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Digital 3D modelling of dinosaur footprints by photogrammetry and laser scanning techniques: integrated approach at the Coste dell'Anglone tracksite (Lower Jurassic, Southern Alps, Northern Italy)

Fabio Massimo PETTI[1,2*], Marco AVANZINI[1], Matteo BELVEDERE[3], Mauro DE GASPERI[4], Paolo FERRETTI[1], Stefano GIRARDI[5], Fabio REMONDINO[5,6] & Riccardo TOMASONI[1]

[1]Museo Tridentino di Scienze Naturali, Via Calepina 14, 38100 Trento, Italy
[2]Dipartimento di Scienze della Terra, Sapienza Università di Roma, P.le Aldo Moro 5, 00185 Rome, Italy
[3]Dipartimento di Geoscienze, Università degli Studi di Padova, Via Giotto 1, 35137 Padova, Italy
[4]Servizio Geologico Provincia Autonoma di Trento, Via Roma 50, 38100 Trento, Italy
[5]Fondazione Bruno Kessler, Via Santa Croce 77, 38100 Trento, Italy
[6]Institute of Geodesy and Photogrammetry, ETH Hönggerberg, 8093 Zürich, Switzerland
[*]Corresponding author e-mail: *fabio.petti@mtsn.tn.it*

SUMMARY - *Digital 3D modelling of dinosaur footprints by photogrammetry and laser scanning techniques: integrated approach at the Coste dell'Anglone tracksite (Lower Jurassic, Southern Alps, Northern Italy)* - This paper provides an evaluation of 3D modelling of dinosaur footprints using high resolution digital photogrammetry and laser scanner. The results have been compared with the ones obtained from standard methods. The new techniques have been tested on tridactyl tracks from the recently discovered Coste dell'Anglone ichnosite (Lower Jurassic, Southern Alps, Trentino-Alto Adige, Northern Italy). The 3D track models yield many and accurate morphological and morphometrical information, providing paleoichnologists with the opportunities to formulate new hypotheses about dinosaur walking dynamics. Although these methods are still experimental, they look very promising for the virtual documentation, exhibition and preservation of tetrapod tracks, often affected by weathering. Furthermore digital 3D track models could produce a remarkable advantage within the field of scientific communication, enabling different researchers to use the same virtual models of the studied specimens.

RIASSUNTO - *Modelli 3D di orme di dinosauro ottenuti con le tecniche di fotogrammetria e laser scanner: un approccio integrato applicato all'icnosito di Coste dell'Anglone (Giurassico inferiore, Alpi Meridionali, Nord Italia)* - In questo lavoro è fornita una prima valutazione dei risultati inerenti all'utilizzo della fotogrammetria digitale ad alta risoluzione e del laser scanner per la rappresentazione 3D di orme di dinosauro. I risultati sono stati confrontati con quelli conseguiti mediante le metodologie tradizionali. Le nuove tecniche di rappresentazione sono state sperimentate sulle orme tridattile dell'icnosito recentemente scoperto alle Coste dell'Anglone (Giurassico Inferiore, Alpi Meridionali, Trentino-Alto Adige, Italia settentrionale). I modelli 3D delle orme forniscono numerose e accurate informazioni morfologiche e morfometriche che consentono ai paleoicnologi di formulare nuove ipotesi sulla dinamica della locomozione nei dinosauri. Sebbene queste tecniche siano ancora in fase di sperimentazione, risultano molto promettenti soprattutto per quel che riguarda la documentazione virtuale e la preservazione delle orme di tetrapodi, soggette all'azione erosiva degli agenti atmosferici. I modelli 3D digitali possono, inoltre, produrre benefici importanti nel campo della comunicazione scientifica, consentendo a più ricercatori la fruizione virtuale degli esemplari studiati.

Key words: dinosaur footprints, photogrammetry, laser scanner, Southern Alps
Parole chiave: orme di dinosauro, fotogrammetria, laser scanner, Alpi Meridionali

1. INTRODUCTION

To date paleoichnologists have made use of several techniques to analyze and interpret dinosaur footprints. Track reproductions were mainly based on drawings, supplied by photographs and casts made of several materials such as plaster and silicon rubber. Drawings and photographs present and cause different problems, mainly in defining the actual morphology of the footprints. The footprint sketches are too simplified and subjective, properly called "interpretative", and this causes the loss of information. Furthermore, the accuracy of drawings as well as photographs are dependent on the direction and intensity of light. For this reason it has been always suggested to reproduce or photograph tracks under appropriate light conditions (grazing and lateral illumination). Such conditions are not always obtainable, for the different exposure and lighting of the outcrops.

The most useful technique is *in situ* casting that allows to thoroughly study tracks in the laboratory. Indeed it provides more objective morphological information and accurate numerical data under artificial light conditions, not reachable in the field. However, making a copy of a whole "megasite", constituted by hundreds or thousands of tracks and/or trackways is technically and economically impossible, and the loss of several detailed and accurate data that comes from is definitely significant.

In the last few years GPS, close-range photogrammetry, and laser scanning, used also in other research fields (i.e. cultural heritage site documentation), provided new tools to easily analyze and measure tracks and trackways. Even if the experimentation of these new methods is still in progress, we think that they could significantly improve analysis and preservation of dinosaur footprints, and at the same time extend and facilitate scientific communication. The aim of this paper is to shortly illustrate the results of dinosaur tracks 3D digital modelling obtained on theropod footprints from the Lower Jurassic Coste dell'Anglone ichnosite (Lower Jurassic, Southern Alps, Trentino-Alto Adige, Northern Italy).

2. THE COSTE DELL'ANGLONE DINOSAUR TRACKSITE

In March 2007 hundreds of dinosaur tracks, mostly arranged in long trackways (up to 50 m), were discovered at Coste dell'Anglone, along the eastern slope of Monte Brento (Dro, Southern Alps, Trentino-Alto Adige; Fig. 1). The Museo Tridentino di Scienze Naturali is currently carrying out the ichnosite analysis. Each *in situ* trackway was labelled with the acronym CA. The Coste dell'Anglone ichnosite is located in the central sector of the Southern Alps, north of the Garda Lake, about 8 km to the east of one of the main tectonic lineaments of the area, the Ballino-Garda fault (BG in Fig. 2). This fault is a Neogene segment with a transpressive left lateral movement that separates the Mesozoic shelf deposits of the Trento Platform from the pelagic deposits of the Lombard basin. It derives from the reactivation and tectonic inversion of an extensional structure ("Garda escarpment"), active since the Early Jurassic up to the whole Cretaceous (Castellarin 1972; Castellarin *et al.* 1993, 2005).

Dinosaur tracks were recognized on a wide bedding surface dipping about 30° SE (Fig. 3). Lithostratigraphically the Coste dell'Anglone track site belongs to a Lower Jurassic shallow water carbonate succession, the Calcari Grigi Group, which extends through the eastern sector of the Southern Alps (see Avanzini *et al.* 2007 for a review). This unit, several hundred meters thick, has been recently raised to group rank and subdivided into four formations and one member (CARG project - Geological Map of Italy at the scale 1:50.000; Avanzini *et al.* 2007). It is composed of alternating subtidal, peritidal and supratidal deposits. From bottom to top the following units have been identified: Monte Zugna Formation (Hettangian to Sinemurian), Loppio Oolitic Limestone (mid to late Sinemurian), Rotzo Formation (Sinemurian *p.p.* to Pliensbachian) locally partially heteropic with the Tovel Member (Sinemurian to Pliensbachian), Massone Oolitic

Fig. 1- Locality map showing the Coste dell'Anglone tracksite. Photography: courtesy of NASA/JPL – Caltech, el. MTSN 2006.
Fig. 1 - Ubicazione geografica del sito delle Coste dell'Anglone. Foto: cortesia del NASA/JPL – Caltech, el. MTSN 2006.

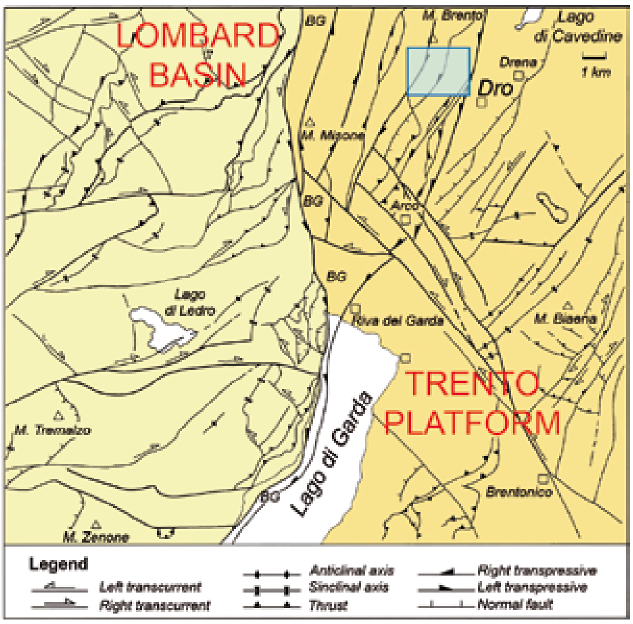


Fig. 2 - Tectonic sketch map of the sheet 080 "Riva del Garda" (Geological Map of Italy, scale 1:50.000; from Castellarin *et al.* 2005). In the light blue box the tracksite area. BG: Ballino-Garda system fault.
Fig. 2 - Schema strutturale del foglio 080 "Riva del Garda" (Carta Geologica d'Italia, scala 1: 50.000; da Castellarin et al. *2005). Nel riquadro azzurro l'area dell'icnosito.*

Fig. 3 - Panoramic view of the Coste dell'Anglone tracksite. Tracks are preserved on the tilted bedding plane below the vertical cliff.
Fig. 3 - Vista panoramica dell'icnosito delle Coste dell'Anglone. Le orme sono preservate sul piano di strato inclinato al di sotto della parete verticale.

Limestone (late Pliensbachian) (Fig. 4). The footprints bearing level belongs to the mainly subtidal Tovel Member, composed of metric oolitic and bioclastic grainstone and packstone beds, alternating with decimetric finely laminated, miliolids-rich grey mudstone, related to small supratidal ponds. The tracks come from one of these latter levels, composed of poorly fossiliferous dark grey stromatolitic and peloidal mudstone. Other dinosaur tracks and trackways discovered across the Adige Valley also belong to the Calcari Grigi Group, but come mostly from its basal unit, the Monte Zugna Formation (Avanzini *et al.* 2006). Among these it is worth mentioning the Lavini di Marco megatracksite, near Rovereto, one of the most important European dinosaur ichnosite (Avanzini *et al.* 2001a, 2005, 2006). Other trampled levels of the Calcari Grigi Group come from the Sarca Valley (loose block belonging to the Tovel Member; Avanzini *et al*. 2001b) and from Bella Lasta in the Monti Lessini area (near the boundary between the Loppio Oolitic Limestone and the Rotzo Formation; Mietto *et al.* 2000).

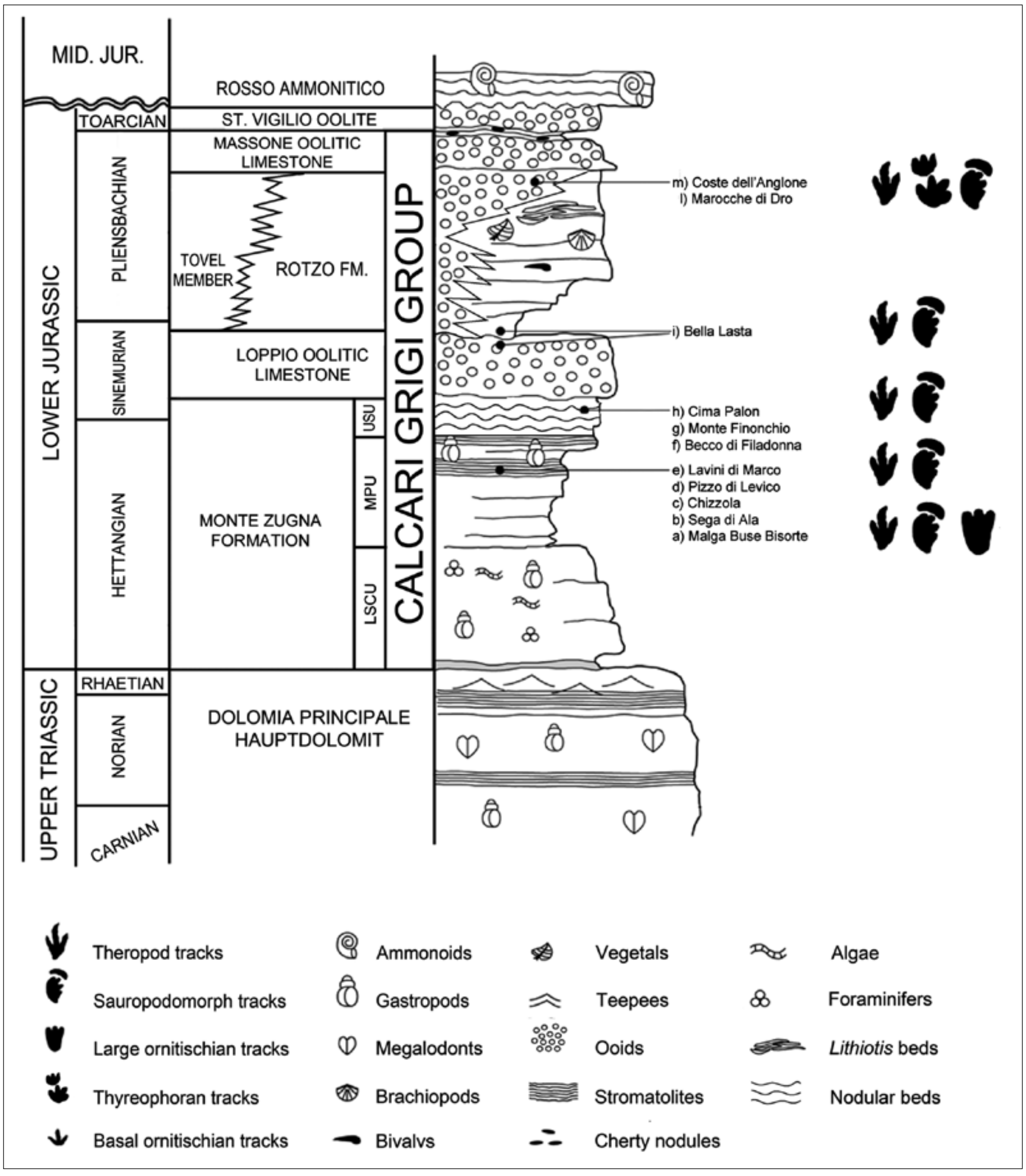


Fig. 4 - Lithostratigraphic scheme of the Lower Jurassic Calcari Grigi Group showing the stratigraphic position of the Coste dell'Anglone tracksite and of the other tracksites from Southern Alps.
Fig. 4 - Schema litostratigrafico del Gruppo dei Calcari Grigi (Giurassico inferiore) con la posizione stratigrafica dell'icnosito delle Coste dell'Anglone e di altri icnositi delle Alpi Meridionali.

3. PREVIOUS WORKS

Over the last years the use of new technologies (laser scanning, close-range photogrammetry, anaglyph stereo imaging and global positioning systems) has been gaining ground to study tracks (Arzarello *et al*. 2000; Breithaupt & Matthews 2001; Matthews & Breithaupt 2001; Arakawa *et al.* 2002; Breithaupt *et al.* 2004; Manning 2004; Gatesy *et al.* 2005; Matthews *et al.* 2005; Bates *et al.* 2006a, 2006b; Hurum *et al*. 2006; Manning 2006; Matthews *et al.* 2006; Schader *et al.* 2006). These innovative approaches are broadening the horizons of ichnology, offering a wider availability and fruition of the obtained results. All the researches experimented up to now are under evaluation; nevertheless the enormous and interesting potentiality of these techniques appears evident. In most cases tracks were studied through integrated approaches using different technologies (Matthews *et al*. 2006). Among these, the use of the laser scanner is becoming more frequent, as for the Fumanya dinosaur tracksite (Bergueda Region, Catalunya, Barcelona) which has been recently modelled by Bates *et al.* (2006a, 2006b) using Light Detection And Range (LIDAR) imaging. The use of laser scanner at Fumanya has been necessary because the tracks are preserved on sub-vertical surfaces that do not allow direct contact of the material. The 3D model of the trampled surface will allow remote analyses and measures even in case of the outcrop weathering.

As previously pointed out, the standard methods adopted to illustrate and study tracks have been characterized by a high degree of subjectivity and by inaccuracy mostly in collecting morphometric parameters of the tracks. Nevertheless, these effects are highly reduced if we analyze a large number of specimens. A comparison between old and new methodologies has been carried out on dinosaur and bird footprints from China and Japan (Arakawa *et al.* 2002). Tracks previously studied using standard techniques have been reproduced and re-examined using a 3D digitizer (VIVID 700). This technology provided high-resolution track images, even if it presented some problems in analyzing shallow footprints. The drawn outlines resulted considerably different from those of the same specimens from the previous studies; footprints parameters such as length, width, interdigital angles, were similar, while footprint depth values displayed different and more accurate measures.

It is worth noting that digital photogrammetry was already used in the Lavini di Marco megatracksite (Rovereto, Northern Italy) to obtain a 3D model of one bipedal trackway (Arzarello *et al*. 2000).

4. ADOPTED TECNIQUES AND SOFTWARE

The present study originates from the recently discovered dinosaur tracks from the Coste dell'Anglone site and is a part of a new research project which includes the test of new technologies finalized to the realization of 3D digital models of some Italian dinosaur ichnosites. This experience has been carried out in a joint project between the Museo Tridentino di Scienze Naturali (Trento, Italy), the Fondazione Bruno Kessler (Trento, Italy), and the Institut of Geodesy and Photogrammmetry (ETH, Zürich, Switzerland).

4.1. High Resolution Digital Photogrammetry

Photogrammetry is the science of obtaining reliable measurements from photographs (images), i.e. it turns 2D image data into 3D information like digital models. Starting from precise measurements in the images, photogrammetric techniques allow the acquisition of metric information about the size, shape and position of an imaged object. The fundamental task of photogrammetry is to rigorously establish the geometric relationship between the image and the object as it existed at the time of the imaging event. Once the relationship, described with the "collinearity" mathematical model, is correctly recovered, one can then derive information about the object strictly from its imagery (Mikhail *et al.* 2001; Luhmann *et al.* 2006). Photogrammetry can be seen as a subfield of Remote Sensing. Generally the term Remote Sensing is more associated to satellite imagery and their use for land classification and analysis or changes detection. In photogrammetry, passive optical sensors like cameras are used to capture the natural light waves reflected by the object from which an image is generated. On the contrary, active sensors (like laser scanners or stripe projection systems) measure the light they emit and that is reflected by the observed object.

Similar to human vision, if an object is seen in at least two images from different viewpoints (images), the different relative positions of the object in the images (so-called parallaxes) allows stereoscopic view and the derivation of 3D information in the overlapping areas of the images. Indeed, by intersecting rays coming from homologous 2D points visible in different images and passing through the cameras projection centers, we can derive the required 3D coordinates.

Photogrammetry is used in many fields, from the general and traditional mapping to the video-games industry, from the industrial inspections to the movie production, from the heritage documentation to the medical field. Traditionally, photogrammetry was always considered a manual and time-consuming procedure, but in the last decade many developments lead to a great improvement of the performances of the technique and nowadays many semi- or fully automated commercial procedures are available.

In the case of paleontological sites or objects, the advantages of photogrammetry become readily evident: (i) images contain all the information required for 3D modelling and documentation (geometry and texture); (ii) taking images of an object is usually faster and easier than physically measuring it; (iii) image measurements help avoiding potential damage caused by surveying activities; (iv) an object can be reconstructed even if it has disappeared or considerably changed using available or archived images; (v) photogrammetric instruments (cameras and software) are generally cheap

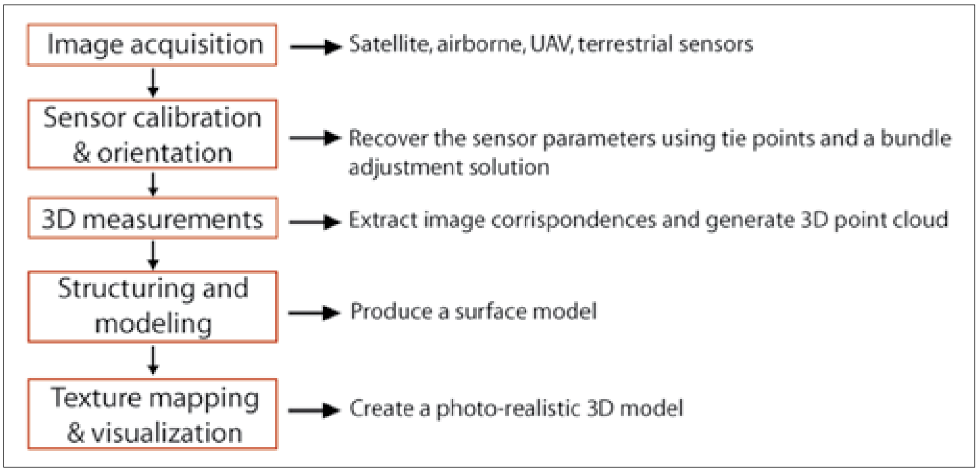


Fig. 5 - Photogrammetric 3D modelling pipeline: from image acquisition (using different platforms or sensors) to the visualization of the final 3D model.
Fig. 5 - Procedura della modellizzazione fotogrammetrica 3D: dall'acquisizione dell'immagine (usando differenti piattaforme o sensori) alla visualizzazione del modello 3D.

(we can work with consumer digital cameras or even mobile phones), very portable and easy to use. Nevertheless, the integration of the photogrammetric approach with other measurement techniques (like laser scanner) should not be neglected and their combination is leading so far to quite good documentation results as it allows the use of the inherent strength of both approaches.

Compared to other imaging techniques used to derive 3D information (like computer vision, shape from shading, shape from texture, etc.), photogrammetry does not aim at the full automation of the procedures, but it has always as first goal the metric results, associated to high accuracy values. Photogrammetry can be applied using a single image (e.g. for ortho-rectification purposes), or using two (stereo) or more images (block adjustment).

The entire photogrammetric workflow (Fig. 5) used to derive metric and reliable information of a scene from a set of images consists of (i) calibration and orientation, (ii) 3D measurements, (iii) structuring and modelling, (iv) texture mapping and visualization (see Remondino and El-Hakim, 2006 for a recent review of the entire terrestrial image-based modelling technique).

For the image-based digital documentation and 3D modelling of the dinosaur footprints, we employed a calibrated Kodak DSC Pro SRL camera, 14 Mega pixel, equipped with 50 mm lens. Each footprint was imaged with 5-6 images and, after the image orientation, a surface matcher (Remondino & El-Zhang 2006) was used to derive the 3D geometry of the print. The matcher employes different image features (feature points, grid points and edges) and is able to simultaneously combine multiple images and derive accurate 3D measurements.

4.2. Active Sensors

In recent years active sensors like laser scanners or stripe projection systems have become a very common source of documentation data, in particular for non-expert users, as they provide range data of surfaces in high resolution and generally with high accuracy. Therefore range-based approaches are often complementary or combined to image-based ones. Indeed in many applications there aren't good conditions to acquire images due to constraints or occlusions in the acquisition and it is impossible to work with a good intersection angle, baseline and overlap. These are the major obstacles that lead up to use in some applications active sensors instead of images. Also (i) the easiness of use of range sensor, (ii) the possibility to reach high level of detail generally with good accuracy and (iii) the fast acquisition time, recommend the use of scanners, even though the last studies in the photogrammetric field are changing this trend. Like photogrammetry, active sensors are suitable for different scales. An advantage of active sensors is that they directly provide the required 3D information and they do not require a mathematical model like photogrammetry to derive 3D data from 2D images. While the recording devices are still expensive, important progress has been made in recent years towards an efficient processing and analysis of the range data. Range-based systems (Blais 2004) are mainly based on two principles: triangulation and time delay.

Triangulation-based systems (Fig. 6) work on short distance (between 250 mm and 900 mm) and can achieve very high accuracy. The considered object is pointed by a light beam that is seen by a CCD camera. A triangle is formed by

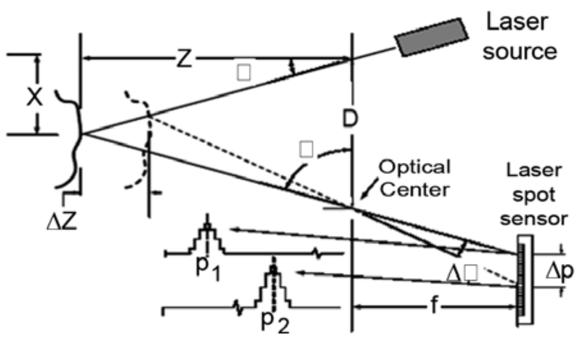


Fig. 6 - Triangulation-based laser scanner principle scheme.
Fig. 6 - Schema di principio dello scanner a triangolazione ottica.

the point source of the light spot, the light point on the surface of the object and the projected point on the CCD camera. The triangle in uniquely defined by two angles and the distance can be measured. The process has to be repeated for all points of the object. In many cases, to decrease the amount of scanning time, stripe light is projected instead of a single dot. In these systems, called slit laser scanners, the laser line is projected on the object and imaged at an angle. The deformation of the profile is a direct function of range. Active sensors that use pattern projection technique (instead of a laser light) are also based on the triangulation principle. A grid of lines is imaged from a viewpoint that is in a different position from the source spot viewpoint. The pattern is equivalent to a second camera used in the stereo-photogrammetry and the position of a point is determined through the triangulation principle. These systems are really fast compared to laser scanners and can generally also achieve higher accuracy.

Time delay active sensors are instead employed for large objects and scenes, as for example architectures, rooms, walls or archaeological sites. These sensors work on longer distances (i.e. 2-1000 m), but are less accurate than triangulation-based systems. The systems measure the time that light needs to propagate from the laser source to the object and back. Assuming a constant speed light, the distance to the object can be calculated. There are two main methods to calculate the distance. The first one is based on pulse principle (also called Time of Flight, TOF) that detects the time a laser is reflected back to the receiving detector, usually a photodiode. The second method is the amplitude modulation of the optical carrier that measures the range from the phase variation between transmitted and received signal. This second method gives generally better precisions but works only until a predefined and shorter range.

For the digitization of the dinosaur footprints, we employed a triangulation-based laser scanner ShapeGrabber SG1002 (Fig. 7). The cumbersome equipment and the required electric generator were transported by a helicopter of the Autonomous Province of Trento. The ShapeGrabber scanner head (Fig. 8a) moves along a sliding bar with a horizontal translation of ca 60 cm and works in a range between 30 and 80 cm. Before each acquisition epoch, the instrument must be accurately calibrated, using a dedicated calibration plane (Fig. 8b). This procedure is performed to retrieve the interior parameters of the CCD camera and the precise displacement between the camera and the laser beamer (position and angles).

Afterwards the scanner is used to acquire, in different locations, the 3D shape of some footprints in the paleontological site. As the footprints are distributed along a trackway, the acquisitions are performed along a strip, having enough overlap between them for the successive registration phase. Indeed, as each scan is in its independent reference system, at the end of the work, they have to be transformed into the same reference system, taking one scan as reference. This alignment was performed using Polyworks IMAlign©. The alignment is generally performed first with a raw registration of each scan pair, giving at least 3 common points between the two scans and then with a final alignment which considers all the points contained in the scans. This second phase is based on the so called ICP algorithm (Iterative Closest Point). The algorithm, starting from the raw alignment, tries to minimize the differenc-

Fig. 7 - Laser scanner ShapeGrabber SG1002.
Fig. 7 - Laser scanner ShapeGrabber SG1002.

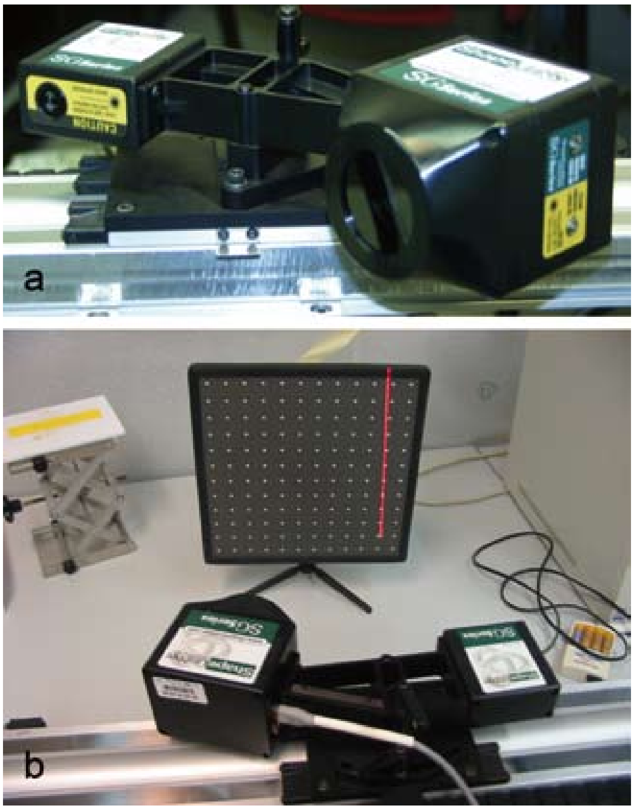


Fig. 8 - a. ShapeGrabber SG1002 head; b. ShapeGrabber SG1002 calibration procedure.
Fig. 8 - a. Testa dello ShapeGrabber SG1002; b. Procedura di calibrazione dello ShapeGrabber SG1002.

es between the scans in their overlapping areas computing the 3 translations and 3 rotations necessary for the operation. The final standard deviation gives an idea of the quality of the registration.

For the investigated footprint area, we performed 5 scans at 0.3 mm resolution, which were then registered together achieving a final std of 0.11 mm.

5. ICHNOLOGICAL ANALYSIS

In order to test the validity of 3D dinosaur tracks acquisition through high resolution digital photogrammetry and laser scanning techniques, a sequence of three consecutive footprints from the CA2 trackway has been considered (CA2 17, CA2 18 and CA2 19). The CA2 trackway is composed of 29 tridactyl tracks, preserved as concave epirelief (Fig. 9). Foot length (FL) values, taken in the field, vary from 22.70 cm to 27.30 cm (20.75 cm on average). Foot width (FW) ranges from a minimum of 12.30 cm to a maximum of 17.69 cm with a recurrent value of 16.15 cm. Pace angulation (PA) varies from 97° to 178°, while average stride length (SL) is about 1.30 m. Total divarication (II^IV) varies from 43° to 65°. The interdigital angles are rather similar in most of the tracks. Also, the proximal part of digit IV extends backward with respect to that of digit II, and falls along the digit III axis. The digit II widens distally. Field analysis allowed to individuate three digital pads and a claw trace on digit III, in one of the examined specimens only (CA2 2). On some specimens the distal portion of digit III widens to tapering again in its end. In several footprints the digit IV narrows in its middle part, probably because of a mud collapse from its outer margin. Three phalangeal pad impressions are clearly visible on digit IV, two on digit II. The derived phalangeal formula is 3:4:5 and allows us to attribute CA2 trackway to a medium-sized theropod, even if the pace angulation values are unusual for a theropod trackmaker. Derived hip height, obtained using the formula developed by Thulborn (1990) for small-medium theropods ($h = 3.06 \times FL^{1,14}$), is 1.07 m. Estimated body length and mass values derived from Paul's (1988) formulas [$L = 4h$; $M_b = (4.73 \times h)^3$] are 4.28 m and 129.64 kg. SL/h ratio values clearly indicate a walking gait of the animal which speed could be estimated between 0.80 m/s and 1.16 m/s, depending on the adopted formula (respectively Weems 2006 and Alexander 1976).

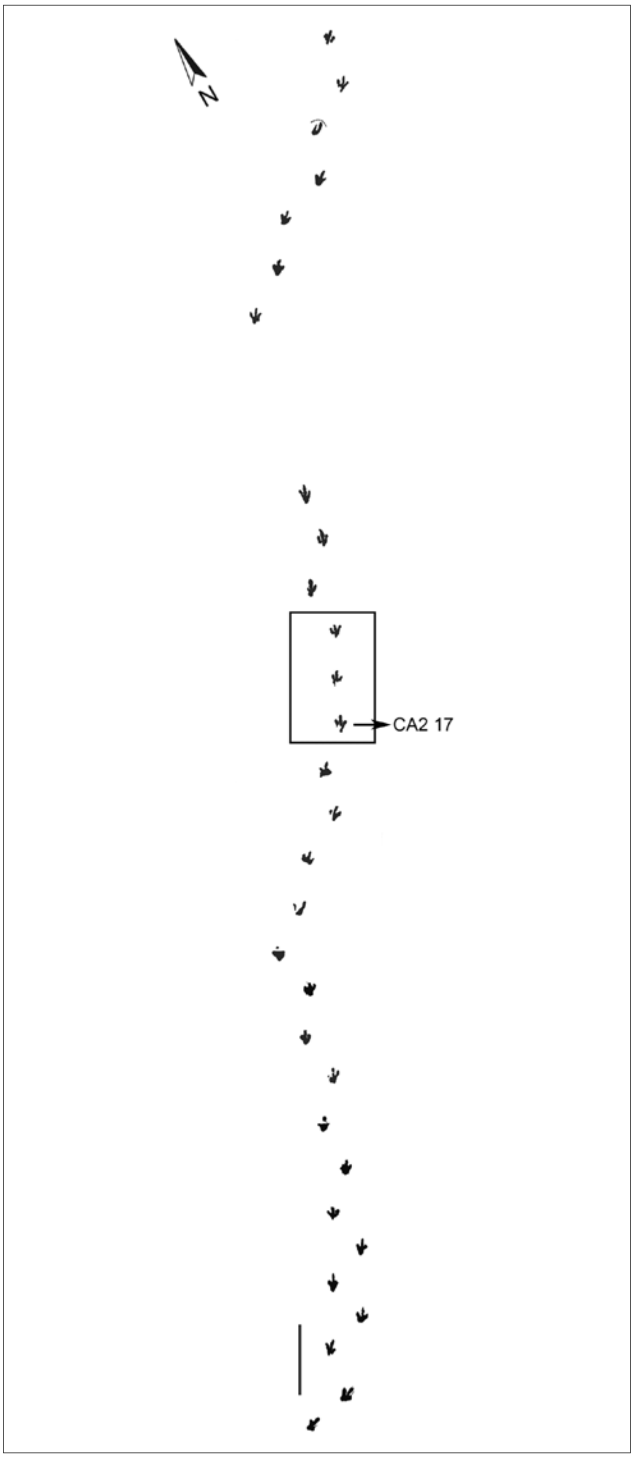


Fig. 9 - Schematic drawing and orientation of the CA2 trackway from the Lower Jurassic Coste dell'Anglone tracksite. Scale bar 1 m.

Fig. 9 - Disegno schematico e orientazione della pista CA2 dell'icnosito delle Coste dell'Anglone (Giurassico Inferiore). Scala 1 m.

6. RESULTS AND DISCUSSION

A detailed description of the CA2 17 footprint, chosen from the 3D modelled trackway because of its better preservation, is given herein, along with a close comparison of the morphological and numerical data obtained both by standard and traditional methods.

CA2-17 (Figs 10, 11, 12, 13, Pl. I) is a medium-sized theropod track, functionally tridactyl and mesaxonic. The track is a concave epirelief of a right foot and is almost complete, moderately well preserved, with recognizable impressions of all the digits.

The *in situ* interpretative drawing (Fig. 10; Pl. I a, d) displays the clear impression of the whole digit III, while digits II and IV appear not well preserved in their distal portion. The proximal pad of digit IV is set backward compared to the one of digit II that vanishes in its proximal portion. Two digital pads are clearly impressed on digit II, three and two respectively on digits III and IV (the proximal and the distal ones). Claw traces were not observed even if digit III impression tapers distally. Hypex between digits III and IV seems to lie posteriorly in comparison with that between digits II and III.

The CA2-17 laser scanner derived 3D model (Fig. 11) confirms the occurrence of three digital pad impressions on digit III that represent the deepest areas of the footprints. The digit IV is more deeply impressed (12 mm) than digit II (6 mm) and displays a clear and deep digital pad lying at the same height of the boundary between the proximal and the middle pads of digit III. According to this image the most deeply impressed area is the middle digital pad of digit III (16 mm). This suggests a functional prevalence on digits III and IV and a pronounced digitigrady. This hind limbs posture is also confirmed by the topographic image (Fig. 12; Pl. I

Fig. 10 - Photograph and on site interpretative drawing of the CA2 17 footprint. Scale bar 5 cm.
Fig. 10 - Fotografia e disegno interpretativo dell'orma CA2 17. Scala 5 cm.

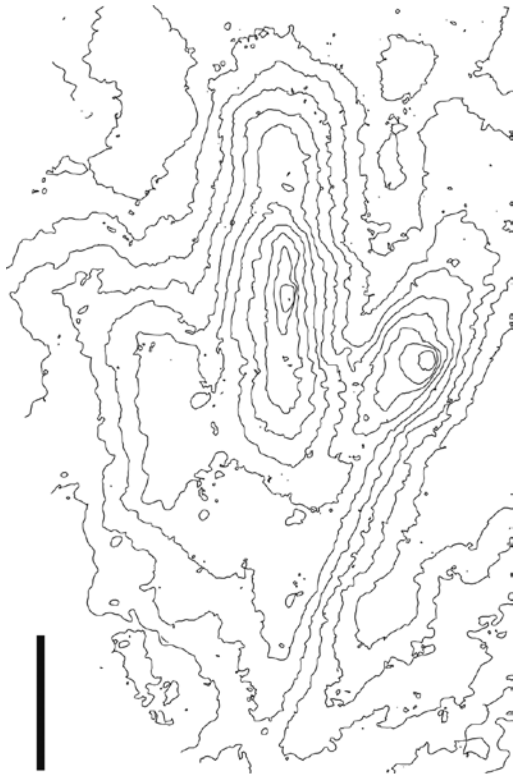


Fig. 12 - Contour map of the CA2 17 footprint. The contour interval is 2 mm. Scale bar 5 cm.
Fig. 12 - Modello topografico dell'orma CA2 17. L'equidistanza è di 2 mm. Scala 5 cm.

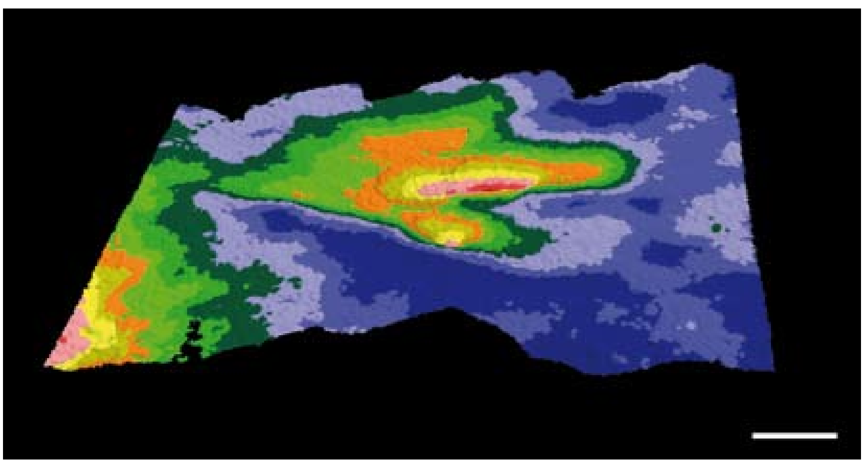


Fig. 11 - 3D Laser scanner derived image of the CA2 17 dinosaur footprint. Scale bar 5 cm.
Fig. 11 - Immagine 3D dell'orma CA2 17 realizzata con il laser scanner. Scala 5 cm.

b), where the medial pads of digits III and IV are clearly the deepest impressed. Three evident ridges appear on digit III by zooming and rotating the model from all the perspectives. These ones delineate the three digital pad impressions. The 3D contour image highlights also the occurrence of a steep slope ("track wall" *sensu* Brown, 1999) represented by the outer margin of digit IV and the shallower impression of digit II whose external margin fades outward. The 3D model analysis does not allow to recognize clear claw traces even though all the digits taper distally.

The photogrammetry derived 3D model (Fig. 13; Pl. I c) displays several interesting information not recognizable in the field. The 3D-coloured illustration clearly indicates the deepest areas of the track, which coincide with the proximal and medial pads of digit III and the distal pad of digit IV, as already above. The trace of digit II appears to be wider in comparison with digits III and IV. Three digital pads and a faint claw trace, probably inward directed, can be observed on digit III. Furthermore a faint claw trace occurs on digit IV. The proximal part of digit IV is clearly backward with respect to the ones of digits II and III and shows a probable digital pad impression. Both the scanned and the image-based models show the outward rotation of digit IV and the inward bending of digit III.

The foot length (FL) measured in the field is 24.61 cm, and foot width (FW) is 17.31 cm; the interdigital angles are 14° between digit II and III, 24° between digit III and IV. Total divarication is 38°. The same measures taken on the models reveal slight differences: FL 24.53 cm, FW 16.30 cm, II^III 8.5°, III^IV 23.6° and total divarication 32.1°.

The comparison between data collected in the field and those acquired from the processed 3D digital models underlines the great improvements that this new analytical methods can offer. The most interesting aspect is the opportunity to achieve a lot of both morphological and numerical data, some of which are hard, if not impossible, to measure *in situ*. The above discussed methods tested at the Coste dell'Anglone track site allowed to individuate interesting elements and accurate measurements that can provide significant information about the posture and the biomechanics of the trackmaker hind limbs. The digit III and IV impressions are deeper than the digit II impression. We can infer that the weight of the trackmaker has probably been loaded mainly on these two digits, and in particular on their middle portion

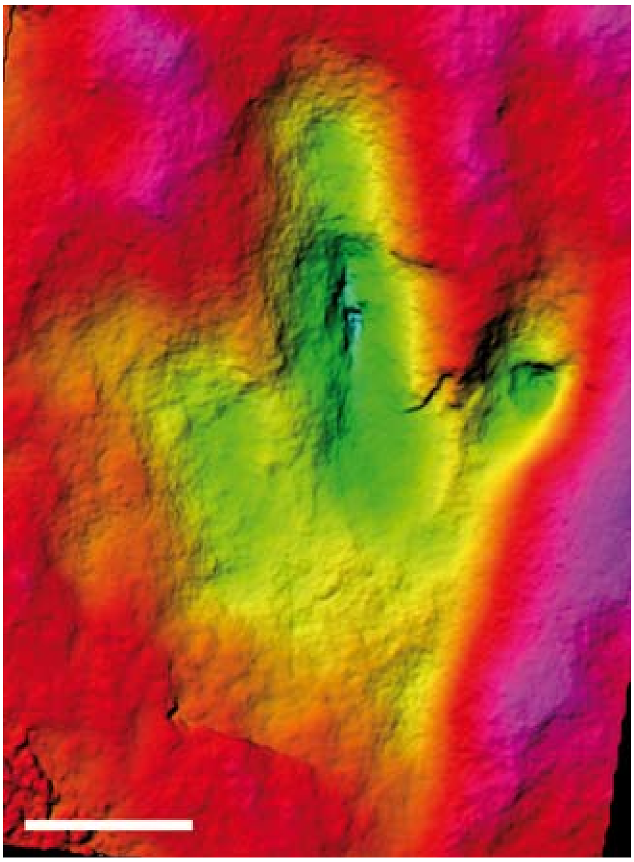


Fig. 13 - Photogrammetry derived 3D model of the CA2 17 footprint. The surface model, here shown in colour-code mode, has a resolution of 0.5 mm. Scale bar 5 cm.

Fig. 13 - Modello 3D dell'orma CA2 17, realizzato con la fotogrammetria. Il modello, rappresentato in modalità colour-code, ha una risoluzione di 0,5 mm. Scala 5 cm.

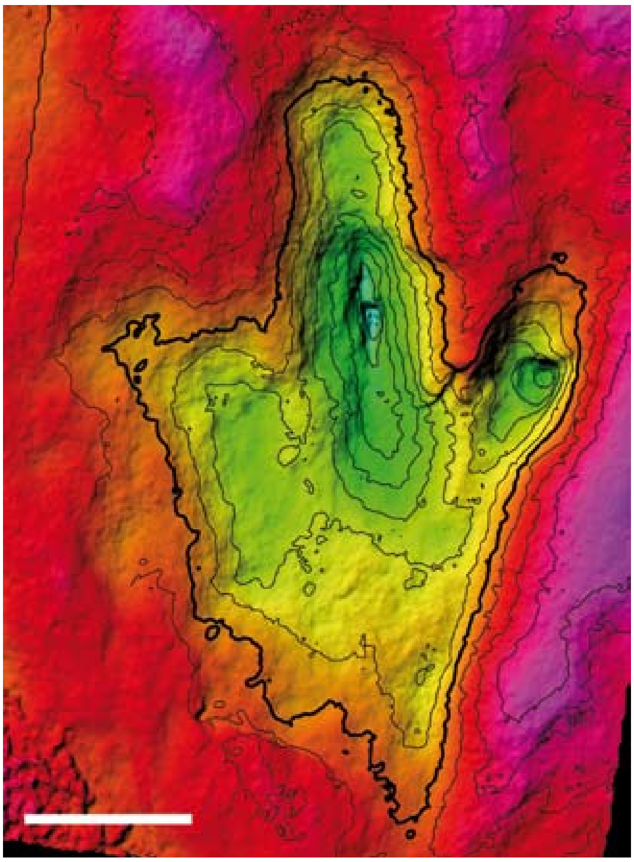


Fig. 14 - Superimposition of the contour map by laser scanner and photogrammetry derived 3D model. Scale bar 5 cm.

Fig. 14 - Sovrapposizione del modello topografico ottenuto con il laser scanner e del modello 3D realizzato con la fotogrammetria. Scala 5 cm.

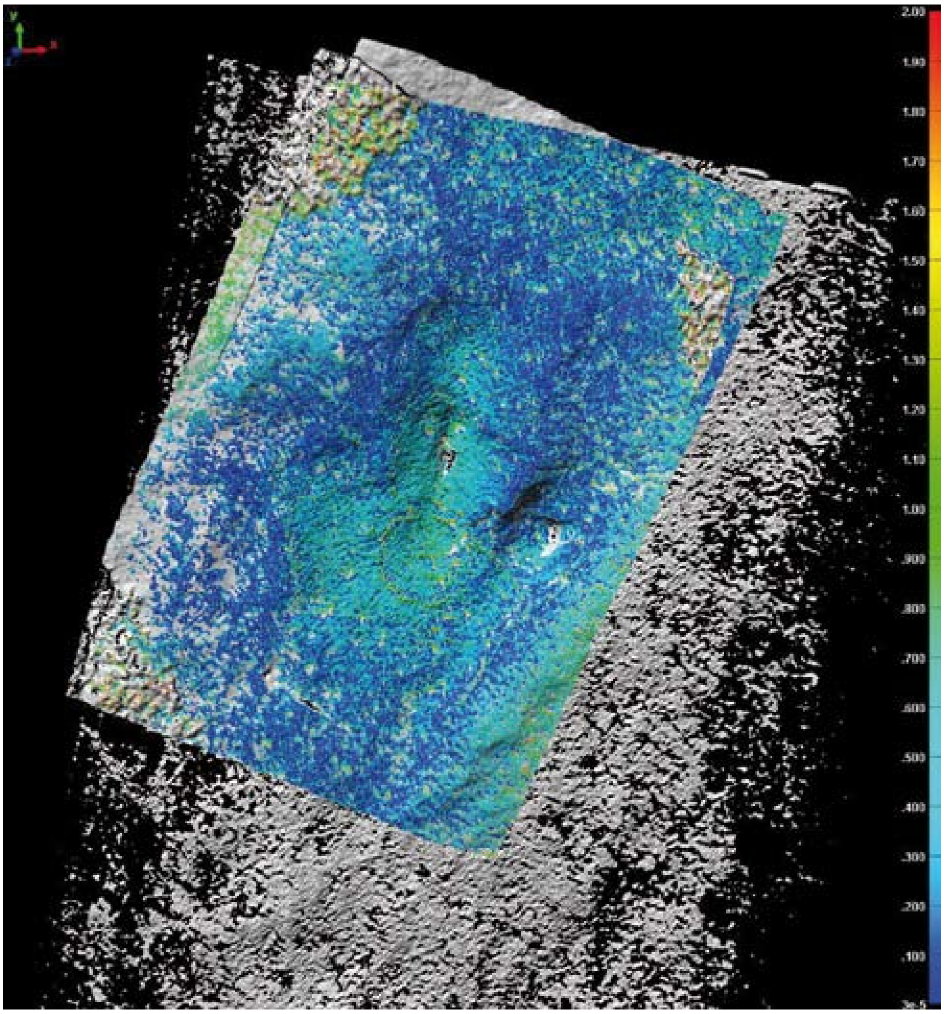


Fig. 15 - Colour-coded difference between the laser scanner and photogrammetric models. Note as in the track area the difference between the two models is on average less than 1 mm.
Fig. 15 - Differenza, codificata a colori, tra il modello fotogrammetrico e quello ottenuto con il laser scanner. Nell'area interessata dall'orma la differenza tra i due modelli è in media inferiore a 1 mm.

as evidenced by the 3D countour image. Meaningful to note is the occurrence on the outer margin of digit IV of a vertical wall, that could testify a downward and outward movement of this digit, as previously suggested for the Late Triassic and Early Jurassic dinosaur footprints of East Greenland and Northern Italy (Milán *et al*. 2006). This walking kinematics could be linked to particular joints position of the hind limbs. Thus the 3D modelling gives important information useful to attribute a track to a trackmaker.

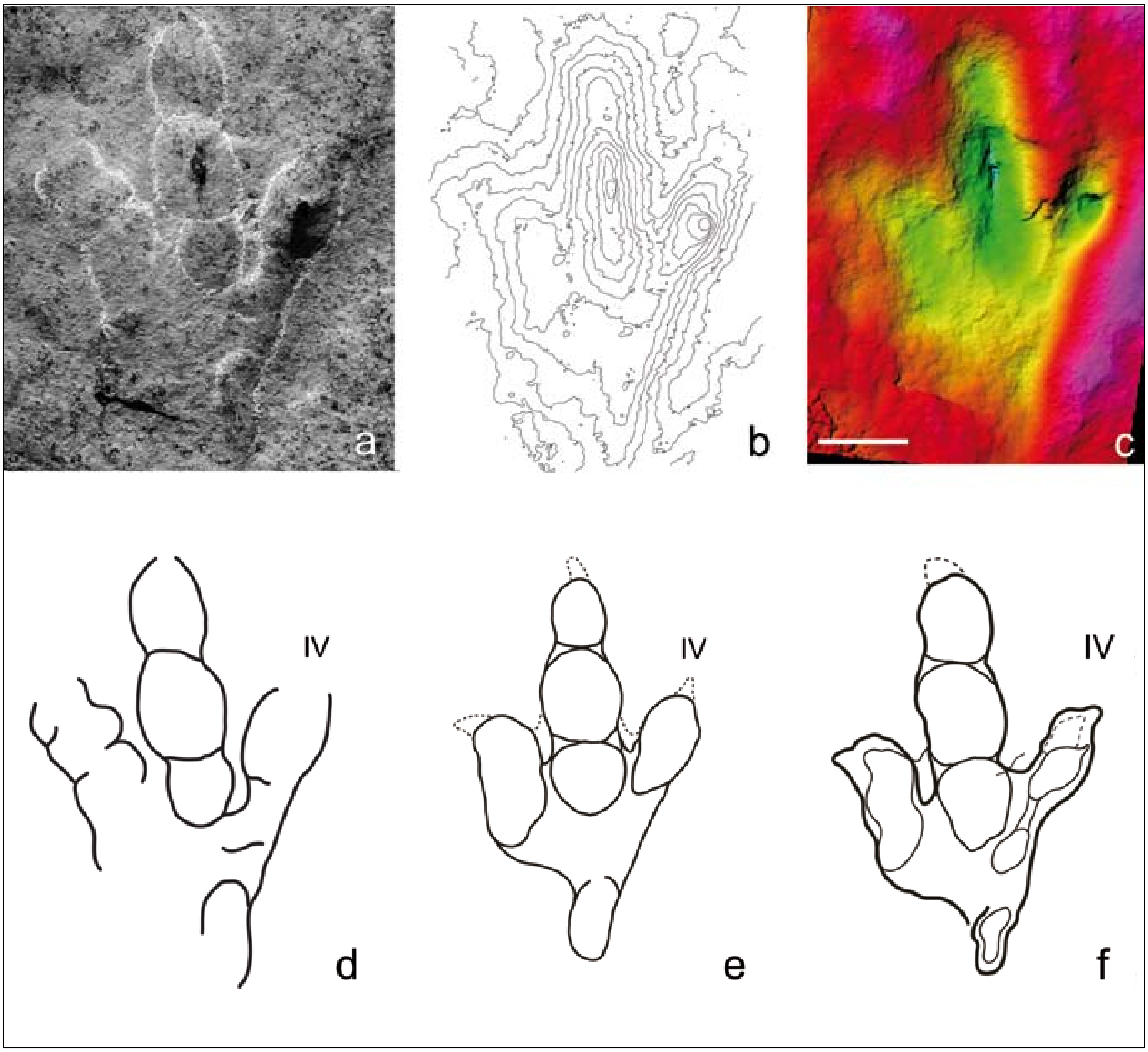
Furthermore the comparison between the laser scanner and photogrammetry derived 3D models (Fig. 14) clearly demonstrates the high resolution of both digital technologies. The overlapping of the two models, compared by Polyworks IMAlign©, highlighted an average difference less than 1 mm in the area occupied by the track (Fig. 15).

7. CONCLUSIONS

The 3D dinosaur tracks modelling, adopting the integrated high-resolution digital photogrammetry-laser scanning approach opens a new route for thorough and more accurate ichnological analyses. These techniques provide us the tool to make a rapid and detailed morphological and morphometrical analysis, even on extremely shallow tracks. Data could be acquired directly in the field and processed in a brief period. With these applications we are able to analyze in laboratory 3D footprint model, under different perspectives and without the light direction problem, and to obtain a large number of accurate quantitative measurements, not easily achievable in the field (e.g. footprint's depth in shallow footprints). Furthermore laser scanner technique allows to analyze inacessible outcrops characterized by exposures that do not allow *in situ* analyses and measures (i.e. sub-vertical cliffs). The applied technologies can keep tracks as well as whole tracksites permanently in their recorded state of preservation, overcoming the weathering effects.

The products of this integrated approach are 3D images, drawn models and contour images available in different file formats (.wrl, .dxf, .ply) that can be analyzed and measured with several softwares (VRML view©, Meshlab©, AUTOCAD©, Polyworks©).

The analysis of theropod footprints 3D models from the Coste dell'Anglone tracksite reveals that the outlines are



Pl. I - CA2 17 track from the Lower Jurassic Coste dell'Anglone tracksite. a. Photograph; b. laser scanner contour map; c. photogrammetric model; d. on site interpretative drawing; e. laser scanner model interpretative drawing; f. photogrammetric model interpretative drawing. Scale bar 5 cm.

Pl. I - Orma CA2 17 dell'icnosito delle Coste dell'Anglone (Giurassico inferiore). a. Fotografia; b. immagine topografica ottenuta con il laser scanner; c. modello fotogrammetrico; d. disegno interpretativo effettuato sul terreno;e. disegno interpretativo del modello realizzato con il laser scanner; f. disegno interpretativo del modello fotogrammetrico. Scala 5 cm.

surely more objective and informative than those by traditional methods, but, even if to a minor extent, they are still dependent on the interpreters (Pl. I e, f).

Moreover, the application of these technologies allows to make further hypotheses about the relationship between tracks, gait and substrate consistency (opportunity to obtain serial profiles through a single track). As to the other methodologies, it will be possible to have a "consensus" among the different preserved tracks of a trackway, in order to achieve an idealized track and to reconstruct phalangeal pad formula. Through the 3D model it is possible to study the deformation of the tracking surface, and thus to recognize functional prevalence of the track maker foot, and consequently to gain data about tetrapod limb biomechanics. Thus, 3D models could significantly improve the traditional techniques in the effort to attribute a track to the appropriate trackmaker, possibly converting a virtual 3D model of the foot into a physical object using 3D printers (prototyping technology). Digital 3D track models could determine a significant advance within the field of scientific communication. Indeed the models can be easily shared among researches, allowing repeatibility of experiments and improving data exchange. Furthermore they provide the opportunity to make comparisons without the need to observe specimens or type materials directly *in situ* or through replicas. Consequently the creation of a virtual 3D data-base of the erected ichnotaxa, favouring and improving comparisons and consequently ichnotaxonomic attributions, is welcomed.

The benefit of these methods becomes more remarkable if we evaluate the chance to reach, enter and visualize whole 3D virtual ichnosites.

If we evaluate the cost/time ratio, it is easy to understand that laser scanners are expensive, bulky and time-consuming while high-resolution digital photogrammetry is cheap, portable and time-saving. Nevertheless, they both allow to realize comparable digital 3D models of dinosaur tracks and tracksites and to make their fruition easier possibly through virtual visits on the web or as a virtual tool in museum exhibitions. However even if the use of three-dimensional modelling in dinosaur track analysis represents an exciting and important advance, future studies must include data obtained using traditional methods.

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