Digital photogrammetry of the site

Vincent Dumas, Giulia Boetto

Digitalna fotogrametrija nalazišta

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Od 1960-ih godina potreba za vjerodostojnim nacrtima podmorskih arheoloških ostataka potaknula je razvoj metode bilježenja podataka fotogrametrijom, koja je bila prilagođena prirodi nalaza, brodskom teretu i ostacima broda u podvodnom okruženju. Početni pokušaji su se bazirali na upotrebi filma stereoskopskog fotoaparata (Dumas *et al.* 2015, 127-130).

Primjena digitalnih fotoaparata i detaljna razrada postupka za stvaranje oblaka točaka preko guste epipolarne korelacije (Hulo 2010) napravila je preokret u metodologiji arheološkog dokumentiranja, kako u kopnenom, tako i u podvodnom okruženju. Osim toga, smanjenje troškova tehnike, sve veća snaga računala i razvoj sve većeg broja komercijalnih računalnih programa ili onih nastalih u slobodnom računalnom svijetu, ovu su tehnologiju učinili pristupačnom u svakom pogledu.

U sklopu toga, od 2008. godine skupina nautičkih arheologa iz Centra Camille Jullian nastoji razviti sustavnu i lako održivu metodu dokumentiranja na osnovi primjene digitalne fotogrametrije, a koja je u skladu s

Since the 1960s the need for reliable plans of underwater archaeological remains has led to the development of photogrammetric recording methods that are capable of being used on both cargoes and hull remains in an underwater environment. Initial attempts were based on the use of stereoscopic film cameras (Dumas *et al.* 2015, 127-130).

The move to digital cameras and the elaboration of the procedures necessary to generate point clouds using dense epipolar correlation (Hulo 2010) have revolutionized methods of archaeological planning in both dry and wet conditions. Moreover, the reduction in the cost of the materials required, increased computing power, and the development of an increasing number of commercial software packages and freeware programs have rendered this technique within reach on all levels.

Within this context, from 2008 the nautical archaeology team from the Centre Camille Jullian committed to developing a coherent and easily reproducible method suited to its own research needs for producing problematikom njezina istraživanja (Dumas 2011; 2012; Dumas *et al*. 2015).

Tome u prilog iznijet ćemo različite faze dokumentiranja broda iz Zambratije.

site plans using digital photogrammetry (Dumas 2011, 2012; Dumas *et al*. 2015).

Here, we first describe the various stages of the planning process carried out on the Zambratija wreck.

Položaj nalaza

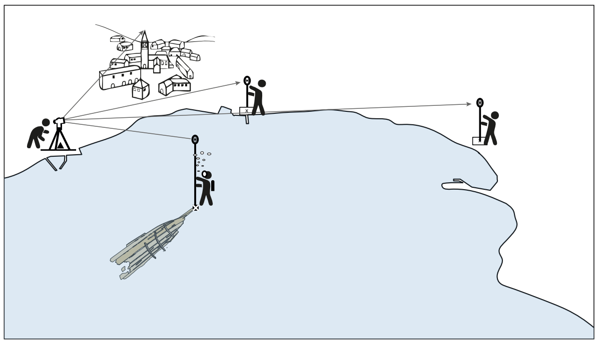
Istraživačka kampanja tijekom 2013. godine rezultirala je otkrivanjem sačuvanih dijelova strukture broda (na površini od otprilike 6,5 m²). Zahvaljujući maloj dubini nalazišta (2,2-2,5 m) te blizini obale (oko 150 m), nalazište je georeferencirano uz pomoć totalne stanice. Za izmjeru je odabran planimetrijski sustav projekcije MGI/Balkans, zona 5. Izmjera je obavljena prema tršćanskom mareografu (Dumas 2011, 121-124).

Zbog pješčanog morskog dna u koje nije bilo moguće postaviti dugotrajnije fiksne točke oko broda, odlučeno je da se one postave na brodsku konstrukciju. Ove fiksne točke mjerene su s obale korištenjem prizme koja je bila postavljena na teleskopski štap (Sl. I.60, I.61).

Site location

The 2013 excavation season uncovered all the preserved timbers (about 6.5 m²). As the site is in shallow water (2.2-2.5 m) and near to the shore (about 150 m) the position of the site could be recorded using a total station. The MGI/Balkans zone 5 projection was chosen to georeference the site. The Trieste record was referred to for heights above sea-level (Dumas 2011, 121-124).

As the sandy seafloor did not allow stable fixed points to be placed around the wreck, they were placed directly on the hull. These fixed points were measured by using a prism on an extensible pole viewed from the shore (Figs I.60, I.61).



I.60
Shematski prikaz postupka topografskog bilježenja podvodnih ostataka s obale
Diagram showing the procedure for recording the topography of the underwater archaeological remains from the shore
(crtež / drawing by: V. Dumas)

I.61
Georeferenciranje olupine Zambratija totalnom stanicom prema fiksnim točkama na obali
Georeferencing the Zambratija wreck from fixed points on land using a total station
(fotografija / photo by: Ph. Groscaux)

Priprema olupine

Prije fotogrametrijskog dokumentiranja (faza mjerenja), brodski dijelovi su detaljno očišćeni od svih preostalih elemenata (sedimenti i alge) koji bi mogli prekriti katkad slabo vidljive detalje (sljubnice platica, elementi spajanja, tragovi alata, oznake brodograditelja). Najkrhkiji elementi, kao što su jelove letvice koje su prekrivale sljubnice platica, bili su učvršćeni inoks spojkama. Tim je postupkom omogućeno zadržavanje letvica na mjestu, a ujedno

Preparing the wreck

Before starting the photogrammetric planning process (data acquisition phase), the wooden structures were carefully cleaned of all residues (sediments and seaweed) that might mask difficult-to-see details (planking joints, fasteners, tool marks, and carpenters' marks). The most fragile parts, such as the fir laths that covered the plank seams, were reinforced using stainless-steel staples. This allowed the laths to be held in place, preventing su izbjegnuti rizici od klizanja ili pomicanja uslijed različitih snimanja. Očišćeno je i područje 50 cm oko ostataka brodske konstrukcije.

Za potrebe snimanja postavljene su dvije vrste oznaka: u prvoj su svi arhitektonski elementi imali alfanumeričke oznake (Pomey, Rieth 2005, 99-102), dok se druga koristila za označavanje manje vidljivih detalja poput sljubnica platica ili elemenata spajanja.

Za prvi tip označavanja odabrane su žute plastificirane etikete s crnim tekstom (ispisane na etiketirki tipa Dymo) koje su vidljive i na 3D teksturiranim modelima[1] i na ortofotografijama. Te su oznake bile dobro pričvršćene za brodsku konstrukciju inoks čavlićima ne bi li se spriječilo njihovo pomicanje tijekom faze snimanja, što je moglo dovesti do pogrešne izmjere modela.

Elementi spajanja označeni su pribadačama različitih veličina i boja, ovisno o vrsti spoja[2]. Takvo označavanje ujedno omogućava i optimiziranje 2D ili 3D grafičkog prikaza, jasno određujući položaj i vrstu spojeva.

Privremeno mrežište

Privremeni lokalni koordinatni sustav, izrađen je postavljanjem metalne pravokutne mjerke, usmjerene prema magnetskom sjeveru uz sjeverni kraj brodske konstrukcije.

Druga pravokutna mjerka je postavljena na južnom dijelu, ne bi li se omogućila sigurnost u slučaju nedovoljnog preklapanja te kako bi se mogla provjeriti izmjera i nagib. Zatim su, horizontalno te paralelno s uzdužnom osi trupa broda, postavljene dvije fotoskale ne bi li se, s jedne strane, provjerila točnost mjerila modela, te s druge strane, kako bi to poslužilo kao mjerna referenca različitih fotomozaika generiranih iz fotogrametrijskih modela (Sl. I.62).

Ovakvo privremeno mrežište omogućilo nam je dobivanje fotogrametrijskog modela u mjerilu, usmjerenog prema magnetskom sjeveru i u odnosu na horizontalnu os.

Faza fotografske dokumentacije

Ovu je fazu obavio fotograf koji je, uzimajući u obzir svjetlosne uvjete i zamućenost, izabrao najbolje moguće uvjete vidljivosti. Sve osobe iz istraživačkog tima su prije fotografiranja napustile nalazište, da bi se izbjegao rizik od zamućenja tj. pomicanja sedimenta.

Za snimanje je korišten profesionalni digitalni fotoaparat[3] s vodootpornim kućištem s bljeskalicama

1 3D teksturirani modeli su površinski modeli isprepleteni u tri dimenzije izrađeni na osnovi digitalnih fotografija.

2 Najčešće su korištene pribadače u bijeloj i žutoj boji. Budući da se lokalitet nalazi na maloj dubini, za ovo snimanje su korištene i pribadače u crvenoj boji.

3 Fotoaparat Nikon D700, opremljen senzorom punog formata od 12 megapiksela i fiksnim žarišnim duljinama od 24 ili 20 mm.

them from slipping or moving while the photographic record was being made. A zone about 0.5 m around the wreck was also cleared.

Two series of labels and markers were used: the first tagged each element of the timber structure with an alpha-numeric code (Pomey, Rieth 2005, 99-102); the second marked difficult-to-see details, such as scarfs in the planking, or fasteners.

For the first type of labelling, plastic-coated yellow labels with black lettering (printed with a Dymo-type labelling machine) were used, which were visible on the texture-rendered 3D models[1] and on the orthophotographs. These labels were fixed to the structure with small stainless-steel nails to prevent them from moving during the data-gathering phase, which could jeopardize the correct calculation of the model.

The assembly system was marked using drawing pins and tacks of different sizes and colours for different features[2]. This also meant the accuracy of the 2D plan and 3D models could be optimized while allowing the precise position and types of fasteners to be recorded.

Temporary grid

A temporary, site-specific, coordinate system was materialized using a metal set square horizontally positioned and aligned to magnetic north, placed to one side of the wreck, near its northern limit.

A second set square was also installed to the south to guard against problems caused by insufficient overlap and to check the scale and inclination. Two photographic scales were placed horizontally and parallel to the main axis of the hull remains both to check that the model is correctly scaled and to serve as a visual metric reference on the various photo mosaics generated from the model (Fig. I.62).

This temporary grid allowed us to produce a scaled photogrammetric model, oriented to magnetic north, and with a horizontal axis.

Data acquisition phase

Data acquisition was carried out by a photographer who took account of light and turbidity to select the best possible conditions in terms of visibility. The rest of the team left the site to avoid causing disturbance (movement of items or particles).

A professional-standard digital camera[3] in a waterproof housing with flashlights on articulated arms was

1 The 3D textured models are 3D mesh surface models rendered using the appropriate digital photographs.

2 The most commonly used colours are white and yellow. As the site is shallow, we also used red.

3 A Nikon D700, equipped with a full format, 12 mega pixel sensor and 24 and 20mm fixed focal lengths.

I.62
Olupina spremna za izmjeru.
Jedna od dvije metalne pravokutne mjerke, usmjerena prema magnetskom sjeveru, i dvije fotoskale postavljene za potrebe izrade 3D modela
The wreck prepared for survey.
One of two metal set squares, oriented to magnetic north, and two photographic scales are placed around the wreck to aid calculation of the 3D model
(fotografija / photo by: Ph. Groscaux)

I.63
Fotografiranje olupine za izradu fotogrametrijskog modela
Photographic documentation of the wreck for the photogrammetry (fotografija / photo by: V. Dumas)

postavljenima na pomične zglobove (Sl. I.63). Prvo je fotograf procijenio približnu rezoluciju snimaka s obzirom na senzor aparata, udaljenost predmeta snimanja i primijenjene žarišne duljine. Taj rezultat omogućio mu je da odredi površinu dohvata kamere te tako procijeni broj potrebnih fotografija za pokrivenost područja istraživanja. Ta je procjena uzela u obzir preklapanje od 60 % pojedine fotografije.

Ukupno su obavljena dva snimanja, prije i poslije podizanja rebrenica, u cilju dopune 3D modela unutarnje oplate broda.

Dokumentiranje brodskih rebrenica

Radi izrade modela odlučeno je da se rebrenice broda u Zambratiji izvade s nalazišta, kako bi ih se bolje proučilo na kopnu. S obzirom na nedostatak vremena te složenost oblika rebrenica, nisu izrađeni crteži na plastičnoj foliji (debela plastična folija ili acetatni film) u mjerilu 1:1[4] već je primijenjena metoda fotogrametrije. Radi cjelovite

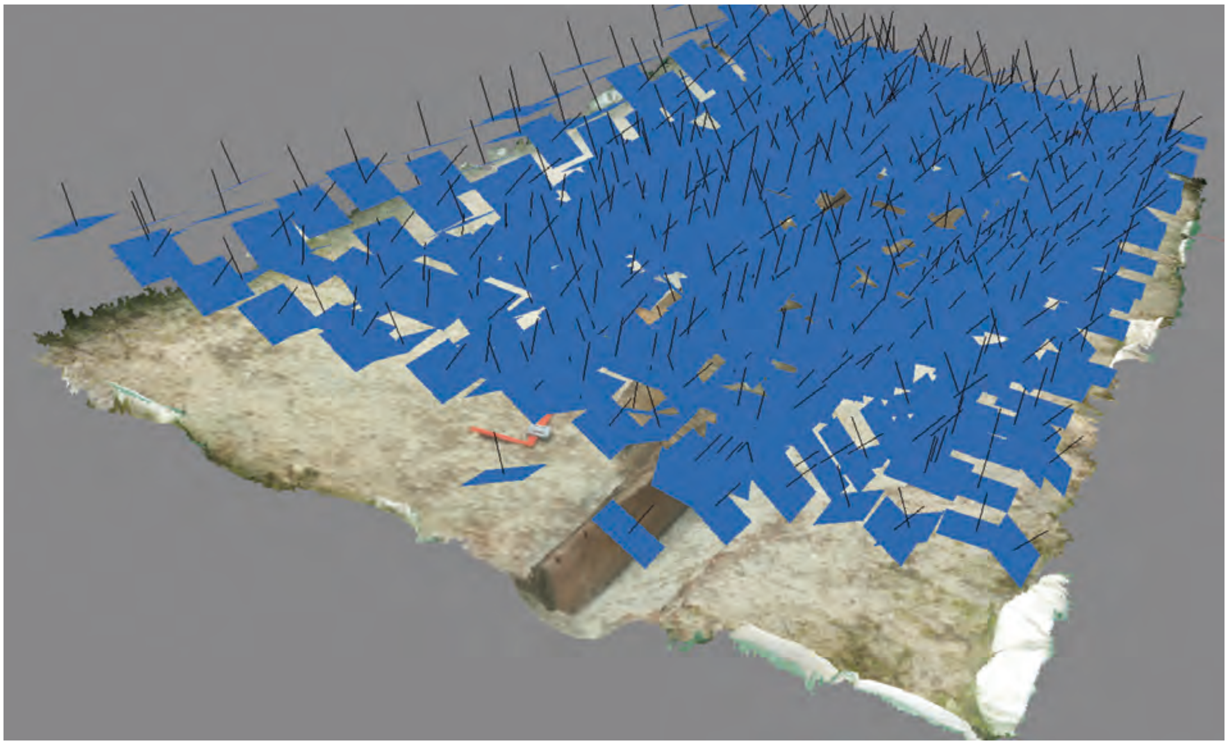
4 Sustavi mjernih ruku opremljenih mjernim ticalima koji omogućavaju 3D bilježenje kontura predmeta i njegovih karakterističnih linija vrlo su krhki i ne odgovaraju u potpunosti našim uvjetima rada (Ravn *et al.* 2011, 232-249; Kocabaş 2012, 1-15; Ranchin 2014, 58-60; Marlier *et al.* 2017). Prilikom dokumentiranja nije bila moguća upotreba prijenosnog skenera zbog nedostatnih financijskih sredstava.

chosen to take the photographs (Fig. I.63). Firstly, the photographer selected the approximate picture resolution according to the camera's sensor, the distance from the object, and the focal setting. These allowed the photographer to calculate the area covered by each image and thereby estimate the approximate number of images required to cover the zone to be recorded. This figure is calculated including a 60% overlap of each image. Finally, two complete series of photographs were taken, before and after the boat's frames were removed in order to complete the 3D model of the wreck's planking.

Recording the floor-timbers

At Zambratija we chose to raise the floor-timbers to study them on dry land. As there was little time and they had complex shapes, we chose not to trace them at 1:1 scale on transparent film (plastic or acetate)[4]. Instead, we used photogrammetry and, in order to have all faces of the timbers recorded, a minimum of two sets of data

4 Systems using measuring arms which allow a 3D record of the edges of an object are fragile and not suited to our working conditions (Ravn *et al.* 2011, 232-249; Kocabaş 2012, 1-15; Ranchin 2014, 58-60; Marlier *et al.* 2017). It was not possible to use a portable scanning device due to lack of funding.



I.64
Vizualizacija pozicioniranja snimaka upotrijebljenih za izradu 3D modela ostataka
Diagram showing the position of individual views used to build the 3D model of the wreck remains
(izrada / made by: V. Dumas, Ph. Groscaux)

izmjere dijelova rebrenice sa svih strana, bila su potrebna najmanje dva dokumentiranja za pojedinu rebrenicu. Ova dva oblaka točaka spojena su kako bi se dobio bazni teksturirani 3D model. Interpretativni crtež kasnije je obrađen u računalnom programu CAO (Rhinocéros®).

Dokumentiranje kompaktnih i cjelovitih dijelova broda iz Zambratije predstavljalo je određeni problem. Naime, slomljene rebrenice i rebrenice složenijeg oblika zadavale su poteškoće prilikom rukovanja, što je dovelo do značajnih promjena u njihovoj geometriji te posljedično i do problema prilikom slaganja 3D modela.

Modeliranje gustom epipolarnom korelacijom

Za izradu 3D modela ostataka broda iz Zambratije korišten je program Photoscan (Agisoft), koji je dobro prilagođen analizi strukture i oblika broda. Naime, taj program omogućava stvaranje georeferentnog oblaka točaka u boji i fototeksturirane mreže. Proizvod se zatim može koristiti za izradu ortofoto planova (JPEG i GeoTIFF), oblaka točaka ili 3D modela koji se mogu eksportirati u više 3D formata (PLY, OBJ, VRML, Collada, PDF).

Za izradu prvog modela napravljeno je 618 snimaka prostorne rezolucije od 0,001 m/pixel, uz fiksnu žarišnu duljinu od 20/*f*2.8 mm na visini snimanja od 1,25 metara (Sl. I.64). Gustoća dobivenih točaka je 18.259 točaka po kvadratnom metru.

Drugi je model izrađen istim uređajem uz prostornu rezoluciju od 0,0008 m/pixel. Za izradu drugog modela

were recorded. These two point clouds were then used together to build a basic textured 3D model. An interpretative drawing of the framing was made later with the help of a CAO program (Rhinoceros®).

Recording the compact and solid pieces raised from the Zambratija wreck posed a specific problem. By contrast, the fractured frames, and those with more complex shapes proved difficult: when moved to obtain information for each of their sides, their shape altered significantly, making it difficult to match up the different parts when building the 3D model.

The dense epipolar correlation model

Photoscan (Agisoft) was chosen to calculate the 3D model of the Zambratija wreck because it was well adapted to the analysis of boat structure and shape. The program allows a coloured and georeferenced point cloud and a photo-textured mesh to be created.

These can then be used to produce orthophoto plans (JPEG and Geo TIFF) as previously established, point clouds, or 3D models, which can then be exported in a variety of 3D exchange formats (PLY, OBJ, VRML, Collada, PDF).

For the first photogrammetric series, 618 pictures were taken, providing a spatial resolution of 0.001 m/pixel, with a fixed focal length of 20/f2.8 mm, taken at a distance of 1.25 m (Fig. I.64). The density of points obtained was 18,259/m^2.

The second passage was carried out with the same bilo je potrebno manje snimaka (546) jer nije bilo rebrenica. Dobivena gustoća točaka slična je prvoj: 18.986 točaka po metru kvadratnom (Sl. I.65).

set up for a spatial resolution of 0.0008 m/pixel. Fewer pictures were necessary (546) because the floor-timbers had been removed. The point density achieved was similar to that of the first series: 18,986/m^2 (Fig. I.65).

Obim 3D modela

Mrežasti 3D model (Sl. I.66) ostataka broda iz Zambratije teksturiran je korištenjem neobrađenog fotogrametrijskog modela na kojem su vidljive prethodno postavljene oznake strukturalnih karakteristika broda (Sl. I.67).

Stvaranje shematskog 3D modela broda[5] predstavlja prvi korak u postupku razumijevanja i rekonstrukcije izvornih oblika proučavanog broda (Sl. I.68). Pojedinačni dijelovi (kobilični element, rebrenice, oplata i spojni elementi) zasebno su iscrtani temeljem mrežastog modela nakon što je završena njihova zadovoljavajuće kvalitetna snimka, što nije bilo uvijek moguće za određene složenije sisteme brodskih spojeva.

Ovaj je pročišćeniji prikaz čitljiviji i predstavlja osnovu za rad i promišljanje te donosi velik broj informacija

5 Svi sačuvani dijelovi ponovno su iscrtani na osnovi glavnih linija vidljivih na mrežnom 3D modelu.

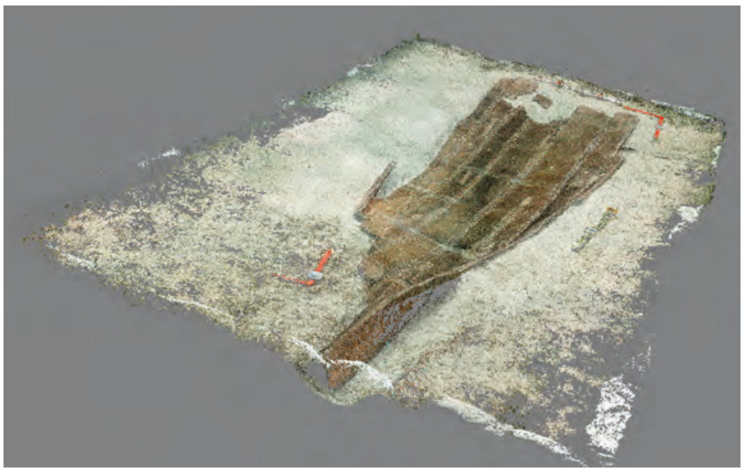
The range of 3D models

The 3D mesh model (Fig. I.66) of the Zambratija wreck was texture rendered using the raw photogrammetric model, in which the various labels used to mark the different preserved structural characteristics of the vessel are visible (Fig. I.67).

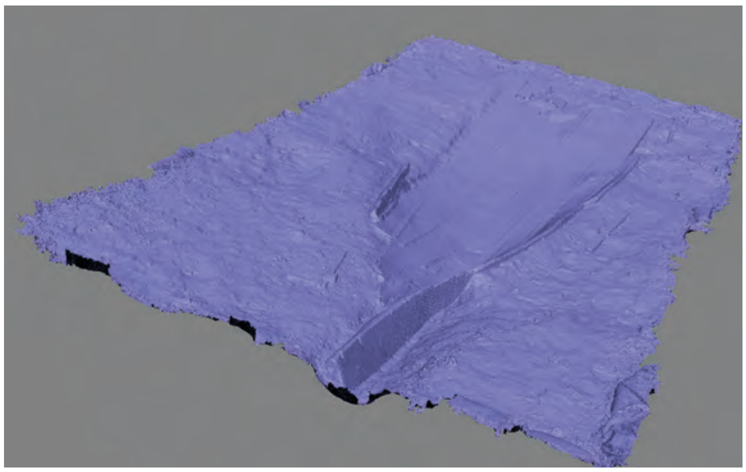
The creation of a schematic 3D model of the remains[5] is the first stage in the process of understanding and reconstructing the original shape of a boat (Fig. I.68). Each piece (keel-like timber, frames, planking, and fasteners) was redrawn separately using the mesh model once a sufficiently complete record of each element was made, which was not always possible for certain complex systems of fasteners.

This simplified representation is more easily read

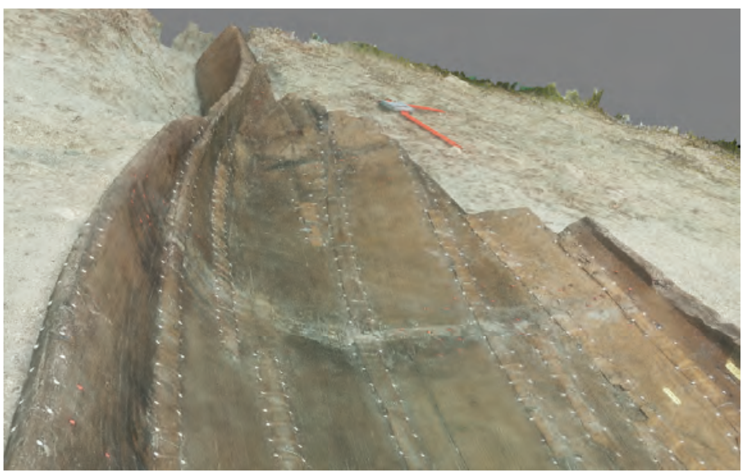
5 All of the preserved timbers were redrawn within the main lines recognized in the 3D mesh model.



I.65



I.66



I.67

I.65
3D oblak točaka
The 3D dense point cloud
(izrada / made by: V. Dumas, Ph. Groscaux)

I.66
Mrežasti 3D model
The 3D mesh model
(izrada / made by: V. Dumas, Ph. Groscaux)

I.67
Detalj mrežastog i teksturiranog 3D modela
Detail of the textured 3D mesh model
(izrada / made by: V. Dumas, Ph. Groscaux)

do kojih je prije bilo teško i naporno doći. Osnovna mjerenja (duljina, širina, debljina) mogu se obaviti mnogo preciznije i jednostavnije na ovakvom modelu nego na izvornome nalazu u moru. Obrada mjera je automatska, a mjerenja (primjerice razmak između malih drvenih čavala) se mogu primijeniti na sve vidljive elemente na modelu. Pa ipak, kako je prethodno navedeno, i dalje postoji potreba za obavljanjem brojnih zapažanja direktno na nalazištu, za vrijeme istraživanja.

Naposljetku, 3D model izrađen fotogrametrijskim snimanjem poslužio je kao temelj za izradu prve hipoteze 3D digitalne rekonstrukcije izvornih oblika broda iz Zambratije.

and represents a base for future work and reflection. It contains a great deal of information that was previously difficult and laborious to obtain. Measurements (length, width, and thickness) are much more precise and more simply taken from the model than directly from the wreck under water.

The computation of volumes is automatic and the calculation of average spacings, such as between the pegs that wedge the stitches in place, can include all the visible examples in the model. However, as has been noted, there is still need for a number of observations to be made directly from the hull during the excavation.

Finally, the 3D model built from the photogrammetric survey of the remains was the basis for the first attempt at a 3D digital reconstruction of the original shape of the Zambratija boat.

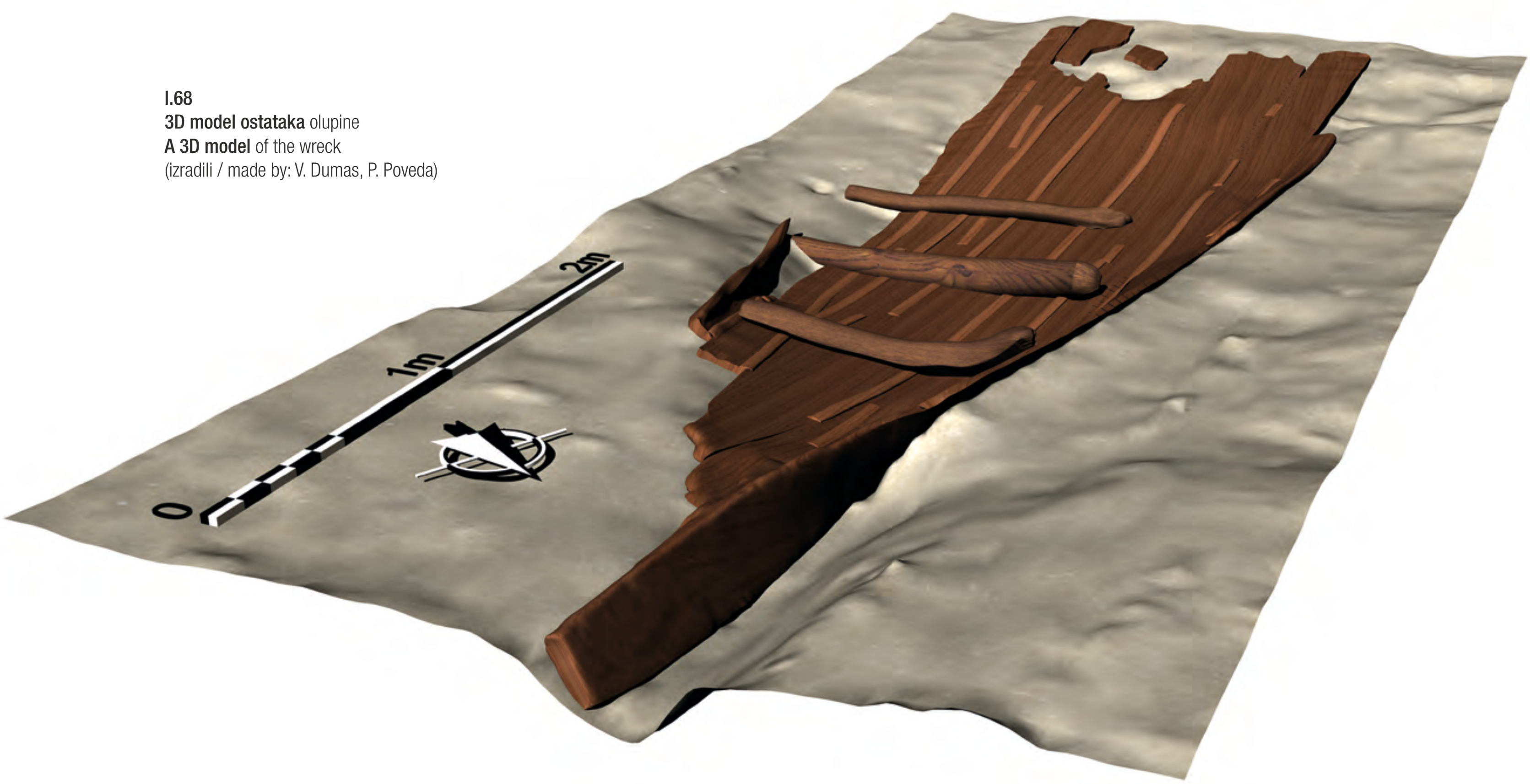
Grafička rekonstrukcija

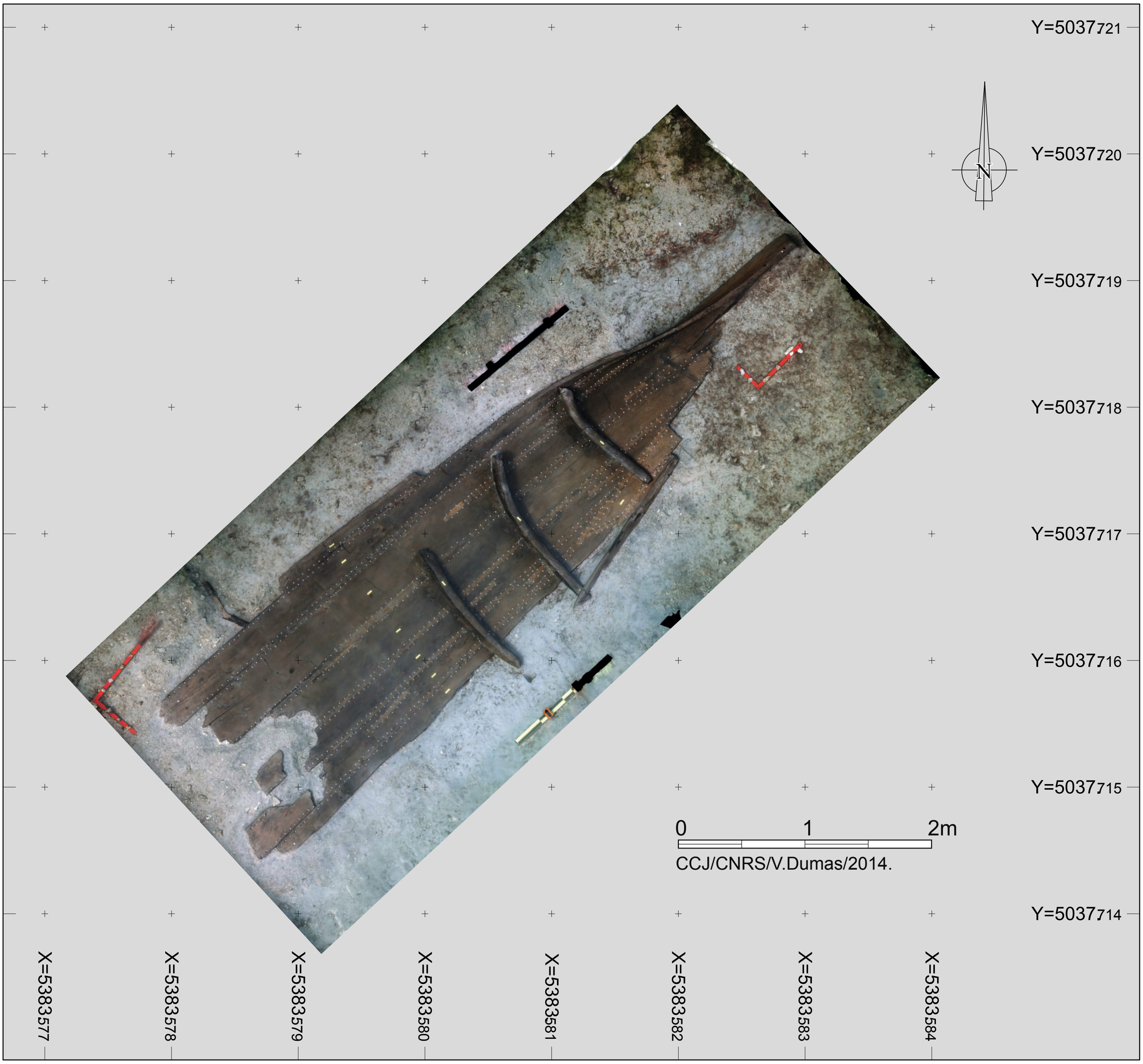
Premda trodimenzionalno modeliranje postaje nezaobilazan element u postupku proučavanja i rekonstrukcije, konvencionalni prikazi u dvije dimenzije (tlocrti, presjeci) i dalje ostaju nezaobilazni za znanstvene potrebe, kao i za primaran način ilustracije te usporedbe proučavanih olupina.

Graphical reconstruction

Although 3D models have become an inescapable stage in the analysis and reconstruction process, conventional 2D representations (plans and sections) are still the primary means of illustrating scientific reports and comparing wrecks that have been studied archaeologically.

I.68
3D model ostataka olupine
A 3D model of the wreck
(izradili / made by: V. Dumas, P. Poveda)





I.69
Ortofoto broda Zambratija
Orthophoto of the Zambratija boat
(izradili / made by: V. Dumas, Ph. Groscaux)

Za izradu tlocrta korišten je ortofoto snimak brodske konstrukcije (prostorne rezolucije 0.002m/pixel) izrađene u računalnom programu Photoscan (Sl. I.69).

Na početku je odrađen prvi dio posla u programu CAD (AutoCAD) za potrebe georeferenciranja različitih ortofotografija i automatskog slaganja više različitih podatkovnih slojeva, uz korištenje njegovih brojnih opcija za crtanje.

Radi izrade finalnog modela te dobivanja rezultata koji bi bio što sličniji crtežu crtanom rukom, snimak je zatim

For plans, an orthophoto has been used (resolution 0.002 m/pixel) for the wrecksite generated directly using Photoscan software (Fig. I.69).

An initial attempt was made using a CAD program (AutoCAD), in order to use its capability of georeferencing the various orthophotos, which allowed different layers of data to be overlaid automatically, and to benefit from its powerful drawing tools.

In order to finalize the results and obtain drawings closer to those drawn by hand, the plan was then eksportiran u program za vektorizaciju koji se temelji na upotrebi Bezierovih krivulja, poput Illustratora (Adobe).

Poprečni i uzdužni presjeci načinjeni su na osnovi trodimenzionalnog modela primjenom računalnog programa Rhinocéros®, koji može raditi i na bazi oblaka točaka i na bazi poligonalnih mreža. Ti su presjeci zatim ubačeni u Illustrator, kako bi ih se upotpunilo podacima koji su prethodno zabilježeni na skicama rađenim tijekom istraživanja.

exported to a vectorizing program based on Bezier curves, such as Illustrator (Adobe).

Transversal and longitudinal sections were created from the 3D model using Rhinocéros®, which is able to utilize both the point cloud and the polygonal mesh. These were then exported to Illustrator to be annotated with data marked on sketches made directly on site.

Zaključak

Upotreba gustog oblaka točaka za dokumentiranje i modeliranje ostataka broda iz Zambratije omogućila je izradu kvalitetne dokumentacije, s jednakom razinom preciznosti kakva bi se mogla postići na kopnenom nalazištu.

Predmetni fotogrametrijski plan bio je presudan ne samo za izradu standardizirane grafičke dokumentacije, nego i kao potpora analizi arhitekture broda. Trodimenzionalni model ostataka broda nastao iz fotogrametrije bio je osnova za rekonstrukciju izvornog oblika i strukture brodskog korita te njegovog pogona, koji zasad nema analogija na širem geografskom području.

Conclusion

In conclusion, the use of the dense point cloud for the plan and the model of the Zambratija wreck remains enabled us to produce a high-quality record with the same level of precision that could be obtained for a terrestrial structure.

The photogrammetric plan was not only fundamental in producing a standard graphic record, but also supported the structural analysis of the boat. The 3D model of the remains generated from the photogrammetric survey served as the basis of the proposed reconstruction of the shape and structure of the hull and the propulsion system of this boat that is currently without parallel.

Računalni programi:

http://logiciels.ign.fr/?-Micmac,3
http://www.123dapp.com/catch
http://www.photomodeler.com/
http://www.agisoft.ru/

Computer programs:

http://logiciels.ign.fr/?-Micmac,3
http://www.123dapp.com/catch
http://www.photomodeler.com/
http://www.agisoft.ru/