HISTORIC STONE PAVEMENT PHOTOGRAMMETRIC 3D-SURVEY: A WAY TO GET A CATALOGUE TO PASS ON ANCIENT CRAFTS

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ABSTRACT:

In Tuscany, the art of paving has never been codified in written form, being already encapsulated in knowledge based on practical experience, with specialized tradesmen and stonemasons relying on direct observation and passing on their knowledge to apprentices through repetition of gestures. The streets of Volterra, a historic town in Tuscany, are still paved with the local stone, the *panchina volterrana* (Volterran *panchina* stone). Photogrammetry techniques allow high-resolution reconstruction of 3-D pavement models and geometric representation of the macrotexture component resulting from the chiselling of the stone, as well as gaining high-resolution, high-precision geometry information along with colour information. In this way, it is possible to fully characterize the stone and generate a catalogue, which can become an operational tool for those involved in monitoring and maintaining pavements. This paper presents the methodology of photogrammetric surveying and the possibility of obtaining indices of the macrotexture of the processed surface of the stone, in terms of Virtual Mean Texture Depth (V-MTD), in analogy with the analysis of asphalt surfaces. The classification is also proposed by integrating the geometric macrotexture data with the data derived from a segmentation of the different textures obtainable for the model (diffuse, ambient occlusion). This geometric information could be then enriched by the stonemason's indications, constituting, therefore, a tool for passing on one's knowledge and experience.

1. INTRODUCTION

Historic pavements represent a heritage of knowledge of materials and techniques, the value of which is also implicitly recognized and protected by the Italian *Codice dei beni culturali e del paesaggio* (Code of cultural heritage and landscape), which in the list of assets potentially subject to protection procedures also mentions "public squares, streets, roads and other urban open spaces of artistic or historic interest" (Legislative Decree 42/2004 in Art. 10, paragraph 3, letter g). In this sense, streets and their paving represent a fundamental factor of local identity and as such a value to be protected.

In Tuscany, "surfacing the roads with stone" was an ancient custom and an art form worthy of respect (Gurrieri, 2012). The art of paving has never been codified in writing because it was already encapsulated in knowledge based on practical experience, with specialized tradesmen and stonemasons relying on direct observation and passing on their knowledge to apprentices through repetition of gestures (Romby, 1990). It was not until the first decades of the nineteenth century that the disciplinary and instructional regulations for the Corps of Engineers (1826) arranged for a specific section called '*Lastrici e selciati'* formed by standards, which assimilated the empirical basis of the very valid local experience handed down by the stonemasons.

The streets of Volterra, a historic town situated on the top of heights dividing the Era and Cecina valleys in the Tuscan countryside, are still paved with the local stone named *panchina volterrana* (Volterran *panchina* stone) (Ulivieri, 2017). This community has been able to seize the potential of the place by exploiting the local availability of *panchina* since ancient times and accumulating a wealth of local know-how, which has been perpetuated and repeated, albeit laboriously, over the centuries.

The City of Volterra still employs a stonemason, Roberto Guerrieri (in the past there were many more), who continues to care for the city's stones. But the lack of skilled workers, the consequent loss of technical knowledge, the closure of the last *panchina* quarries, and the use of new materials and new, more convenient technologies, are putting a strain on the preservation of "the very useful way of paving roads".

In this regard, modern three-dimensional surveying techniques and particularly those related to photogrammetric techniques can be of great help. Photogrammetry makes it possible to reconstruct at high resolution the three-dimensional model of the pavement and to represent geometrically the macrotexture component due to the chiselling of the stone. With photogrammetry techniques, it is also possible to juxtapose high-resolution, high-precision geometry information with colour information. In this way, it is possible to fully characterize the stone and generate a kind of catalogue, which can become an operational tool for those involved in monitoring and maintaining pavements.

The consolidated methodology of Structure from Motion (SfM) and Multi-View Stereo (MVS) photogrammetric surveying allows surveys with very high geometric resolution and accuracy as well as a faithful acquisition of the colour component (Olkowicz et. al, 2019, Tan & Li, 2019).

From the dense point cloud 3-D model is possible to define the indices of the macrotexture of the processed surface of the stone, in terms of virtual Mean Texture Depth (MTD), in analogy with the analysis of asphalt surfaces (Losa et. al, 2007).

Road pavement texture is defined, according to ISO regulation 13743, as the deviation of the pavement surface from a perfectly flat reference surface. The macrotexture represents the part of texture referring to the wavelength range included between 0.5 and 50 mm (BS EN ISO 13473 1:2019). The same regulations

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define texture depth (TD) as "in the three-dimensional case, the distance between the surface and a plane through the top of the three highest peaks within a surface area in the same order of a size as that of a car tyre/pavement interface".
As mentioned, photogrammetry allows to increase automation to achieve high geometric accuracy models. This opens new possibilities, previously unattainable due to time requirements and complexity, for this otherwise traditional surveying methodology. The main open issue of photogrammetry is its strong dependency from surface textures, with poorly detailed or homogeneous textures resulting in noisy point clouds, due to difficulties in extracting the features required by the matching algorithms.
While in other applications surface textures do restrain performance of this technique, pavement textures are always rough and heterogeneous, thus contributing to the achievement of more accurate models for macrotexture index assessment.
These indices allow to characterize the chiselling with a numerical, objective parameter, also enabling a semi-automatic classification of the wear condition of stones from an overall survey of a pavement, deferring the manual visual analysis to a second step in which only the critical issues that have emerged are evaluated.
The classification is also proposed in this paper by integrating the geometric macrotexture data with the data derived from a segmentation technique of the different UV textures obtainable for the model (diffuse and Ambient Occlusion (AO)) (Chun et. al, 2019; Piemonte & Caroti, 2022).
The integration of all this information allows the creation of a catalogue of the different types of stone processing based on objective, detectable and replicable data. The catalogue is then enriched by the stonemason's indications, constituting, therefore, a tool for passing on one's knowledge and experience.
The methodological approach was tested on the historic pavements of Volterra with the valuable collaboration of the city stonemason, mr. Roberto Guerrieri.

2. MATERIALS

2.1 *Panchina volterrana* and finishing type

Volterra, "city of wind and boulder", is made up of massive and imposing buildings of arenaceous limestone. Here, the paving of *panchina volterrana* for streets, alleys and squares penetrates every patch of open space. The *panchina* was the main building material used in Volterra since the Etruscan era; from the Middle Ages on, the use of *panchina* was the norm. Its yellow-orange colour creates a perfect chromatic continuity between the ancient city of Volterra, enclosed in its walls, and the natural base on which it rests. It is arenaceous limestones, i.e. sandy masses welded together by limestone cement and frequently affected by the presence of marine fossils (Trinciarelli & Marrucci, 1990) (Fig.1). From a stoneworking point of view, "this stone is fairly submissive to iron when just excavated, and then hardens with time" (Rodolico, 1953). The largely siliceous composition of this rock, its consequent hardness and good mechanical properties also favoured its use for paving road surfaces (Trinciarelli & Marrucci, 1990; Cepolina, Marradi & Ulivieri, 2017).
The great availability of *panchina* stone, which in the past distinguished the Volterra area and the availability of skilled local workers capable of working it, contributed to its wide use over the centuries. Unfortunately, the situation has changed today. The small number of stonemasons employed by the Municipality of Volterra no longer allows for maintenance work; while the closure of the *panchina* caves located at Poggiarone (near Montebradoni), Marmini and Pettina, which have been active for a long time, does not allow the stone to be easily found.

Figure 1. Example of paving with *Pecten* included into the *Panchina volterrana*

2.2 Single stone case studies

In order to test the methodology for the classification of historical paving stones by means of macrotexture indices and UVmap segmentation, five types of stones laid in Volterra were considered. The choice of stones significant for their representativeness was made in collaboration with the local stonemason, mr. Roberto Guerrieri, who shared his knowledge based on local experience with the Authors, patiently explaining the rules of the art that were already part of the cultural background of the stonemasons who preceded him.

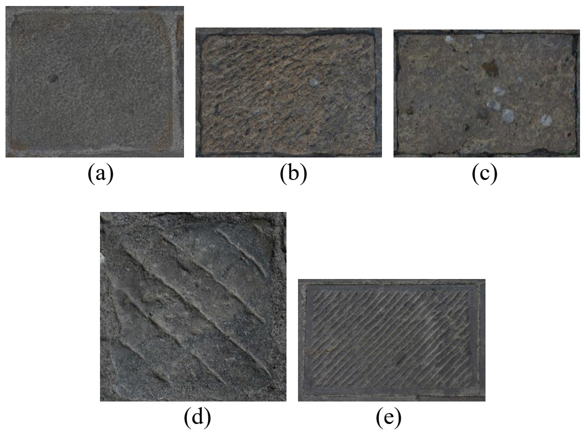

Figure 2. Different Finishes of Stones examples. Hand-Punched Finish (a) (b) (c), Hand-Rifling Finish (d)**,** Machined-Rifling Finish (e)

The chiselling is fundamental; the stones, both new and old, must be frequently chiselled or re-chiselled in order to prevent the surface from becoming too worn and smooth, and therefore dangerous.
The wear of the stone "is remedied by scratching the upper surface of the slabs by incisions along and across the parallel grooves", which serve to create friction. The dressing of stone such as the "*rigatura*" - Hand-Tooled Finish - (Fig.2d) or the "*punzecchiatura*" - Hand-Punched Finish - (Fig.2a,b,c) of the *panchina* slabs are carried out with the *subbia* (a chisel type). The different finish depends both on the hand of the stonemason and on the tool used, i.e. the normal *subbia* or the *subbia* with widia tip which allows you to engrave more deeply. In fact, each stonemason has a different hand due to the intensity of the percussion, hence the uniqueness of the historic stone pavements. One of the rules of art employed by the stonemason is that each face of the stone ashlar must be perfectly perpendicular to all the four bordering faces, for this reason the "*nastrinatura*" is carried out. This technique consists in making an incision, a few millimeters deep and approximately 15 mm wide, along the

perimeter of the visible face of the slab by means of chisel, mallet and square (*scalpello*, *mazzuolo* and *squadra*), resulting in a minimal flat surface called "*nastrino*" along the sides of stone slabs, (Fig. 2a, b, c, d). The mechanical finishing of the stone has considerably reduced the use of the chisel and the mallet, which are now used only in the so-called "patch-up" restorations of the old slabs. The mechanization of the processes, if on the one hand is cheaper, on the other provides almost modular and repetitive material (Fig.2e), which does not reproduce the uniqueness of manual processing.
Mr. Guerrieri recalls that Piazza San Giovanni with the Baptistery overlooking the Cathedral was completely re-chiselled manually in the 1980s by a local stonemason known as "Ganghe" (Fig. 2b), while the paving of Vicolo dei Lecci - located between via Lungo le Mura and Via Guarnacci - was re-chiselled (with *nastrinatura* and *rigatura*) a few years ago by Guerrieri himself (Fig. 2d).

2.3 Pavement portions case studies

The classification of single stones could be an interesting technique if it could also be applied in a semi-automatic extensive analysis of existing pavements. In order to test this possibility, in addition to the survey of single stones, the photogrammetric survey of certain portions of the pavement was also conducted. These areas were also chosen in agreement with mr. Guerrieri for their significance and importance in the urban context.
The pavement of the steep ramp of *Castello*, which constitutes the shortest connection between the city center and the hill of Volterra, partly unpaved until the nineteenth century, currently shows obvious joint disconnections between stones (Fig. 3).
Piazza Maggiore (currently Piazza dei Priori) has been the central core of the social and political life of the city since ancient times; it covers a total area of 6300 *braccia quadre* (about 2100 square meters) and is paved with *Selice panchina* stone (Fig. 2c), with a series of stone guidelines, which in addition to giving greater stability to the system and being reference points for installation, create an original geometric design (Fig. 4). The best interstice between stone and stone is the so-called "*a filo mestola*" (mason trowel thickness), i.e. as narrow as possible so that the tip of the trowel does not pass throught it.

Figure 3. Ramp of *Castello*.

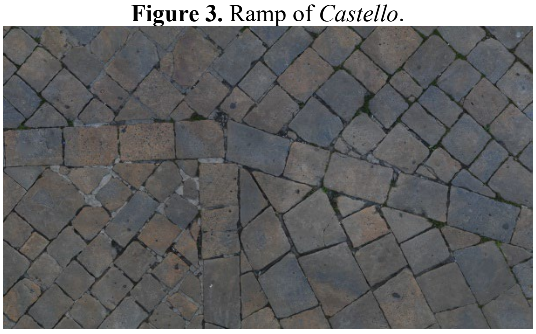

Figure 4. Stone guidelines – Piazza dei Priori

2.4 Photogrammetric equipment

Photogrammetric surveying was carried out by means of a Nikon D700 DSLR camera fitted with a 50mm lens. This camera has a sensor size of 4256x2832px - 36mmx24mm, with a pixel size on the sensor = 0.0084mm.

2.5 Photogrammetric datasets and available outputs

For each of the case studies, photogrammetric acquisitions were made in order to return a 3-D model with an expected precision <1mm. This involved shooting with the available camera placed on a tripod at a distance of 60-70cm and f11 aperture to ensure the necessary DoF (Depth of Field). The resulting GSD (Ground Sampling Distance) was 0.15mm. An x-rite classic colour checker was inserted into the scene, which allowed the colour profile of the images to be defined and the model to be scaled thanks to the scale references on it.
For each of the case studies, Agisoft's Metshape software (ver. 1.8.2) obtained the dense point cloud, the DEM, a high-poly model, the diffuse and the AO texture.

3. METHODS

3.1 Photogrammetry system analysis

For studies involving roughness measurements on small objects, both sampling resolution and measure accuracy are crucial in achieving high quality data sets.
Spatial resolution of photogrammetry reconstruction is primarily linked to the camera-object distance. Reconstruction accuracy depends on an adequate overlapping of the input images and their position, as well as on image quality, which is ultimately dependent on the properties of camera sensor and lens. Among quality-related parameters, the most important are image sharpness and digital noise levels. Image sharpness can be affected by several causes, e.g. unwanted camera movements during exposure, unsuitable lighting conditions, effects due to light refraction on the iris. Sample matter features can affect the overall reconstruction accuracy, due to their influence on feature matching detection and both extrinsic and intrinsic orientation parameters, including distortions, of cameras.
For the purpose of this research, settings of photographic and photogrammetric survey must be considered with the utmost care.
The first setting required is the "pixel size in object space units" or GSD. In order to be able to use photogrammetry data for macrotexture measurement, this dimension was established considering the smallest value of the wavelength range to be measured.
Since the value of the smallest wavelength to detect is 0.5 mm, the GSD size has been established in 0.1mm. similar to the resolution of the profilometer that is normally used for MTD measurement.
The shooting distance, D, was calculated according to the following relationship (1), where p is the pixel size on the sensor, f is the focal length:

$$D = GSD/(p \cdot f) \qquad (1)$$

and was equal to about 60 cm. The projected overlap was 90%.
The highest aperture size ensuring a detector pixel size smaller than the sensor pixel size along with a DoF equal to or greater than the stone width is f/11.
To avoid micro-blur phenomena on the images, the same were collected from a fixed camera on a tripod using a remote shutter release.

In order to provide the model with a scale, the ruler integrated into the colour checker was used as scale bar.
The output of the photogrammetric process is a dense point cloud with a resolution of the order of 0.1mm.

3.2 “Virtual MTD” measurement

Firstly, the model derived from the photogrammetric survey could be used to obtain sections and apply the MTD calculation in a similar way to standard methodologies using measurements obtained from a profilometer.
However, photogrammetric surveys provide much richer products in terms of information than simple sections, which intrinsically are a discrete sample representation of the surveyed object.
The photogrammetric model is a virtual replica (i.e. digital twin) of the stone, with a resolution defined by the GSD and therefore of the order of 0.1mm.
Based on this virtual model, it is therefore possible to obtain directly the volumes of the cavities, similar to what is done in the standard volumetric measurement of MTD; this also enables measurement of the Virtual MTD (V-MTD) on the digital twin of the analysed stone.
Although the operations described are not linked to a specific software, the experiments and the images produced for this paper are derived from the use of the open source software CloudCompare in version 2.13.
Starting from the detected dense point cloud (Fig. 5a), segmentation is performed by eliminating the edge of the single stone, which is characterised by coarse irregularities and model edge noise (Fig.5b).

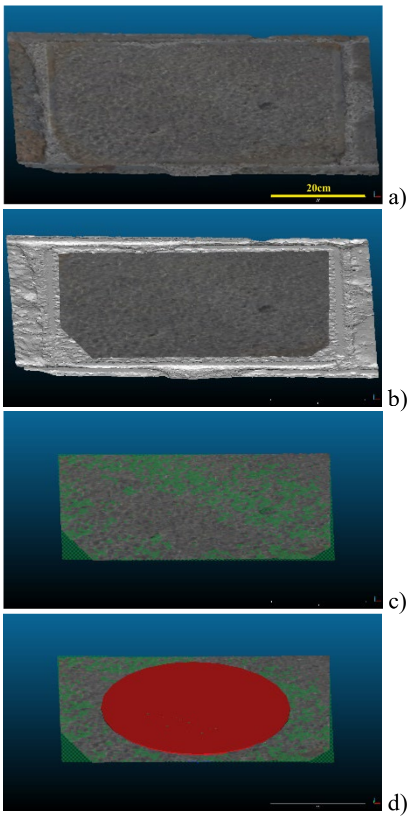

Figure 5. Surface preparation steps for V-MTD calculation

The best-fitting plane of the remaining point cloud is then determined and, noting its orientation, a roto-translation of the reference system is performed to make the plane normal coincident with the Z-axis (Fig. 5c).

A cylinder of known diameter (d) and height (h) 2cm is then constructed along the Z axis (Fig. 5d), extracting a circumference which represents the intersection between the plane interpolating the upper surface of the stone and the cylinder. This circumference will serve for a further segmentation of the upper surface of the stone in order to consider in the calculation of the MTD only the circular element of known diameter taken at the center of the surface.
At this point, the C2M (Cloud to Mesh) algorithm calculates the point-to-point distance between the point cloud and the cylinder (Fig.6). Once the maximum distance between the surface of the cylinder and the point cloud has been calculated, the cylinder is translated vertically by this amount, effectively making the cylinder tangent to the point cloud.

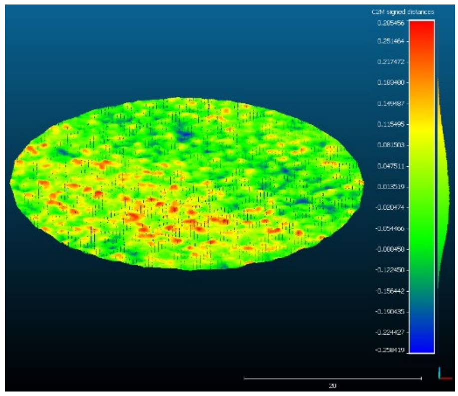

Figure 6. Point-to-point distance between the point cloud and the cylinder

It is therefore possible to calculate the volume of the cylinder (VC) and the volume of the circular portion of known diameter of the point cloud (VN) with respect to a horizontal reference plane. The difference between the two gives the void volume (VV) from which:

$$V - MTD = VV/[\pi \cdot (d/2)^2] \quad (2)$$

It should be specified that the standard regulations for the determination of the MTD in asphalts, from which the determination of V-MTD index of this test was inspired, provides for the analysis on a cylinder with a fixed diameter of 10cm because this is the area of interest, which is supposed to be the interface between asphalt and tyres.
In the experimentation on the historical pavement’s stones, the V-MTD index wants to return an evaluation of the state of the chiselling on the whole surface of the finished stone. For this reason, the diameter of the cylinder has been adjusted, from time to time, to different values so that the cylinder itself comprised as much stone portion as possible.

3.3 Further information deriving from the 3-D survey

First, the three-dimensional model was used to obtain the V-MTD index, but there are other information that can be obtained and which may be of interest for a more complete description of the stone surface.
The DTM can provide information on the depth of the chiselling and rifling and on any curvature or irregularity of the stone surface.
It is then possible to obtain, from the dense point cloud, a mesh model and subsequently the photorealistic texture that colours it. The stones have a predominantly flat surface and the UVmap returns an "almost orthographic" representation of the stone's surface.

Since the colour profile has been defined for the images, the representation of the diffuse RGB texture provides important information on the colour of the stone. The availability of the high-poly model also allows the creation of normal map and AO textures. The latter is easily segmentable and can provide information on the shape of the chiselling and rifling for the individual stones, while for the portions of the pavement it can also provide the limits of the mortar joints between stone and stone. Based on the joint limits, the individual stones can be automatically extracted and analysed in their characteristics to provide a digital information system of the characteristics and state of maintenance of the pavement.

4. RESULTS AND DISCUSSIONS

By applying the methodology described in paragraph 3.2 and (2) the V-MTD values shown in Table 1 are obtained for the different stones considered.

Stone	(a)	(b)	(c)	(d)	(e)
d [cm]	40.0	24.0	30.0	20.0	24.0
VC [cm^2]	6641.3	2395.1	3774.1	1638.5	2390.4
VN [cm^2]	6240.8	2230.9	3530.0	1556.7	2277.6
VV [cm^2]	400.5	164.2	244.1	81.8	112.8
V-MTD [mm]	3.2	3.6	3.5	2.6	2.5

Table 1. V-MTD.

It is interesting to note that similar types of processing (embossing in cases a, b and c or rifling in cases d and e) correspond to similar values of V-MTD. Similar results were also obtained from the analysis of other samples.
In the different types of stones, the processing varies in terms of density, width and depth of the ashlar or grooves, but the V-MTD index seems to bring them together by macro-typology.
On the other hand, Figure 7 shows the other outputs described in paragraph 3.3 and which can be associated with single stones. Although the outputs are all metrically characterized, even from a purely qualitative analysis the wealth of information that can be archived in a hypothetical catalogue that aims to collect the various possible processes carried out over time on paving stones is evident. This information would then be useful in graphically accompanying the written description of the phases of the artisanal production process.
Taking into consideration the portions of pavement detected, the availability of the AO texture allows the segmentation of the separation lines between the stones (Fig.8) and consequently of the single stones.
The possibility of isolating single portions of 3-D surveys, representing single stones, allows an extensive automatic analysis of the V-MTD indices and consequently the analysis of the condition of the pavement.
However, a criticality found in the extensive analysis should be underlined: in certain parts of the pavement the stones do not have a predominantly flat surface but are characterized by a strong curvature. In these cases, the formulated calculation methodology of the V-MTD fails because the part due to the surface curvature of the stone is also included in the calculation of the voids volume. The methodology should be implemented with a preliminary analysis like in Yong 2018 that detrends the surface by removing the low frequencies from the curvature values.

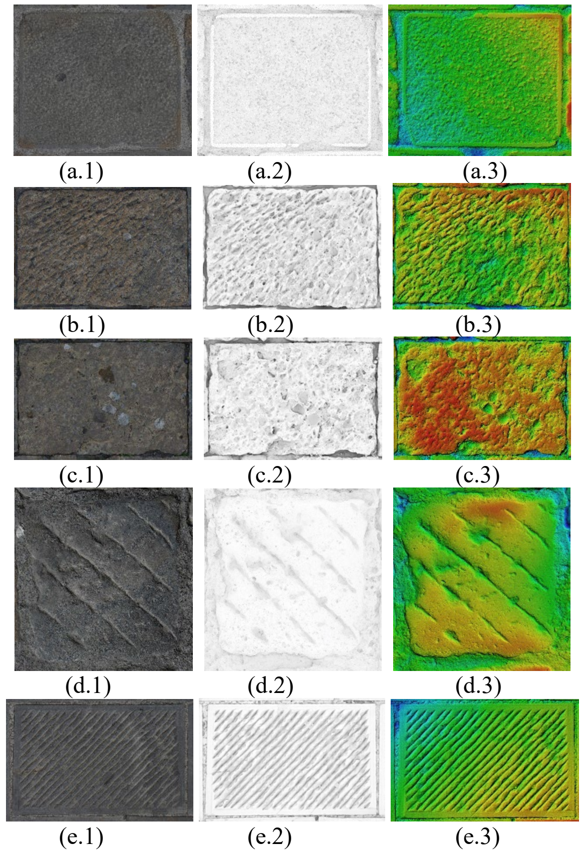

Figure 7. Diffuse texture (*.1), AO texture (*.2), DEM (*.3).

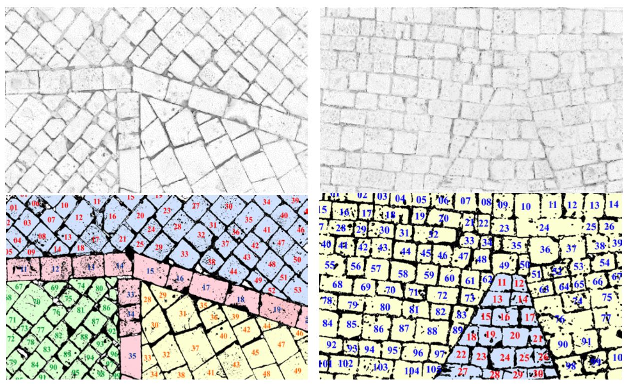

Figure 8. Pavement stones segmentation

5. CONCLUSIONS

In Volterra, the strong characterization of road paving represents an important historical value, which is the subject of preservation efforts by resisting the new needs for speed and resistance.
The sharp reduction, over the years, of the number of stonemasons dedicated to the maintenance of these historic pavements has led, among other things, to the risk of losing knowledge which, by its nature, has always been entrusted to oral and practical transmission.
The use of the new technologies and methodologies illustrated in this paper provides an operational tool for extensive monitoring of the maintenance state of pavements.
Furthermore, by defining objective parameters such as the V-MTD, for example, this methodology could form the basis for the implementation of a catalogue of stone finishing typologies. This objective information, accompanied by the description of the

local stonemasons based on both personal and handed down experience, would provide archival documentation that is indispensable for preserving such an important cultural heritage in the future.

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AUTHOR CONTRIBUTION

Conceptualization, G.C., A.P., D.U.; methodology, A.P., D.U.; survey, A.P.; validation, A.P.; data curation, A.P., D.U; writing-original draft preparation, A.P., D.U.; writing-review and editing, G.C., A.P., D.U.; visualization, A.P.; supervision, G.C., A.P., D.U.; project administration, A.P., D.U.. All authors have read and agreed to the published version of the manuscript.

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