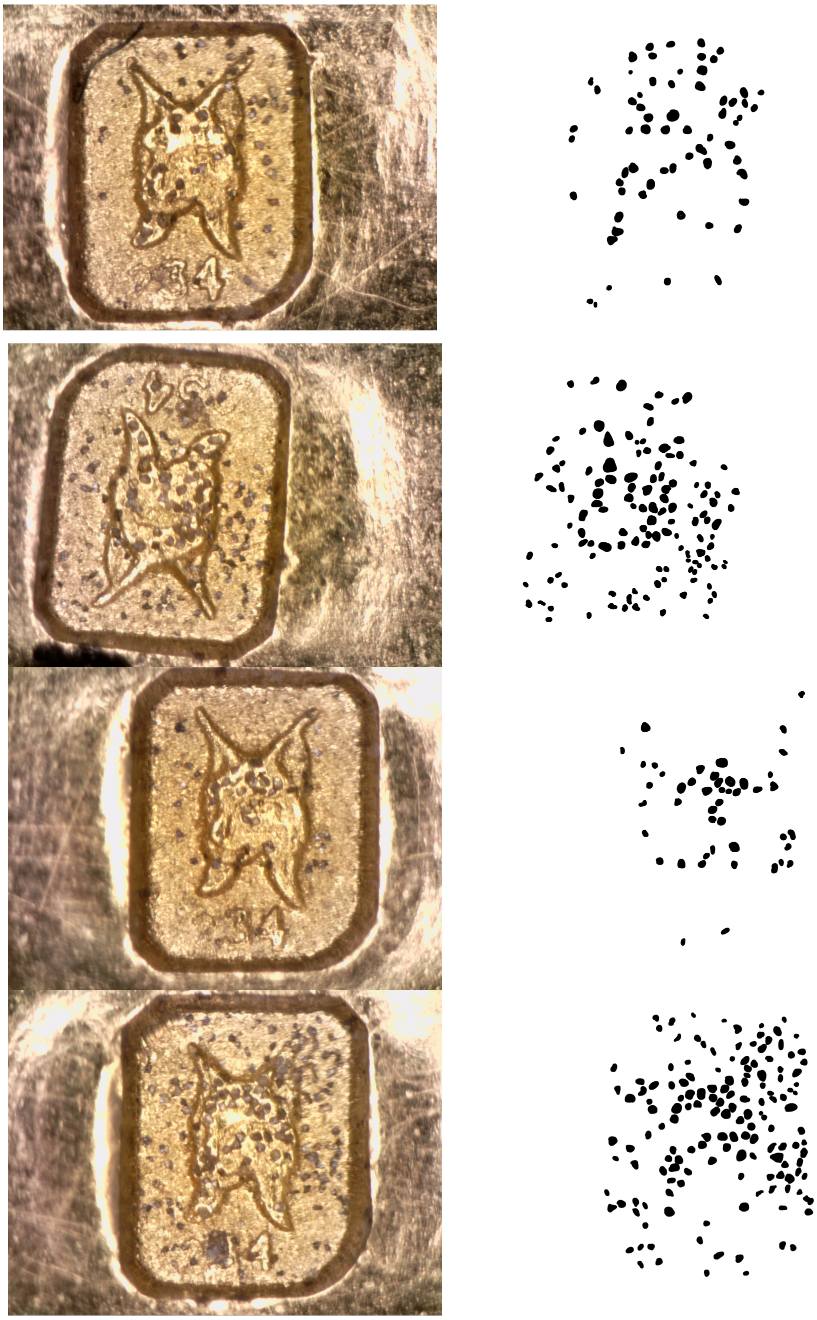


Figure 5. Different examples of unique marks over gold using dispersion of diamond particles. Left column shows the original image of the UniqueMark and right column shows the output of the particle detection algorithm.

The UniqueMark solution for laser markings is to define a specific path for the laser beam that explores the fact that the metal is melt during the passage of it, at the same time the local behaviour of the metal molecules is unpredictable for the magnitude of the effects applied to the material.

The laser path is defined by taking into account several aspects. One of the main aspects is that the laser beam, which usually makes several passages through the same path (it can be up to 100 times or so in some cases), will direct its energy in the incidence points which must belong to the focal plane. There is no concern about the perfection and definition of the designed path for the final result, but about the fact that the metal is under melt state when the marking process is occurring. A better possibility would be to locate the focus plane slightly underneath the surface plane of the metal artefact. This fine tuning of the focal plane can increase the melting production, and thus enhance the desired effects to get a unique and irreproducible laser mark.

Another aspect to be considered regarding the path of the laser beam is the fact that it must be intricate enough so that a reverse engineering process is unable to recover the path. However, it must not be excessively intricate so that after the laser beam passage there is no, or just a few, salient points in the image. Figure 6 shows three examples of distinct laser beam paths. As we can see, the leftmost path (figure 6-left) shows an example with a too small density making it more feasible to recover the path, the rightmost path (figure 6-right) shows an example with a too high density, where the identification of salient and characteristic points can be more difficult, and the centre example (figure 6-centre) shows an adequate density.

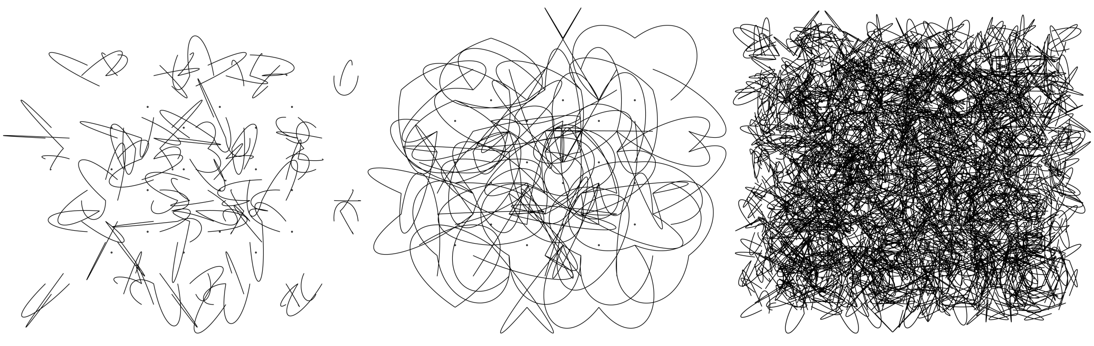
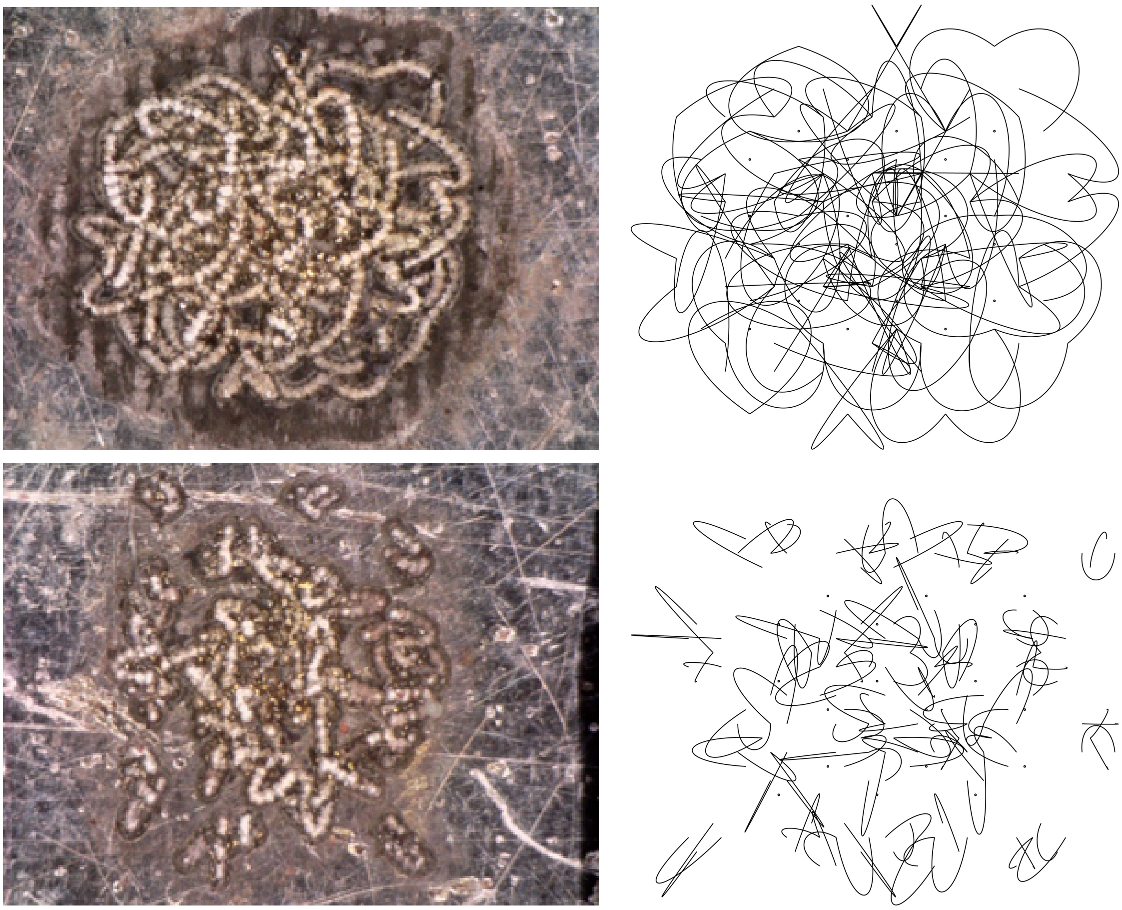


Figure 6. Three different paths used for the laser beam in the creation of UniqueMark marks using a laser. The images show different levels of density of the path.

The extremely high security level of these laser markings are a natural corollary of the following facts:

- each laser path is unique, and will create a unique pattern



a - laser mark (path) A b - laser mark (path) B

Figure 7. Example of two different laser markings (left column) using the paths shown at the right column.

- it is virtually impossible to recover (or estimate with high accuracy) the laser path by observing a hallmarking
- the reproduction of the same laser path in an arbitrary number of different objects will produce distinct and distinguishable markings for each of these objects (since for the scale of the mark itself, the local effects of melting are unpredictable, and this physical process is chaotic)

From the aforementioned, we can conclude that the laser marking in this context is a physical unclonable function (*1*).

Figure 7 shows the result of the laser markings (left column) by applying the paths shown in the right column.

Figure 8 shows the effect of using the same path (shown in figure 6-right) in two different objects - marks A1 and A2. As it can be seen, even if the same path is applied to different objects, the resulting marks contain a high level of distinctiveness. Experiments show that the average difference between different images of the same mark is much lower than the one between images of two different marks with the same object.

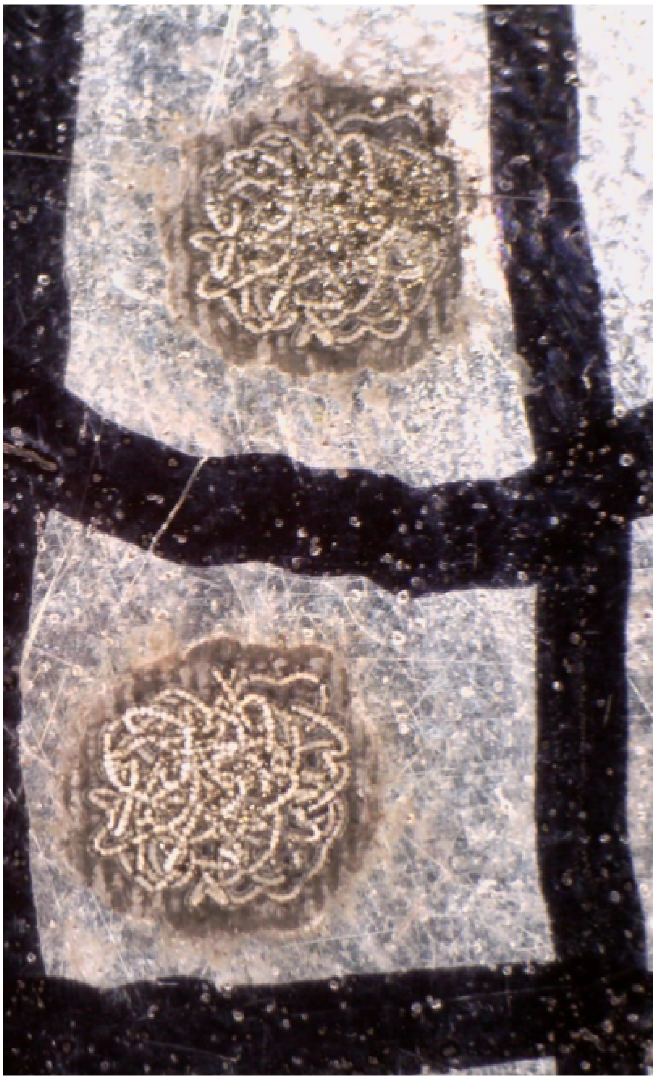


Figure 8. Laser mark with (path) A repeated in two different marks. Top mark is A1 and bottom mark is A2

To show that laser markings using these UniqueMark paths are unique and unclonable, we made the following experiment: we repeated the same path in an object (two marks close to each other) and took several photos of both marks

Figure 9 presents the effect of aligning two different photos of the same mark A1 and figure 10 presents the effect of aligning two different photos of the same mark A2.

On the other hand, figure 11 presents the effect of aligning two photos of marks A1 and A2 (which have the same path but two different realisations of the mark).

As it can be observed, the difference between two images of the same mark

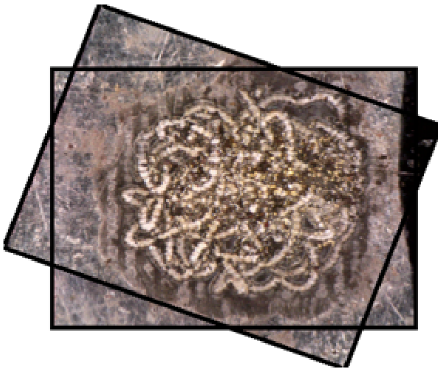


Figure 9. Laser mark A1 in two different photos. Left image is the alignment of the two photos and right image presents the difference between the two images - white pixels represent different pixels in both images.

Figure 10. Laser mark A2 in two different photos. Left image is the alignment of the two photos and right image presents the difference between the two images - white pixels represent different pixels in both images.

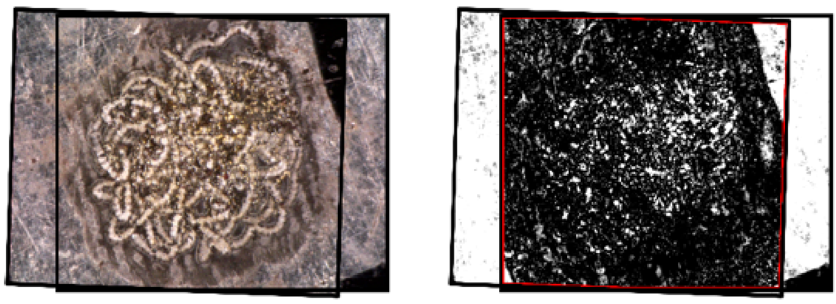


Figure 11. Laser marks A1 and A2 in two photos. Left image is the alignment of the two photos and right image presents the difference between the two images - white pixels represent different pixels in both images.

is very small, usually the percentage of different pixels (after image alignment) is under 5%. However, for images of marks created using the same path but in two different realisations of the laser marking, the percentage of different pixels is nearly 50%. It is straightforward then to infer, that the UniqueMark using the laser is able to produce unique and unclonable marks.

To conclude, in this subsection we described the laser marking process, and showed how it creates unique random marks by using a deterministic path. The characteristics of the path were also discussed.

3.4. *Registration*

All marks must be registered so that they can be associated with a specific object. The registration process should be made right after the marking process.

The object is usually placed in a holder, and then an image of the hallmark is taken. The camera must be focused on the objects surface plane, which is a non-trivial task. As the mark itself is very small, approximately $1mm^2$, the camera to be used must be carefully chosen, with macro lens, the working distance, and the depth of field simultaneously tuned.

After an acquisition of a focused image of the mark, the logical processing of the mark begins. The process includes the following steps:

(1) identification of the mark
(2) rectification
(3) segmentation of the particles
(4) descriptor generation
(5) registration in a database

For the first three steps of this process, the system uses reference method used in computer vision. In particular, three convolutional neural networks (CNN), or a combination of them in a single CNN, can be used in a deep learning process to identity and rectify the mark, and then segment the particles. As mentioned, these steps are straightforward in computer vision applications. According to the state of art, this method can achieve an highly satisfactory accuracy. It can be noticed that due to its very small marks, the resulting image is such a big challenge to be reached.

As for the step 4, the generation of the descriptor, we developed a proprietary algorithm, in conjunction with the University of Coimbra (Portugal), to extract a specific minutiae of the particles that must be able to discriminate two marks from each other.

The last step, registration of the mark in a database, is made to store the descriptor for the validation. Although the system architecture can be tailored for different applications, producers or sellers, the database can also store the image of the mark to forensic analysis and comparisons.

It is worthy to notice that the mark can lose a certain amount of its particles over the years without compromising the validation process, and the ability to verify the authenticity, or identify the mark, and consequently the object.

Extensive experiments in real objects, with stress agitation of them, showed that less than 2 percent of these particles will disappear after an ultrasound stress test, which suggests that the marks will maintain their validation ability for several decades or so.

3.5. *Validation*

We distinguish the validation in two different process:

(1) verification
(2) identification

The verification issue is the validation of authenticity of a claimed identity for the object in a 1-to-1 process. In this case, there is a previous identity that must be tested against the real object. In a first step, the two descriptors are compared and the distance between them is measured by any adequate metric. There are several metrics that can be chosen. If the distance between the presented object descriptor and the claimed object identity is below a certain threshold, then the object is validated. Otherwise it is not. The threshold may also be learned using artificial intelligence. In the case of a failed verification in the first level, one can go on to the second level, where the images of the two marks are directly compared to each other. In this case, the mark images are aligned and the difference is calculated. For this alignment process, it is used an ICP algorithm. This second step is slower than the first one, but can disambiguate the most challenging cases.

The architecture of identification process is more complex, though. In this case, the validation is comprised by a search process 1-to-many. A standard architecture is used, where all marks are searched and their descriptors are compared with the descriptor of the mark to be validated/identified. In this case, the number of comparisons might be dramatically high (the database for jewels and hallmarking can easily reach the order of magnitude of hundreds of millions). There are several techniques to improve the performance of the system. Simple division of the database in metadata characteristics is able to decrease the number of comparison by 3 or 4 orders of magnitude. For instance, if the database is first indexed by metal (e.g. gold, silver, platinum, ...), type of objects (e.g. ring, earrings, tiaras ...), country of issuance, size or other variables, the search can be accelerated with viable response times.

3.6. *Traceability*

The UniqueMark system is also able to track and trace any object throughout the logistic chain, starting at the moment of hallmarking, at the Assay office, until the mark is erased from the object, which should last centuries when the mark is preserved, or until it is deliberately erased.

Nowadays, traceability of objects is a demand on the market since it gives an enhanced power to the owner, and to authorities to protect the object.

4. Discussion

In this chapter we discuss the project results and the impact on the industry.

The UniqueMark system has showed, in its pilot phase, that unique and unclonable marks may be added to precious metal artefacts, such as jewels, artworks or other products made of metal. These marks have usually the same size of legal security marks (approximately $1mm^2$), which are produced through one of two processes: punching or a laser beam.

When comparing the two hallmarking processes, punching versus laser, we observed that both are equally capable of providing good and stable marks, both with high discriminatory capabilities to distinguish between different marks and to be used in validation (either it is verification or identification). The punching process poses some challenges, namely the need to deposit on the supporting material surface a certain quantity of non-agglomerated diamond particles, and the need to precisely hit their location. It can be made manually by our assay markers who are experienced experts in this operation, as well as able to achieve an extremely high level of expertise in performing adequately in just a short period of training. Alternatively, the marking process can be made using an automatic punch. In this case, the challenge is to use an infrared guide to position the hitting point. On the other hand, the laser marking has other constraints. To use a laser marking, the automatic generation of the laser path can use a dedicated software. The main challenge is to simultaneously tune the beam energy and the path density. These two variables have a coupled effect since the result must, on the one hand, have high density to maintain the metal melted and, on the other hand, the energy should not be as high as to destroy the details of the results, since they are important for the unique characterisation of the mark. Extensive results show that the degree of discrimination of punching is slightly higher than laser marks. However, the laser process is still quite important and presents some advantages over the marks obtained by punching, namely the fact that it is the only viable marking process for delicate objects.

As for the capacity of this system to scale and distinguish a large amount of marks, we made real tests with a relatively high number of marks, and the degree of discrimination remained its ability to identify marks, with a positive impact on the searching operation time. Regarding the number of different marks as a whole, preliminary mathematical studies indicated that in practical terms the number of different marks is unlimited, easily reaching orders of magnitude of $10^1$8 depending on the density and dimension of the particles, and the dimension of the marks. Additionally, there are some ways to even increase this number, for instance, by blending particles with different dimensions. In laser markings, the total number of different deterministic designs that can be laser beamed on the metal surface is, for practical reasons, virtually unlimited as well.

The searching time needed to find an answer to the question Is this mark equal to that another one?, which is the verification problem, is very small. Effectively, when there is a claimed identity, the problem is constrained to compare the descriptors of two marks and decide on whether these two descriptors represent the same mark or not. This classification process is extremely easy and straightforward to implement, and can be efficiently solved by convolutional neural networks or other classical methods either using machine learning, thresholding, or others.

On the other hand, when the question to answer is Is this mark registered? or Can you tell me more about this mark?, then the problem is considerably more difficult to solve. The identification problem consists of searching a specific enquiry mark in a (possibly huge) database, which is the case of searching specific fingerprint minutiae in a database of fingerprints. This problem, applied to fingerprints, is usually known as AFIS - Automated Fingerprint Identification System - and served as inspiration to the solution of the UniqueMark system. We developed a search tree, usually built using the k-d tree algorithm. It is able to handle very big databases of mark descriptors.

Another issue worth to analyse is the ability of the descriptor to maintain its properties of distinguishing two marks (punch) in the event of one, or many diamond particles dropped out from the hallmark. Comprehensive mathematical simulations and extensive experiments using real images of marks, showed that the descriptor keeps its identification property when approximately 10% of its particles drop out. For the future, we intend to extend these experiments to higher ratios of dropping out particles.

In any case, the event of dropping out one or more particles is rare, as should be. Effectively, to simulate the time effect, some experiments were made with ultrasound waves in several conditions and, even with higher levels of energy, there was one or two particles that eventually dropped out, suggesting that the particles are deeply incrusted in the supporting material. It is our expectation these marks last for centuries, and might be used for validation of a jewel or metal artefact throughout their lifetime.

In terms of the image acquisition system, ours is based on two different camera systems: (1) a commercial microscope with medium resolution (approximately 5 Mpixel), which is an affordable device to be acquired by any producer, retailers or jeweller, and (2) a smartphone camera with a macro lens. As observed from the experiments with several types and models of smartphone cameras and microscopes, it was noticed that the current standard smartphone camera is able to acquire an image from which our algorithms can detect the most majority of particles (in the punch case), or the salient characteristics (in the laser case), thus producing a valid and strong descriptor. However, it is also true that the accuracy level when using microscopes is higher than when using smartphone cameras with macro lenses. It is our expectation that with the fast-increasing resolution and quality of the current high-end smartphone cameras, in a couple of years the medium smartphone will be able to read and validate a UniqueMark, without the support of a macro lens.

To conclude this discussion, it is worth mentioning that this UniqueMark system may have a strong and widespread impact on the jewellery industry, since the hallmarking can change from a validation of the jewel model or of the jeweller, to achieve a real protection of the object as a single and unique specimen, with a single and unique fingerprint. There are several related applications that can increase the potential of this system, such as the traceability of these marks in all their life path. Additionally, or in a better word, consequently, other very strong application of this system is that one related to marketing. The fact that a unique and unclonable identifier is added to all the artefacts of (precious) metals can open new and profitable possibilities to producers, retailers or jewellers who can achieve such a very strong and powerful communication tool with the customer. Furthermore, the customer themselves can be an important link in this anti-fraud chain, since the validation can be at the customer hand, which will demand more and more security and trustworthiness when purchasing a precious metal artefact.

5. Conclusion

In this paper we presented the UniqueMark system, a novel system able to provide any metal object with a unique and unclonable mark. The marks can be produced by using a punch with a dispersion of diamond powder particles, or by applying a deterministic path in a laser beam to engrave a unique pattern on the metal surface. Along this work, we displayed that these marks are unique and unclonable. Additionally, this paper presented the validation ability of this system, by acquiring an image of the mark, either by an affordable commercial microscope or by a smartphone camera with a macro lens. The validation of these marks implies the search in a database for a specific query image, and we showed that the searching process is effective and efficient. We also presented the industrial details of the processes and discussed the advantages and disadvantages of them.

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