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Comparison of Valentin Hodnik's Stone Model of Triglav and the Actual Shape of the Mountain

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Abstract. In Ribčev Laz near Lake Bohinj there is a model of Triglav, the highest mountain in Slovenia. Made of stones, it is the work of the painter Valentin Hodnik from Bohinj. Although it is a work of art, we wanted to evaluate the correctness of its shape compared to the actual mountain. We photographed it and created a point cloud model using the Structure from Motion process (SfM). By transforming the point cloud to actual size, we were able to compare it with the actual shape of the Triglav mountain range obtained from Laser Scanning of Slovenia (LSS). As expected, the shape of the model varied considerably from the actual shape of the mountain, and the scale of the individual slopes and ridges was not the same. For a qualitative evaluation of the model, we calculated the distances between the transformed model and actual surface. The average absolute distance between the nearest points in both point clouds was 41.8 m (6 cm at a built-model scale) with a standard deviation of 38.0 m (5.4 cm). The results are represented by a picture of absolute distances. We also produced a smaller 3D print of the Triglav model and the actual shape of the mountain.

Keywords: Mount Triglav, Valentin Hodnik's model, 3D model, point cloud, Structure from Motion, 3D print

1 Introduction

Mount Triglav, at 2864 m, is the highest peak in the Julian Alps and in Slovenia. It is particularly prominent and a popular challenge for mountaineers. It has a symbolic significance for Slovenes. Despite its modest height compared to other Alpine peaks, it appeals to the worldwide mountaineering fraternity thanks to its high, magnificent northern face, the remains of a glacier below the peak, valleys with lakes, and recognizable shape. It has also given its name to the only national park in Slovenia, which covers the wider area of the Julian Alps. One of the main entry points to Triglav National Park is Lake Bohinj, the largest permanent natural lake in Slovenia. A stone model of Triglav with its surrounding peaks and huts can be found on its south-eastern shore (Fig. 1).

The model of Mount Triglav and the surrounding area (Fig. 2 left) is about two metres high and 6 metres wide. It is the work of Valentin Hodnik (1896-1935), an artist from Bohinj who studied at the Academy of Fine Arts in Zagreb, Croatia. The Bohinj mountains were one of his favourite painting themes. His depictions of the mountains, some realistic, some humorous, are still found on postcards (Sivec 2006). The Triglav stone model Hodnik created between 1931 and 1932 is a unique work of art. According to the information panel next to the model, he used three tonnes of stones strengthened with cement. In addition to the main peak with the nearby ridges and faces, he also made metal models of the mountain huts around Triglav (*Triglavski dom na Kredarici, Dom Planika* and *Dom Valentina Staniča*). The model imitates the shape of the mountain, but it was presumably based on the painter's subjective perception, without taking any actual measurements. To confirm this, a comparison of the shape of the model and the actual shape of the mountain (Fig. 2 right) was carried out by the Faculty of Civil and Geodetic Engineering of the University of Ljubljana (Petrovič et al. 2018).

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Usporedba kamene makete Triglava Valentina Hodnika i stvarnog oblika planine

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Sažetak. U Ribčevom Lazu kraj Bohinjskog jezera nalazi se maketa Triglava, najviše planine Slovenije, izgrađena od kamena, rad slikara Valentina Hodnika iz Bohinja. Iako je umjetničko djelo, odlučili smo procijeniti točnost njezinog oblika. U tu smo svrhu snimili maketu fotografskim aparatom i korištenjem procesa struktura iz kretanja (SfM) stvorili oblak točaka. Pretvarajući taj oblak točaka u stvarnu veličinu planine, uspoređivali smo oblik makete sa stvarnim oblikom planinarskog područja Triglava dobivenim iz podataka laserskog skeniranja Slovenije (LSS). Kao što se očekivalo, oblik makete značajno odstupa od stvarnog oblika planine, a ni mjerilo pojedinih padina i grebena nije isto. Za kvalitativnu procjenu makete izračunali smo udaljenosti između najbližih točaka transformiranog modela makete i stvarne površine. Prosječna udaljenost između najbližih točaka oba modela je 41,8 m (6 cm u mjerilu makete) sa standardnom devijacijom od 38,0 m (5,4 cm). Rezultati su prikazani s pomoću slike apsolutnih udaljenosti. Osim toga, izradili smo i umanjen 3D otisak makete Triglava i stvarnog oblika planine.

Ključne riječi: Triglav planina, maketa Valentina Hodnika, 3D model, oblak točaka, SfM fotogrametrija, 3D tisak

1. Uvod

Triglav (2864 m), najviši vrh Julijskih Alpa i najviši vrh Slovenije, već je zbog svog prvenstva posebno istaknut i poželjan cilj. Za Slovence ima značaj nacionalnog simbola. Usprkos svojoj skromnoj visini u usporedbi s ostalim vrhovima Alpa, Triglav je zbog visokog i obuhvatnog sjevernog lica, ostataka ledenjaka ispod vrha, dolina s jezerima i prepoznatljivog oblika poznat i u svjetskim planinskim krugovima. Po njemu je nazvan i jedini nacionalni park u Sloveniji koji obuhvaća šire područje Julijskih Alpa. Jedno od središta i ulaznih točaka u Triglavski nacionalni park je najveće stalno prirodno jezero u Sloveniji - Bohinjsko jezero. Uz njegovu jugoistočnu obalu (slika 1) stoji od kamena zidana maketa Triglava s okolnim vrhovima i planinarskim kućama.

Oko 2 m visoka i 6 m široka maketa Triglava s užom okolinom (slika 2 lijevo) rad je slikara Valentina Hodnika iz Bohinja (1896. – 1935.) koji se, među ostalim, obrazovao i na likovnoj akademiji u Zagrebu. Njegovi najznačajniji slikarski motivi bile su bohinjske planine. Njegove crteže i slike planina, kako realne tako i one šaljive, još je i danas moguće zapaziti na razglednicama (Sivec, 2006). Maketu Triglava slikar Hodnik izradio je u 1931. i 1932. godini i ona predstavlja unikatno umjetničko djelo. U nju je ugradio tri tone kamena (podatak s informacijske ploče kod makete Triglava), a učvrstio ga je cementom. Osim glavnog vrha, obližnjih grebena i lica slikar je napravio i metalne makete planinskih kuća oko Triglava (Triglavski dom na Kredarici, Dom Planika i Dom Valentina Staniča). Maketa imitira izgled planine (slika 2 desno), ali možemo pretpostaviti da je bila izrađena uglavnom na osnovu slikareve percepcije oblika, bez ikakvih mjerenja ili mjerne usporedbe s veličinom i oblikom Triglava i okoliša. Za potvrdu te pretpostavke na Fakultetu građevinarstva i geodezije Sveučilišta u Ljubljani izveli smo usporedbu oblika makete sa stvarnim oblikom planine (Petrovič i dr. 2018).

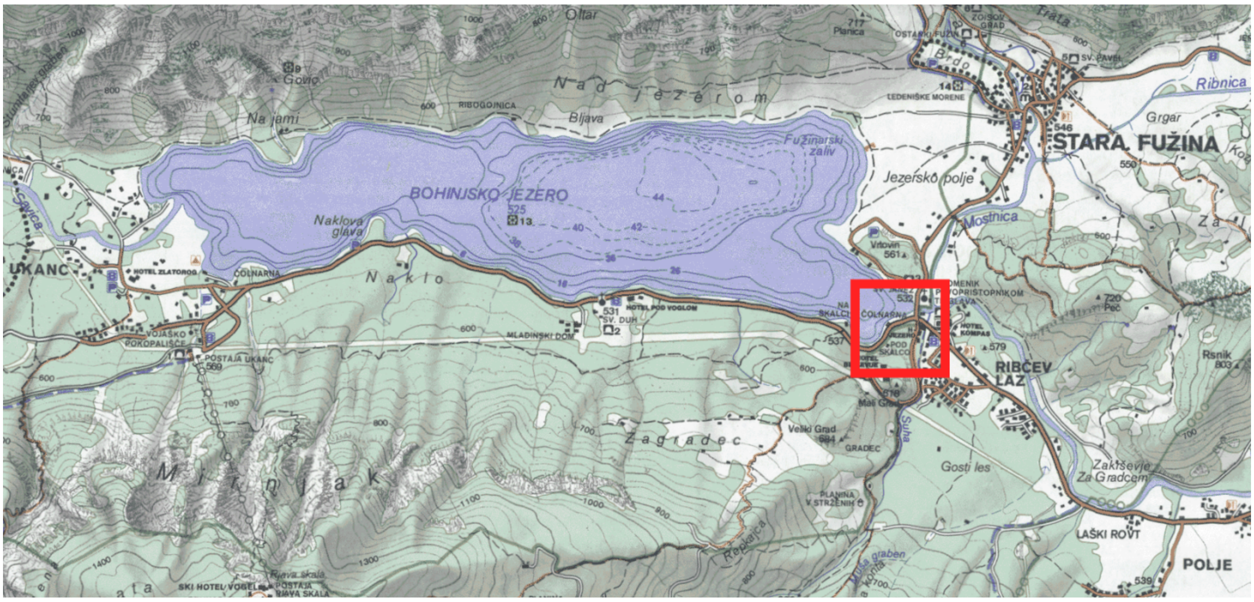

Fig. 1 Location of the stone model of Triglav by Lake Bohinj (excerpt from Mountain Map Bohinj, Geodetic Institute of Slovenia, published by the Alpine Association of Slovenia, 2006).

Slika 1. Položaj makete Triglava uz obalu Bohinjskog jezera (isječak iz planinarske karte Bohinj, Geodetski institut Slovenije, izdavač Planinarski savez Slovenije, 2006).

2 Methodology

In order to compare the shape of the stone model with the actual shape of the mountain, we needed appropriate, comparable digital 3D models of both. Using geodetic measurements to acquire the true dimensions of the stone model, followed by photogrammetric measurements and terrestrial laser scanning technology, the point clouds of the stone model were created. The ground point cloud (OTR) of the actual Triglav mountain range was obtained from the publicly available data of the Laser Scanning of Slovenia project (LSS), carried out in 2014 (Triglav Čekada and Bric 2015).

2.1 Geodetic measurement of the network and reference points

The stone model is naturally much smaller than Mount Triglav. As a basic step, we carefully planned and implemented the geodetic measurement of the reference point coordinates to determine the exact dimensions of the stone model. The measurements were made using a modern Leica Nova MS50 tacheometer and precision prisms, and processed using Leica Infinity software. We allocated seven geodetic network points around the model, labelled from 100 to 700. Nine additional reference points, from 1 to 9 (Fig. 3 right) were marked on the stone model. Network point 100 was defined as the origin of the local coordinate system, where the x-axis was oriented towards the north.

The reference points were distributed to ensure the best possible results of photogrammetric measurement and laser scanning. We marked them with black and white circles with a diameter of 2 cm (Fig. 3 right above). From all network points, observations in three repetitions in both circular positions were done towards the other visible network and reference points. The red lines in Figure 3 (right) show two-sided and yellow one-sided measurements. The accuracy of horizontal direction measurements was 0.40 mgon, of zenith distance, 0.11 mgon, and of incline lengths, 0.07 mm. The coordinates were calculated separately, with horizontal and vertical adjustment in GEM4 and VimWin software tools. The average three-dimensional position accuracy of the reference points after adjustment was 0.4 mm.

2.2 Terrestrial laser scanning of the stone model

The established points of the geodetic network (points 100 - 600) were also used as stands for the terrestrial laser scanning (TLS) of the stone model. We used the same instrument, the Leica Nova MS50, which allows scanning speeds of up to 1000 Hz at a recording distance of up to 50 m (Fig. 4). The intended target scanning density at the maximum distance between the standpoint and model was 4 mm. The result obtained in the Leica Infinity software package was unified and integrated a cloud of scanned points from all six stands.

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Fig. 2 Stone model of Mount Triglav, and view of the real Mount Triglav (photos by Dušan Petrovič).
Slika 2. Maketa Triglava i pogled na stvarni vrh Triglava (fotografije Dušan Petrovič).

Fig. 3 Stone model of Mount Triglav at the time of survey (by Anita Anželak); marker for reference points; geodetic network around the model.
Slika 3. Maketa Triglava za vrijeme izmjere (fotografija Anita Anželak); signalizacija referentnih točaka; geodetska mreža izmjere točaka.

2. Metodologija

Za usporedbu oblika makete sa stvarnim oblikom planine trebaju nam usporedivi digitalni 3D modeli oba oblika. Za izradu modela zidane makete smo, osim klasične geodetske izmjere koja je omogućila određivanje stvarnih dimenzija kamenog modela, koristili i tehnologiju terestričkog laserskog skeniranja i fotogrametrijsku izmjeru. Obje su metode rezultirale oblakom točaka makete. Oblak točaka reljefa (OTR) stvarnog područja Triglava dobili smo iz javno dostupnih podataka Laserskog skeniranja Slovenije iz 2014. godine (Triglav Čekada i Bric 2015).

2.1. Geodetska izmjera referentnih točaka

Maketa je u usporedbi s pravim oblikom Triglavskoga planinskog lanca, naravno, puno manja pa smo zbog toga najprije pažljivo planirali i izveli geodetsku izmjeru koordinata referentnih točaka kojima smo odredili dimenzije makete. Izmjeru smo izveli suvremenim tahimetrom Leica Nova MS50 i preciznim prizmama, a rezultate mjerenja obradili u softveru Leica Infinity. U izmjeru je bilo uključeno sedam oko makete raspoređenih točaka geodetske mreže s oznakama od 100 do 700 i devet referentnih točaka na maketi označenih od 1 do 9 (slika 3). Kao početnu točku lokalnog koordinatnoga sustava koristili smo točku 100, a početni smo smjer x-osi približno usmjerili prema sjeveru.

Referentne točke po maketi smo rasporedili na način da omogućuju što bolje rezultate fotogrametrijske izmjere i terestričkog laserskog skeniranja. Za signalizaciju smo koristili crno-bijele kružne mete promjera 2 cm (slika 3 gore). Iz svih smo točaka geodetske mreže prema preostalim vidljivim točkama geodetske mreže i oslonim točkama mjerili u tri ponavljanja u oba kružna

Fig. 4 Terrestrial laser scanning of the stone model with the Leica Nova MS50 instrument (by Anita Anželak - left and Dušan Petrovič - right).
Slika 4. Terestričko lasersko skeniranje makete instrumentom Leica Nova MS50 (fotografije Anita Anželak – lijevo i Dušan Petrovič – desno).

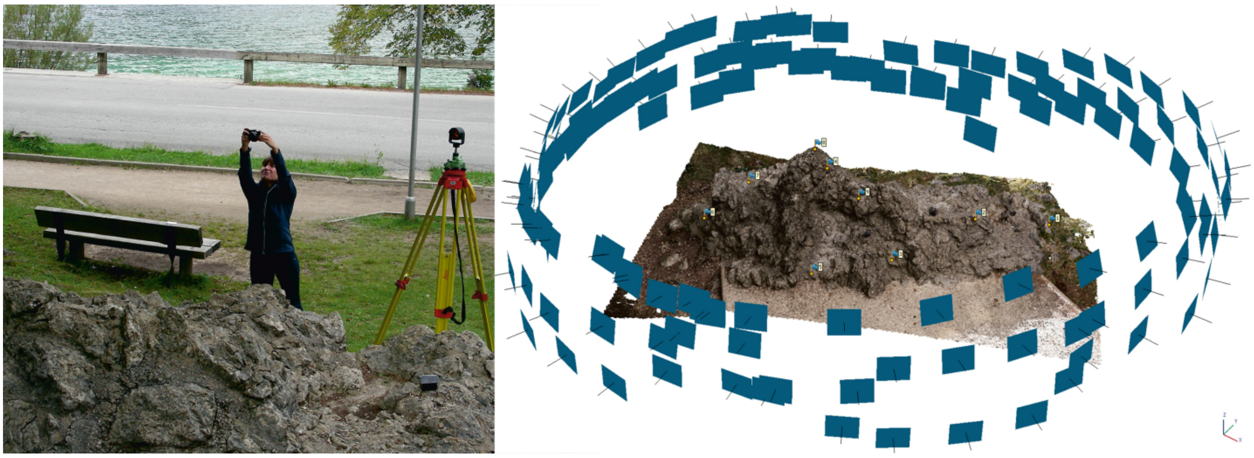


Fig. 5 Photographing the model; point cloud with reference points and space distribution of photos taken around the model.
Slika 5. Fotografiranje modela, oblak točaka s referentnim točkama i raspored snimljenih fotografija oko makete.

2.3 Photographing and photogrammetric modelling

The model was then photographed using a compact Olympus E-PL7 photo camera with a constant focal length of 17 mm (Fig. 5 left). Besides the size of the model, the following requirements were taken into consideration: final spatial resolution of the photos of at least 1 mm, the convergence of the recorded photos, at least 80% overlap for adjacent photos, and the visibility of at least three reference points on each photo taken. Altogether, 125 photos were taken (Fig. 5 right) every ten degrees (0.7-0.9 m) at a distance of 4 to 5 m from the stone model at three heights (squatting - about 0.5 m, standing - about 1.5 m, and from up a ladder - about 2.5 m)

Thus, the photos covered the whole stone model evenly. They were processed in PhotoScan software using a process known in computer vision as 'Structure from Motion' (SfM). By identifying a large number of identical points in photos, it is possible to simultaneously determine the geometric parameters of the camera (internal orientation) and the relative position of the camera in space (relative orientation) to calculate '3D structures' (Westoby and others 2012). At the same time, a low density point cloud was created, which in our case contained 68,000 points (Fig. 6 left).

By measuring the reference points in the photos, their external orientation was calculated in the spatial coordinate system, thus ensuring the right scale for all subsequent products. Careful photography and SfM processing provide accurate measurement data comparable to other modern measurement methods (for example TLS). In our example, the accuracy of the measurements in the photos was estimated at 0.3 pixels, and the deviation at the reference points was 0.4 mm.

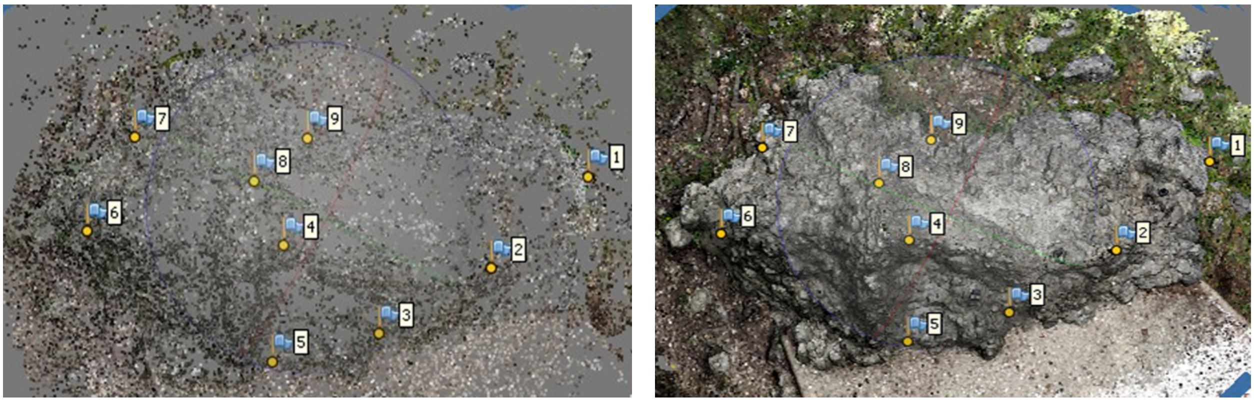


Fig. 6 Low density (68,000 points) and high density point cloud (96 million points), both with positions of reference points.

Slika 6. Rijedak (68 000 točaka) i gust oblak točaka (96 000 000 točaka), oba s lokacijama oslonih točaka.

položaja. Crvene linije na slici 3 prikazuju mjerenja iz obaju smjerova, a žute jednostrana mjerenja. Horizontalne smo pravce mjerili s točnošću 0,40 mgona, zenitne udaljenosti s točnošću 0,11 mgona, a kose dužine točnošću 0,07 mm. Koordinate točaka u 3D prostoru određene su odvojeno. Mreža je prvo definirana kao horizontalna slobodna mreža a onda kao slobodna visinska mreža. Za izjednačenje su upotrijebljeni programi GEM4 i VimWin. Poprečna vrijednost točnosti položaja referentnih točaka nakon izjednačenja iznosi 0,4 mm.

2.2. Terestričko lasersko skeniranje makete

Uspostavljene točke geodetske mreže (točke 100 – 600) istovremeno smo koristili kao stajališta za terestričko lasersko skeniranje (TLS) makete. Snimanje smo izvršili istim instrumentom - Leica Nova MS50 koji omogućava brzine skeniranja do 1000 Hz kod udaljenosti snimanja do 50 m (slika 4). Predviđena ciljna gustoća skeniranja kod najveće udaljenosti stajališta od makete bila je 4 mm. Dobiveni je rezultat programskog rješenja Leica Infinity uspostavljen i sastavljen je oblak točaka skeniranja sa svih šest stajališta.

2.3. Fotografiranje i fotogrametrijska obrada

Maketu smo zatim fotografirali kompaktnim fotoaparatom *Olympus E-PL7* s fiksnom duljinom fokusa 17 mm (slika 5). Kod planiranja snimanja, pored dimenzije makete, u obzir smo uzeli i dodatne zahtjeve: konačnu prostornu rezoluciju fotografija najmanje 1 mm, konvergentnost snimljenih fotografija, najmanje 80% preklapanja fotografija i vidljivost najmanje triju referentnih točaka na svakoj snimljenoj fotografiji. Tako smo na udaljenosti 4 - 5 m od makete na svakih 10° (0,7 - 0,9 m) snimili 125 fotografija (slika 5 desno), raspoređenih u tri visinska pojasa (fotografiranje iz čučnja na visini oko 0,5 m, stojeći na visini oko 1,5 m i s ljestava na visini oko 2,5 m).

Tako smo fotografijama jednakomjerno pokrili cijelu maketu. Fotografije smo obradili programom PhotoScan s pomoću postupka koji je u računalnom vidu poznat kao „struktura iz kretanja“ i označuje se skraćenicom SfM (engleski *Structure from Motion*). Na osnovu prepoznavanja velikog broja identičnih točaka na fotografijama je omogućeno istovremeno određivanje geometrijskih parametra fotoaparata (unutrašnja orijentacija), položaja fotoaparata u prostoru (vanjska orijentacija) i izračun '3D-struktura' (Westoby i drugi 2012). Istovremeno je kreiran i rijedak oblak točaka koji se u našem primjeru sastojao iz 68 000 točaka (slika 6 lijevo).

Mjerenjem referentnih točaka na fotografijama vanjsku smo orijentaciju izračunali u prostornom koordinatnom sustavu i time svim daljnjim proizvodima osigurali pravu veličinu. Oprezno izvršenje fotogrametrijskih mjerenja i obrada fotografija sa SfM omogućava točne podatke mjerenja usporedive s ostalim suvremenim metodama (poput laserskog skeniranja). U svom smo primjeru točnost izmjere na fotografijama procijenili na 0,3 piksela, a odstupanje na referetnim točkama na 0,4 mm. Čak i u slučajevima kada smo neku od referentnih točaka koristili kao kontrolnu točku, njena odstupanja jedva prelaze 0,4 mm. S prostornim presjecima slikovnih zraka identičnih točaka izračunali smo gusti oblak točaka makete koji se sastojao iz 96 000 000 točaka. U gustom oblaku svaka točka ima svoje prostorne koordinate i vrijednost boje (slika 6 desno).

Tako smo korištenjem dviju tehnologija prikupili dva oblaka točaka makete – jedan dobiven iz TLS, a drugi

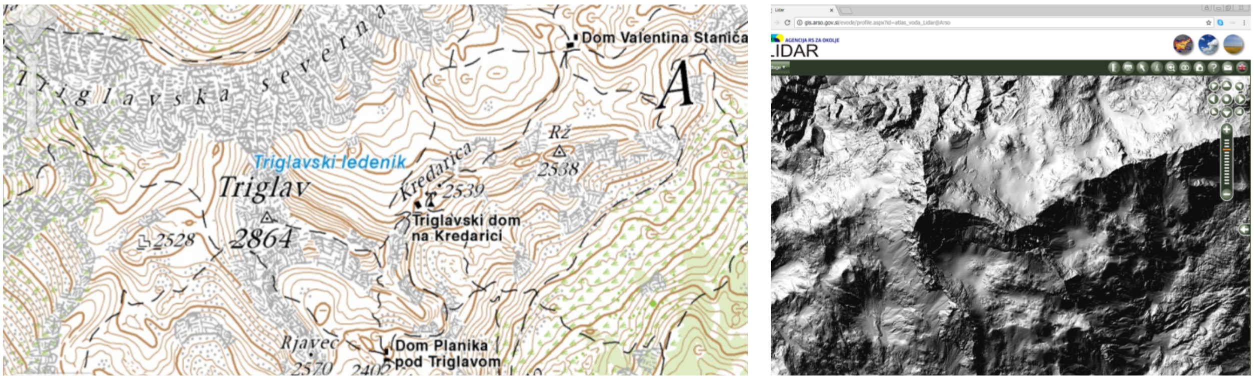


Fig. 7 Area under consideration on topographic map DTK 50 (Surveying and Mapping Authority of the Republic of Slovenia) and the shaded relief of the area based on LSS data (Environmental Agency of the Republic of Slovenia).
Slika 7. Područje rada na topografskoj karti DTK 25 (Geodetska uprava Republike Slovenije) i sjenčani prikaz reljefa područja izrađen na osnovu podataka LSS (Agencija Republike Slovenije za okoliš).

Even when a reference point was used as a control point, deviations barely exceeded 0.4 mm. With spatial cross-sections of image beams of identical points, the high density point cloud of the stone model with 96 million points was calculated. Each point in the high density point cloud had spatial coordinates and a colour value (Fig. 6 right).

Using two technologies, we acquired two point clouds of the stone model, one from TLS and the other from the photo processing. We analysed their similarity and suitability for further processing. Although both were based on the same geodetic network points and the point clouds were oriented with the same reference points, the clouds differed both geometrically and radiometrically. Some differences were based on the technology and method of establishment: the point cloud from the TLS was not coloured, which made interpretation difficult and due to the smaller number of stands (6 compared to 125) some overhangs, edges and others points hidden from TLS stands were not registered. The adjustment also showed inferior position accuracy due to an apparent shift in the position of one of the stands during TLS measurements. Therefore, we used a photogrammetric point cloud for further comparison with the actual shape of the mountain.

2.4 Data on the actual shape of the mountain

For the actual shape of the corresponding Triglav region, we used airborne laser scanning data from the Laser Scanning of Slovenia (LSS) project completed between 2011 and 2015. The main purpose of the project, which was carried out under the auspices of the Ministry of the Environment and Spatial Planning of the Republic of Slovenia, was to provide relevant height data on the hydrography network and land use (Triglav Čekada and Bric 2015). Aerial laser scanning was done by dividing the territory of Slovenia into 19 blocks, where the resolution of recording in each block depended on the morphology and population density of the area. The Julian Alps highlands area was scanned in 2014 with a resolution of 2 points/m2. The LSS resulted in a variety of products: a ground points cloud (OTR), a georeferenced point cloud with ellipsoid altitudes (GOT) and a georeferenced and classified point cloud with orthometric heights (GKOT) - all three in LAS format; a digital relief model with 1 m grid resolution (DMR1) in ASCII format, and an image of analytical hill-shading in TIF format. Most of these data are freely available on the web portal of the Environmental Agency of the Republic of Slovenia (Lidar E-vode 2015). Figure 7 shows the area under consideration on the topographic map and the analytical hill-shading of the relief based on LSS data.

2.5 Comparison of point cloud of stone-built models with LSS data

Based on the distances between the manually identified points from the point cloud of the stone model (peaks, positions of mountain huts) and corresponding actual distances, we calculated the average approximate scale of the stone model point cloud as 1:700. Open-source CloudCompare software was used to process and compare the point clouds. Before comparing the photogrammetric point cloud of the stone model and LSS data, both point clouds needed to be aligned. From the available LSS data, we used ground point cloud data (OTR) which consisted of points classified as ground points only. The OTR was filtered with an octree 1 m in size and reduced to 1 pt/m3.

We also provided a comparable density of the photogrammetric point cloud of the stone model. Initially, iz obrade fotografija. Analizirali smo njihovu sličnost i povoljnost za daljnju obradu. Iako su oba bila uspostavljena na osnovi istih točaka geodetske mreže i oblaci točaka su orijentirani s pomoću istih referentnih točaka, oblaci su se razlikovali geometrijski i radiometrijski. Neke se razlike temelje na tehnologiji i načinu uspostavljanja. U oblaku točaka uspostavljenom iz TLS točke nisu obojene što opterećuje interpretaciju, a zbog manjeg broja stajališta (6 u usporedbi s 125) lošije su modelirane pojedine prevlake, rubovi i druge sa stajališta TLS zakrivljene plohe. Rezultat izjednačavanja ukazao je i na lošiju položajnu točnost zbog očitog pomaka jednog od stajališta u vremenu izvođenja TLS izmjere. Zbog toga smo u daljnjoj usporedbi koristili oblak točaka uspostavljen obradom fotografija.

2.4. Podaci stvarnog oblika planina

Za stvarni oblik Triglavskog planinskog područja koje je obuhvaćeno maketom preuzeli smo podatke aerolaserskog skeniranja prikupljene u projektu Laserskog skeniranja Slovenije (LSS). Projekt Laserskog skeniranja Slovenije (LSS) proveden je između 2011. i 2015. godine. Glavna namjena projekta, kojim je rukovodilo Ministarstvo za okoliš i prostor Republike Slovenije, bila je osigurati relevantne podatke na području hidrografije i stvarne upotrebe prostora (Triglav Čekada, 2015). Kod laserskog skeniranja tehnologijom LiDAR područje Slovenije bilo je podijeljeno na blokove, a gustoća skeniranja u svakom bloku ovisila je o morfologiji i naseljenosti područja. Tako je područje visokih planina Julijskih Alpa skenirano 2014. g. s gustoćom od 2 točke po m2. Rezultat LSS su različiti proizvodi: oblak točaka reljefa (OTR), georeferenciran oblak točaka s elipsoidnim visinama (GOT), georeferenciran i klasificiran oblak točaka s nadmorskim visinama (GKOT) – sva tri u formatu LAS; digitalni model reljefa s ćelijom veličine 1 m (DMR1) u formatu ASCII i slike analitičkog sjenčanja (PAS) u formatu TIF. Veći dio navedenih podataka slobodno je dostupan na web portalu Agencije Republike Slovenije za okoliš (Internet 1). Slika 7 prikazuje područje makete na topografskoj karti i sjenčani prikaz reljefa područja izrađen na osnovu podataka LSS.

2.5. Usporedba oblaka točaka makete s podacima LSS-a

Na osnovu dužina među prepoznatim točkama na maketi (vrhovi, pozicije planinarskih kuća) i njihove usporedbe s dužinama u prirodi izračunali smo prosječno približno mjerilo oblaka točaka makete 1 : 700. Usporedba oba oblaka točaka izvršena je u programu otvorenog kôda CloudCompare, no najprije je trebalo pripremiti usporedive podatke. Od podataka LSS uzeli smo OTR koji se sastoji iz točaka LSS prepoznatih kao točke tla. OTR smo filtrirali filtrom oktree 1 m (*Octree*). Na taj smo način iz OTR napravili oblak točaka gustoće 1 točka/m3.

Usporedivu gustoću točaka pripremili smo i iz fotogrametrijskog oblaka točaka makete. Iz izrađenog oblaka točaka prvo smo uklonili sve točke koje nisu točke tla. To su bile nerazmjerno velike makete planinskih kuća (*Triglavski dom na Kredarici, Dom Planika i Dom Valentina Staniča*) te Aljaževog tornja. Oblak točaka nadalje smo filtrirali s oktree 1,43 mm (1000 mm/700). Napravili smo još translaciju oblaka točaka stvarnog oblika iz državnog koordinatnog sustava u lokalni koordinatni sustav oblaka točaka makete (-409000, -137000, -1000). Da bismo omogućili daljnje prepoznavanje obaju oblaka točaka, u oblaku točaka makete zadržali smo prirodne boje makete dok smo oblak točaka stvarnog oblika planine obojili prema vrijednostima refleksije laserskog zraka pomoću bijelo-plavo-crvene skale boja.

Prije usporedbe obaju oblaka točaka trebali smo ih i lokalno transformirati. Na oblaku točaka makete ručno smo prepoznali 5 točaka koje je program poravnao s identičnim točkama na oblaku točaka stvarnog oblika. Slika 8 prikazuje situacije prije i poslije transformacije - točke R0 do R4 su odabrane točke na modelu stvarnog oblika, a točke A0 do A4 odgovarajuće su točke na modelu makete.

Zbog velike količine podataka, a posebice zbog dosta nehomogenih odstupanja između oblika makete i stvarne planine, na rubovima makete ocjenu uklapanja oblika oblaka točaka napravili smo odvojeno na dvama područjima. U prvom smo se bavili užim opsegom makete oko vrhova Triglav i Mali Triglav (slika 9 lijevo), a u drugom cjelokupnim područjem zidane makete (slika 9 desno).

U tablicama na slici 10 prikazana su standardna odstupanja (RMS) na identičnim točkama (stub „Error") za uže (dolje) i cjelokupno područje (gore),a koja pokazuju procjenu kvalitete kod izjednačenja oblaka.

Dodatno poravnavanje oblaka točaka napravili smo s pomoću postupka ICP (*Iterative Closest Point*) tako da su kvadrati udaljenosti između prepoznatih identičnih točaka u oba oblaka minimalni (Besl in McKay, 1992). S postupkom ICP oblak točaka zidane makete transformirali smo u stvarnu površinu Triglavskog područja. Konačni rezultat finog poravnavanja na užem i na cijelom području prikazan je na slici 11. Za uže područje korijen srednje kvadratne greške (RMS) na identičnim točkama iznosi 16,60 m, a za cijelu područje 32,55 m.

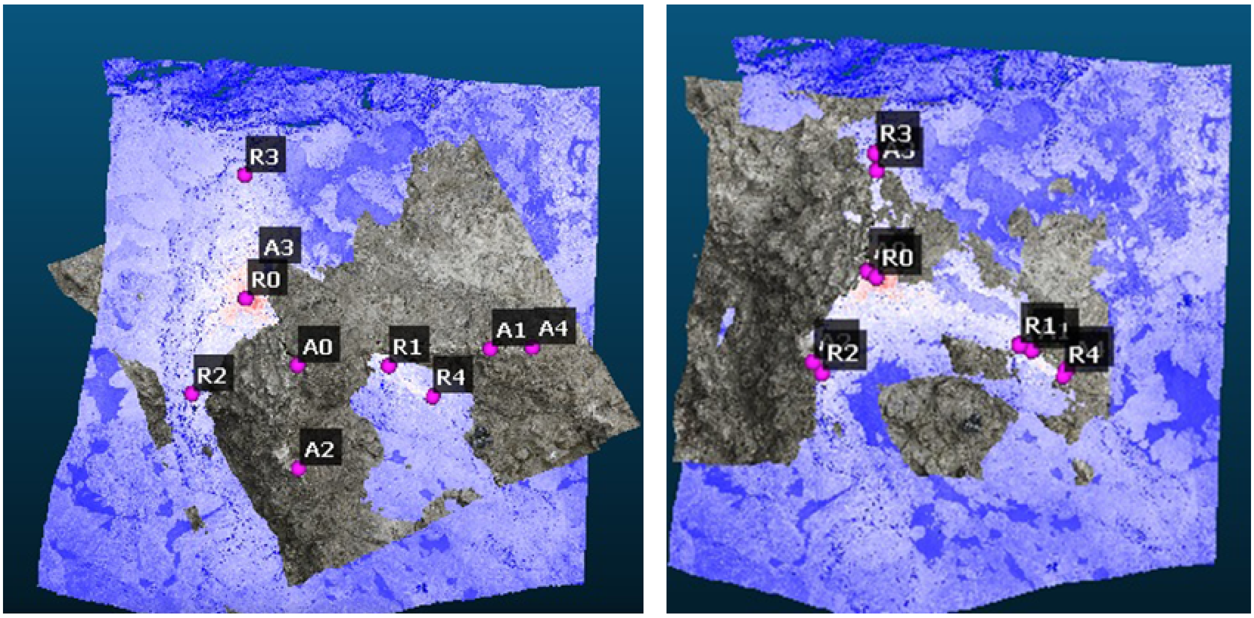


Fig. 8 Transformation of the photogrammetric point cloud of the model (natural colours) into the actual mountain shape point cloud (artificial colours).

Slika 8. Transformacija fotogrametrijskog oblaka točaka (prirodne boje) u lidarski oblak točaka stvarnog oblika (umjetne boje).

we eliminated all non-ground points: the disproportionately large models of mountain huts (*Triglavski dom na Kredarici, Dom Planika* and *Dom Valentina Staniča*) and Aljaž Tower at the top of Triglav. The ground point cloud of the stone model was adequately filtered with an octree 1.43 mm in size (1000 mm /700). We also translated the point cloud of the actual shape from the national coordinate system into the local coordinate system of the stone model point cloud using vectors (-409000, -137000, -1000). To enable further recognition of both point clouds, we kept the real, natural coloured points in the stone model point cloud, while the point cloud of the actual shape were coloured according to laser beam reflection values using a white-blue-red colour scale.

Before comparing the shapes, alignment of the point clouds was performed. We manually identified five points on the stone model point cloud which the programme aligned with identical points on the actual shape point cloud. Figure 8 represents the initial stage and the result of the transformation. R0 to R4 are selected points on the actual mountain point cloud, while A0 to A4 are corresponding points on the stone model point cloud.

Due to the large amount of data and huge non-homogeneous deviations between the shape of the stone model and the real mountain at the edges of the model, further comparison was performed separately for two areas. In the first, only the central area of the model in the vicinity of Triglav and Mali Triglav peaks was used (Fig. 9 left), while in the second, the entire area of the stone model was included (Fig. 9 right).

Tables in Figure 10 show standard deviations at identical points (column 'Error') for the central part (below) and the whole area (above), which represent the estimated quality of cloud alignment.

Additional alignment of the point clouds was carried out using the ICP (Iterative Closest Point) procedure, which allows alignment of point clouds so that the squares of the distances between identifiable points in both clouds are minimal (Besl and McKay 1992). With ICP, the stone model point cloud was transformed into the actual surface of the Triglav mountain range. The final result of fine alignment for the central area and the whole area is shown in Fig. 11. RMS at identical points was 16.60 m for the central area and 32.55 m for the whole area.

3 Results of the comparison of the stone model and the actual shape of the mountain

The correctness of the stone model compared to the actual shape of the mountain was determined by absolute distances between the point clouds in CloudCompare software. We used the default software settings, which computed the distance between two point clouds as 'nearest neighbour distance' (CloudCompare 2018); for each point of the compared cloud (in our case, a photogrammetric point cloud), CloudCompare searched the nearest point in the reference point cloud

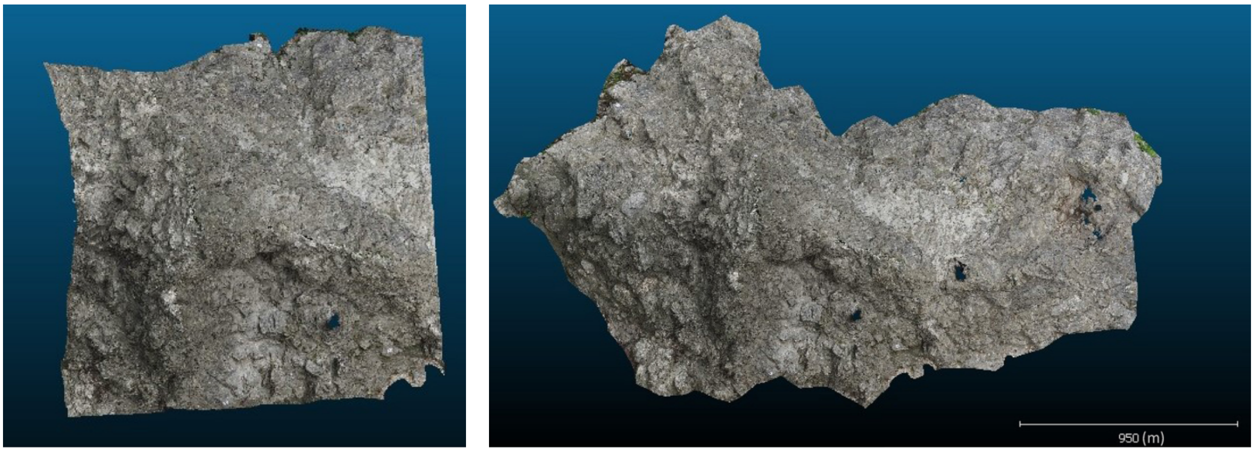


Fig. 9 The central area and the entire area.

Slika 9. Uže i cjelokupno područje.

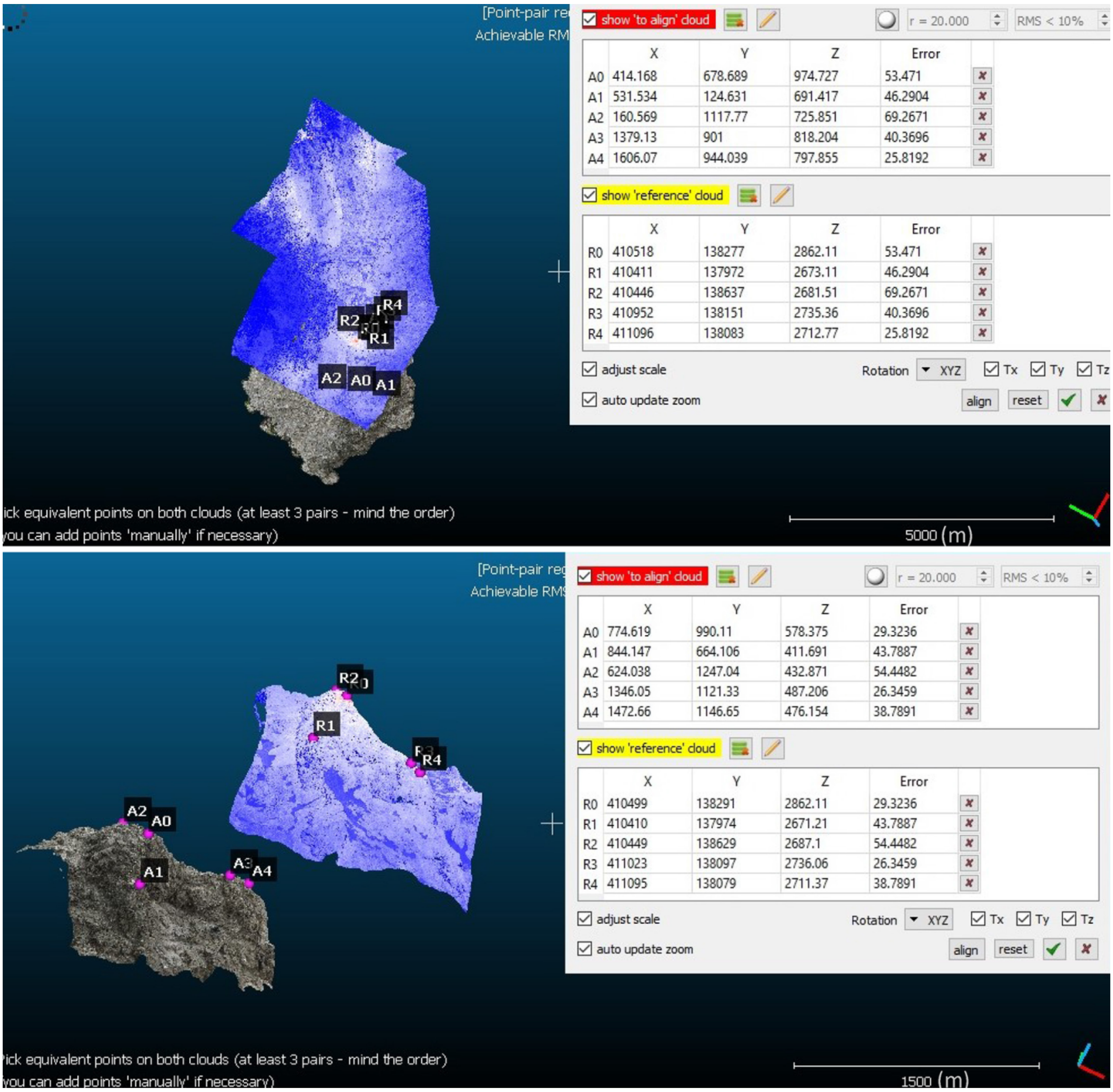


Fig. 10 RMS on identical points after alignment, entire area above, central area below.

Slika 10. RMS na identičnim točkama poslije transformacije, cijelo područje gore, uže dolje.

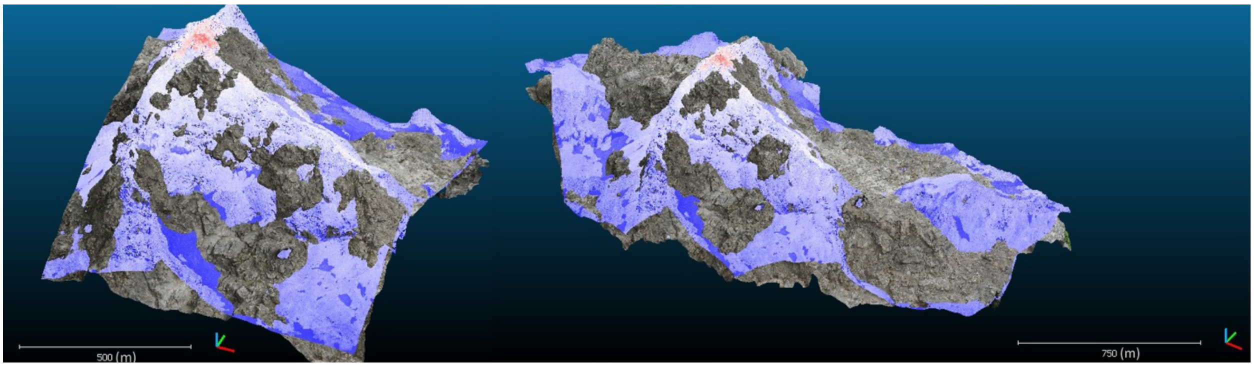


Fig. 11 Comparison of the transformed stone model point cloud (natural colour) and the actual mountain point cloud (artificial colour), for the central area and entire area.

Slika 11. Usporedba transformiranog fotogrametričkog oblaka točaka makete (prirodne boje) i oblaka točaka stvarnog oblika planina (umjetne boje) za uže i cijelo područje.

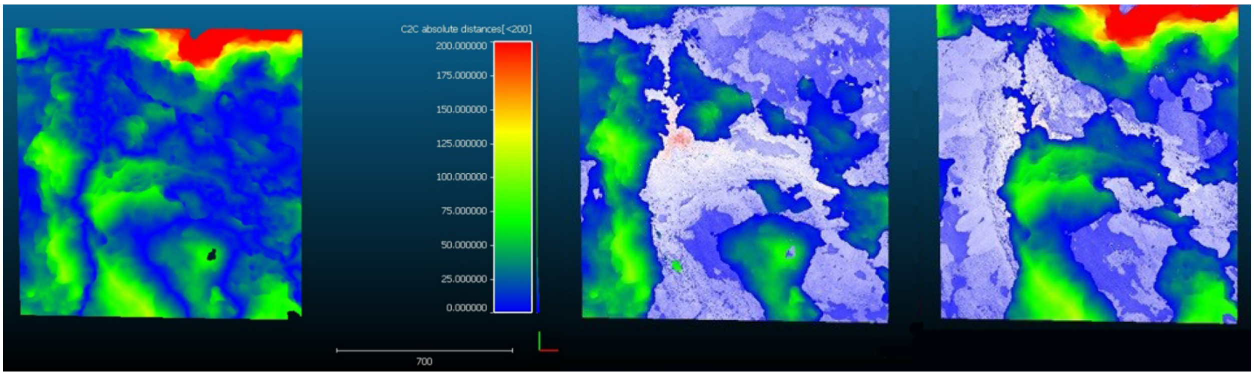


Fig. 12 Central area, without ICP: absolute distances, deviation of the stone model higher than the actual mountain, deviation of the stone model lower than the actual mountain.

Slika 12. Uže područje, bez ICP: apsolutna udaljenost, odstupanje makete iznad stvarne planine, odstupanje makete ispod stvarne planine.

(OTR in our case) and computed the (Euclidean) distance. The results are presented separately for the central area and for the entire stone model, with and without the use of ICP additional matching method. Absolute distances are represented by the blue-green-red colour scale with which the stone model point cloud was coloured. Note that at the model scale of approximately 1: 700, 100 m in real life represents 14.3 cm on the stone model.

For the central area without the use of ICP, the calculated mean absolute distance between the point clouds was 45 m (6.4 cm). Figure 12 shows the minimum absolute distances on the ridges, where they reached up to 25 m. On the slopes, they increased up to 125 m. A greater discrepancy between the stone model and the actual mountain was observed on the southern side of the ridge which runs south from Triglav. The greatest absolute distances, over 200 m, appear on the edges (especially the northern one). The western, some central and partly south-eastern slopes in the model were higher than the actual mountain, while other areas, including those with the greatest absolute distances, were lower than the actual mountain shape.

The mean absolute distance between the point clouds on the same (central) area with the additional use of ICP was reduced to 28 m (4 cm) with a standard deviation of 36.2 m (5 cm). In Figure 13 we can see that the discrepancy in the central part is significantly smaller, and the areas where the model is lower or higher than the real shape are more dispersed. At the northen edge, the model is still more than 200 m lower, while at the southern edge, the absolute distances from the actual mountain are even larger, comparing the results without ICP.

For the entire stone model range the average absolute distance between the point clouds was 67 m (10 cm). Figure 14 shows the best fits in the area around Triglav, the *Planika pod Triglavom* hut and all the way to Kredarica Peak, where the distances were up to 40 m, and occasionally up to 100 m. To the east of the *Triglav* hut at Kredarica, the distances increased to 180 m. In the area around *Valentin Stanič* hut beneath Triglav, the

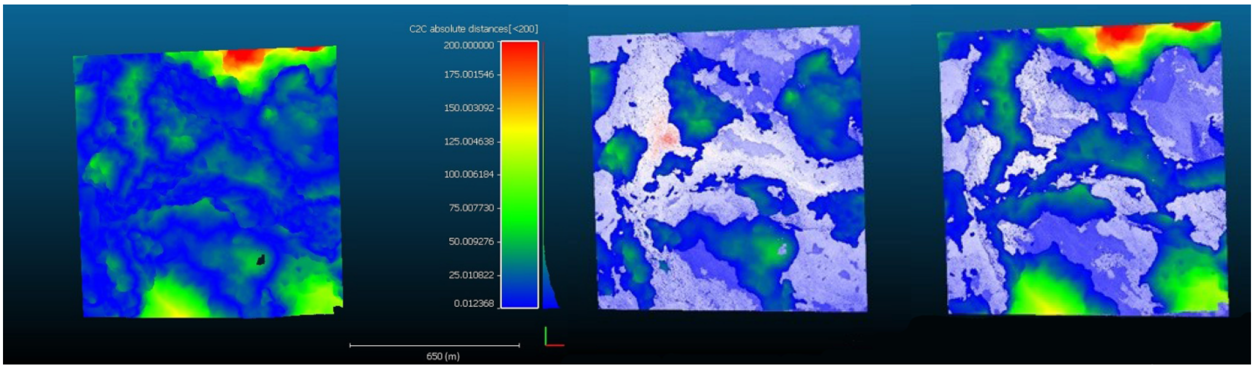


Fig. 13 Central area, using the ICP: absolute distances, deviation of the stone-built model above the actual mountain, deviation of the stone-built model below the actual mountain.

Slika 13. Uže područje, s ICP: apsolutna udaljenost, odstupanje makete iznad stvarne planine, odstupanje makete ispod stvarne planine).

3. Rezultati usporedbe makete i stvarnog oblika planine

Ocjena pravilnosti oblika kamene makete u odnosu na stvarni oblik planine određena je apsolutnim udaljenostima između točaka oba oblaka točaka upotrebom programa CloudCompare. Koristili smo zadane parametre programa koji su izračunali udaljenost između dvaju točaka kao 'najbliže susjedne udaljenosti' (CloudCompare 2018). Za svaku je točku promatranog oblaka (u našem slučaju oblak s fotogrametrijskim točkama) CloudCompare pretražio najbližu točku u oblaku referentne točke (OTR u našem slučaju) i izračunao (Euklidsku) udaljenost. Rezultati su dani posebno za uže i za cijelo područje, bez i sa dodatnim poravnavanjem oblaka točaka s ICP. Apsolutne udaljenosti prikazane su plavo-zeleno-crvenom skalom boja kojima je obojen oblak točaka kamene makete. Za lakše predstavljanje rezultata apsolutnih udaljenosti napominjemo da, s obzirom na približno mjerilo makete 1 : 700, daljina od 100 m u prirodi iznosi 14,3 mm na maketi.

Za uže područje bez korištenja ICP poprečna apsolutna udaljenost između identičnih točaka iznosi 45 m (6,4 cm). Na slici 12 vidi se kako su najmanje udaljenosti na grebenima do 25 m. Na padinama udaljenosti porastu do 125 m. Veća rastojanja između makete i stvarne planine zapažamo na južnoj strani grebena koji se proteže od Triglava prema jugu. Najveće udaljenosti, čak do 200 m, izračunane su na rubovima (najviše sjeverni rub) kamene makete. Na zapadnim, ponegdje središnjim i djelomice jugoistočnim padinama maketa je viša od stvarne planine, dok je na drugim dijelovima, uključujući one s najvećim odstojanjima, maketa niža od stvarne planine.

Srednja apsolutna udaljenost između oblaka točaka za isto (uže) područje s dodatnim korištenjem ICP smanjena je na 28 m (4 cm) sa standardnom devijacijom 36,2 m (5 cm). Na slici 13 vidi se da su odstojanja između oba oblaka točaka u središnjem dijelu značajno manja, a da su područja na kojima je maketa niža ili viša od stvarne planine više porazdijeljena. Na sjevernom je rubu model makete još uvijek niži za preko 200 m, dok su na južnom rubu, usporedivši s rezultatima bez ICP, apsolutne udaljenosti od stvarnog oblika planine čak i veće.

Za područje cijele kamene makete poprečna apsolutna udaljenost između identičnih točaka iznosi 67 m (10 cm). Slika 14 prikazuje najbolja uklapanja oko Triglava, Planinarskog doma Planika i u pravcu do vrha Kredarica, gdje su udaljenosti do 40 m, a samo ponegdje i do 100 m. Istočno od Triglavskog doma na Kredarici udaljenosti se povećaju do 180 m. Na dijelu oko Doma Valentina Staniča iznose oko 110 m. Na južnom i istočnom rubu kamene makete udaljenosti su od 30 do 120 m, a na zapadnom rubu između 100 m i 260 m. Na sjevernom rubu udaljenosti rastu od 100 do preko 300 m. U središnjem dijelu područja kamena maketa viša je od stvarne planine, dok je vječiti zapadni i cijeli sjeveroistočni dio makete niži od stvarne planine.

Dodatnim korištenjem ICP metode za cijelo područje poprečna je apsolutna udaljenost između oblaka točaka smanjena na 41,8 m (6 cm) standardnom devijacijom 38,0 m (5,4 cm) kako prikazuje slika 15. Središnji dio dobro se poklopio, a područja koja leže iznad ili ispod stvarnog oblika opet su porazdijeljena po cijeloj površini. Maketa je uočljivo viša od stvarne planine na sjevernom dijelu (zapadni dio Triglavske sjeverne stijene) i na jugoistoku (vrh Kredarica). Svi su glavni grebeni i veći dio rubnih područja niži od stvarne planine.

Predstavimo još usporedbu izračunanih apsolutnih udaljenosti na užem području (gore) i na cijelom području, obje s dodatnim uspoređivanjem s ICP. Na slici 16. vidi se da se javljaju odstupanja između modela na istim

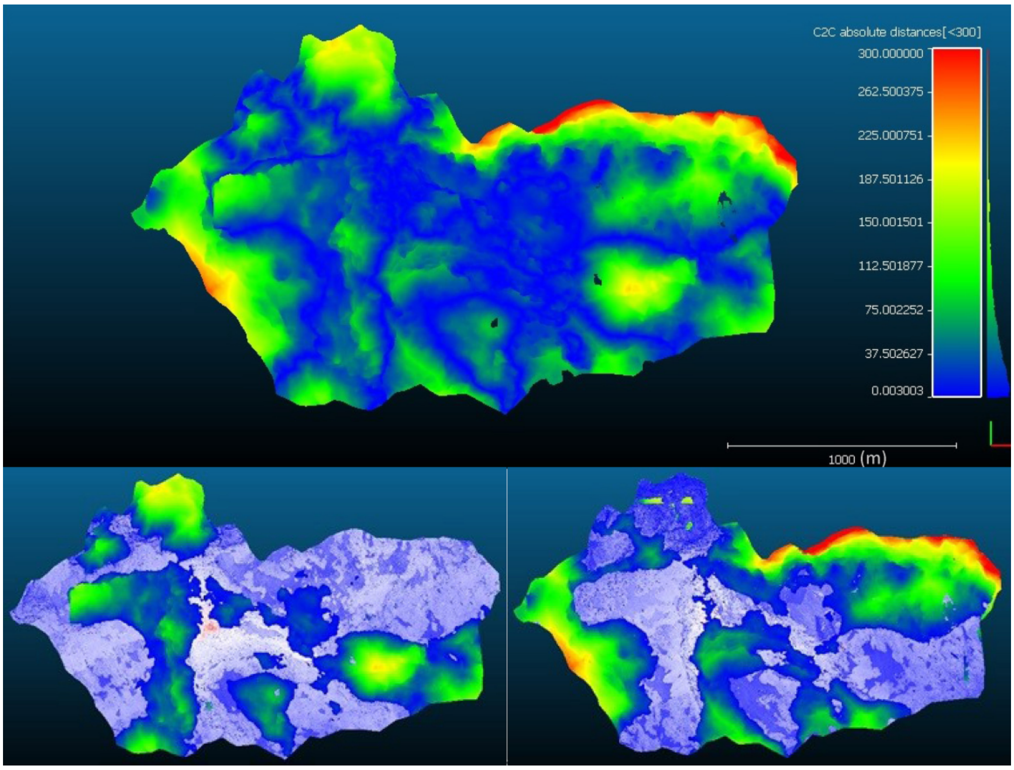


Fig. 14 Entire area, without ICP: absolute distances, deviation of the stone-built model above the actual mountain, deviation of the stone-built model below the actual mountain.
Slika 14. Cijelo područje, bez ICP: apsolutna udaljenost, odstupanje makete iznad stvarne planine, odstupanje makete ispod stvarne planine.

distance was about 110 m. On the southern and eastern edges of the stone model, the distances ranged from 30 to 120 m. On the western edge, the distances were between 100 and 260 m. At the northern edge of the region, the distances between point clouds rose rapidly, ranging from 100 to more than 300 m. In the central part of the area, the stone model was higher than the actual mountain, while the main Triglav ridge, most of the western and entire north-eastern parts of the model were lower than the actual mountain.

When we also used the ICP method, the mean absolute distance between the point clouds were again reduced to 41.8 m (6 cm) with a standard deviation of 38.0 m (5.4 cm) as shown in Figure 15. The central areas fitted well, while the areas higher and lower than the actual shape were again dispersed. The model was significantly higher at the northernmost part (the western part of Triglav's north face) and in the south-east part (Kredarica Peak). All the major mountain ridges and most of edge areas were lower than the mountain's real shape.

A comparison of calculated absolute distances in the central area only (above) and in the entire area (both aligned with the additional use of ICP) is presented in Figure 16. There are noticeable divergences between point clouds, mostly in the same areas, while the deviation values for the central area are smaller.

The results of comparing the stone model point cloud and actual mountain point cloud show that Valentin Hodnik captured the actual shape of Triglav and its surroundings fairly well. The average deviation is less than 50 m compared with real shape, which is only 7.1 cm in the model. The differences are more distinct along the ridges; they are generally lower on the model and less sharp than the actual ones, but this may be due to a physical damage to the model caused by the weather or visitors climbing on it. The differences are least in the area between *Kredarica* hut and the summit of Triglav, which is the central, most interesting part of the model to many visitors. As the distance from Triglav Peak increases, deviations increase. This is especially obvious at the edges of the stone model, where the deviations exceed 200 m. We assume that the author had to adapt the model to the ground configuration of the site. Perhaps he needed to finish the edges smoothly to avoid crumbling.

We also discovered that mountain huts on the stone model were only roughly located, while their actual positions are rather different. We realised this while calculating the approximate model scale, when noticed very different relations between the mountain huts and Aljaž Tower. Figure 17 shows the actual positions of the mountain huts and Aljaž Tower and their positions on stone model.

4 3D printing of shapes

In order to enable visual comparison and evaluation, we produced 3D prints of both shapes. Of course, we

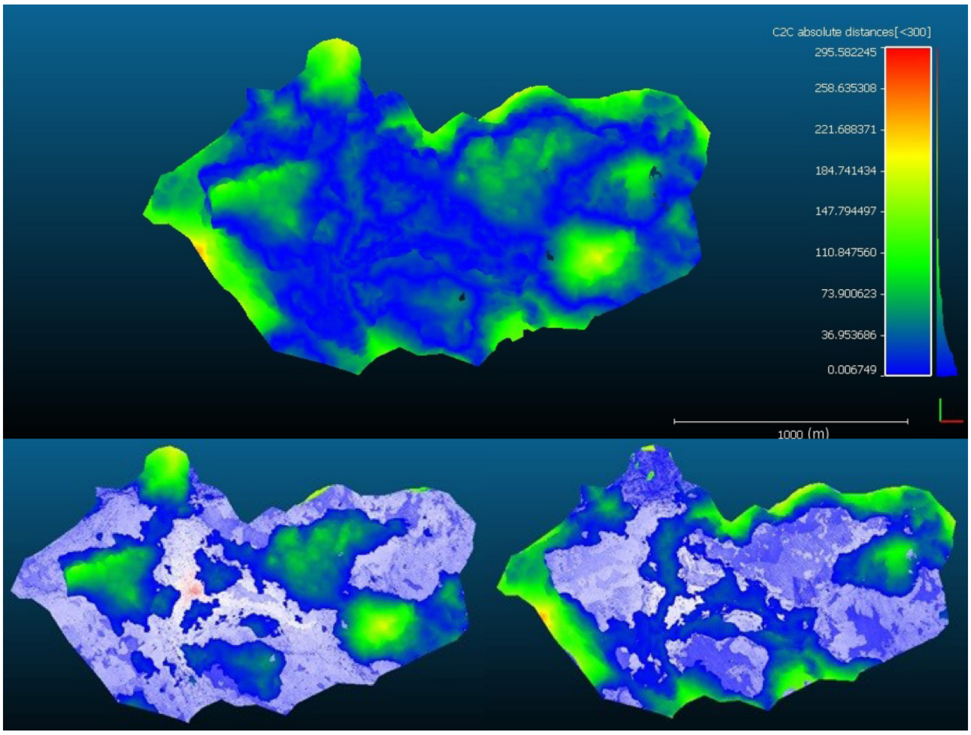


Fig. 15 Whole area using ICP: absolute distances, deviation of the stone model higher than the actual mountain, deviation of the stone model lower than the actual mountain.

Slika 15. Cijelo područje, s ICP: apsolutna udaljenost, odstupanje makete iznad stvarne planine, odstupanje makete ispod stvarne planine.

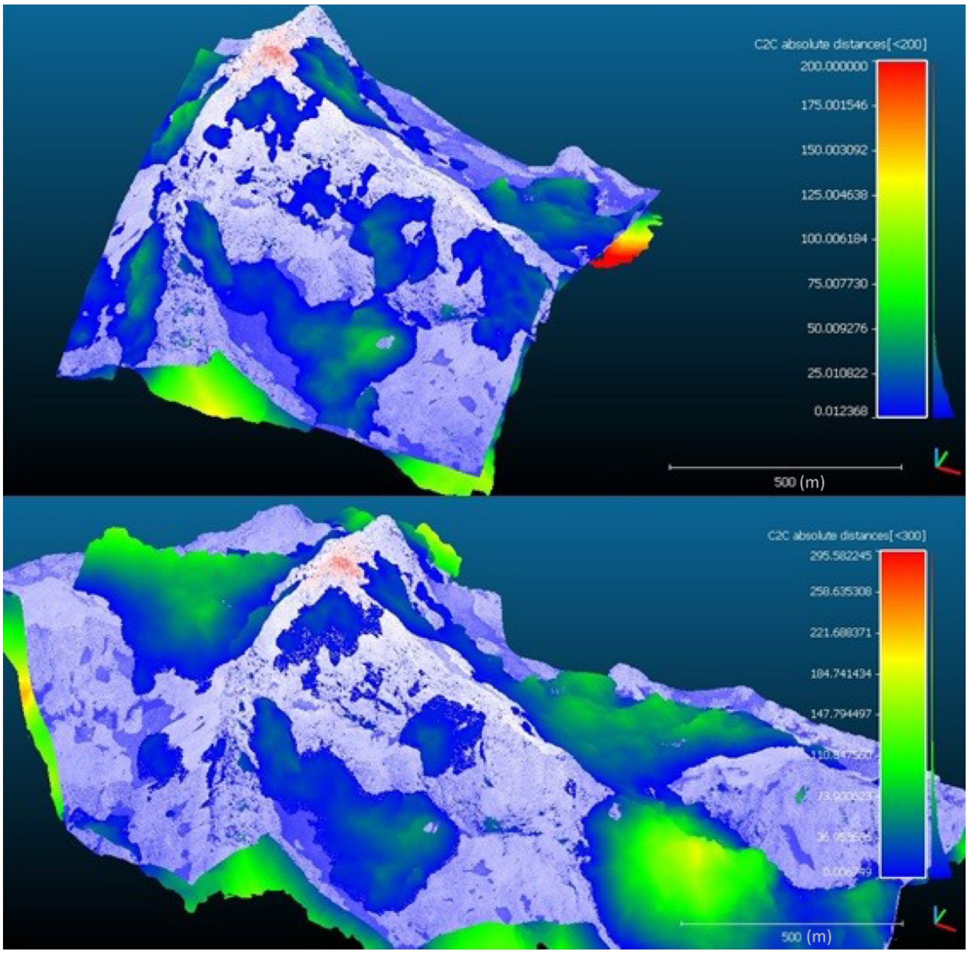


Fig. 16 Deviations between the point clouds of the stone model and the actual mountain calculated for the central and entire area, both using the ICP method.

Slika 16. Odstupanja između oblaka točaka kamene makete i stvarnog oblika planine za uže i cijelo područje, oboje s upotrebom metode ICP.

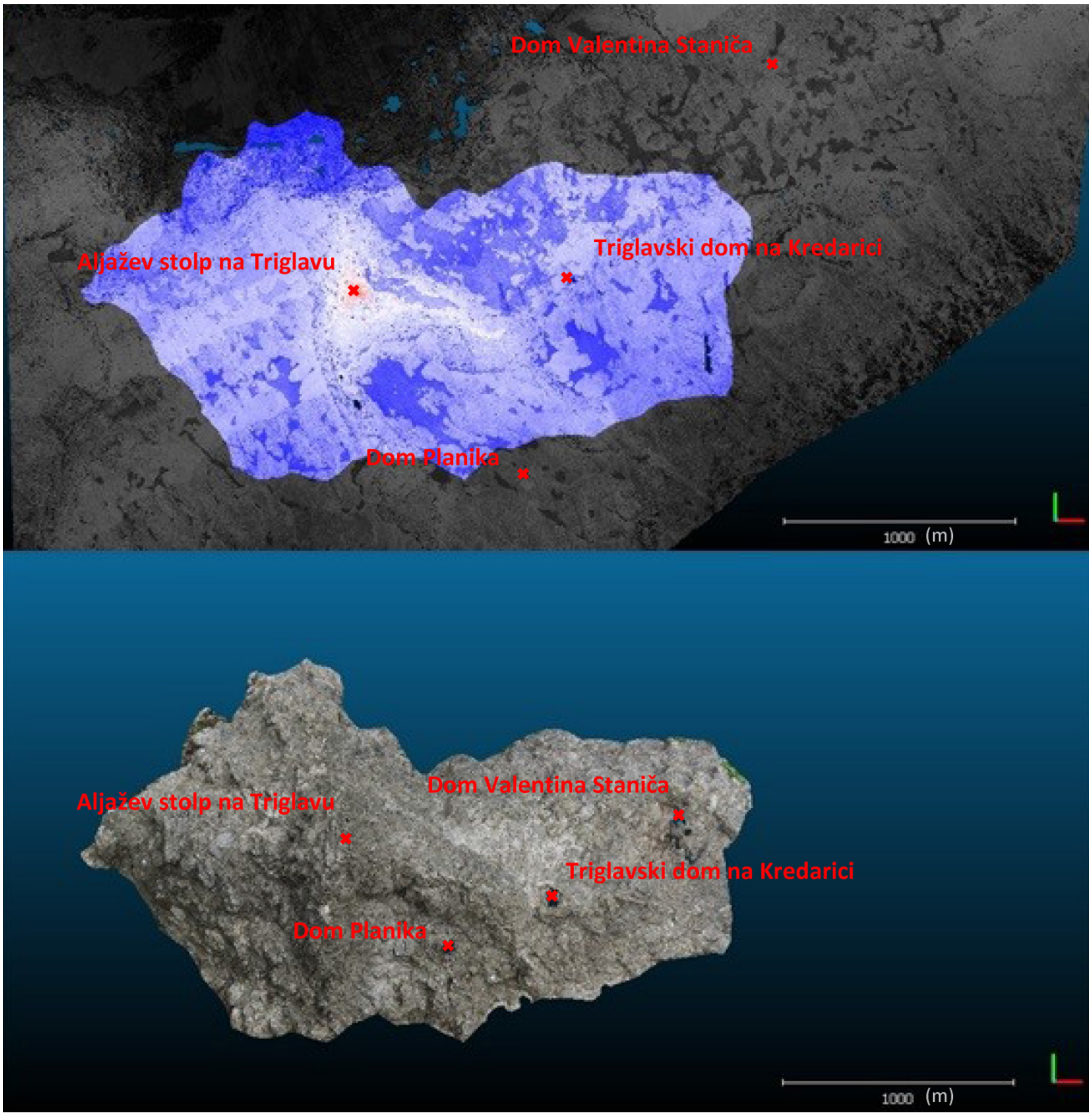


Fig. 17 Comparison of characteristic points (huts and Aljaž Tower) on the actual mountain (above) and on the stone model (below).

Slika 17. Usporedba položaja značajnih točaka (planinarskih domova i Aljaževog stupa) na stvarnoj planini (gore) te na kamenoj maketi (dolje).

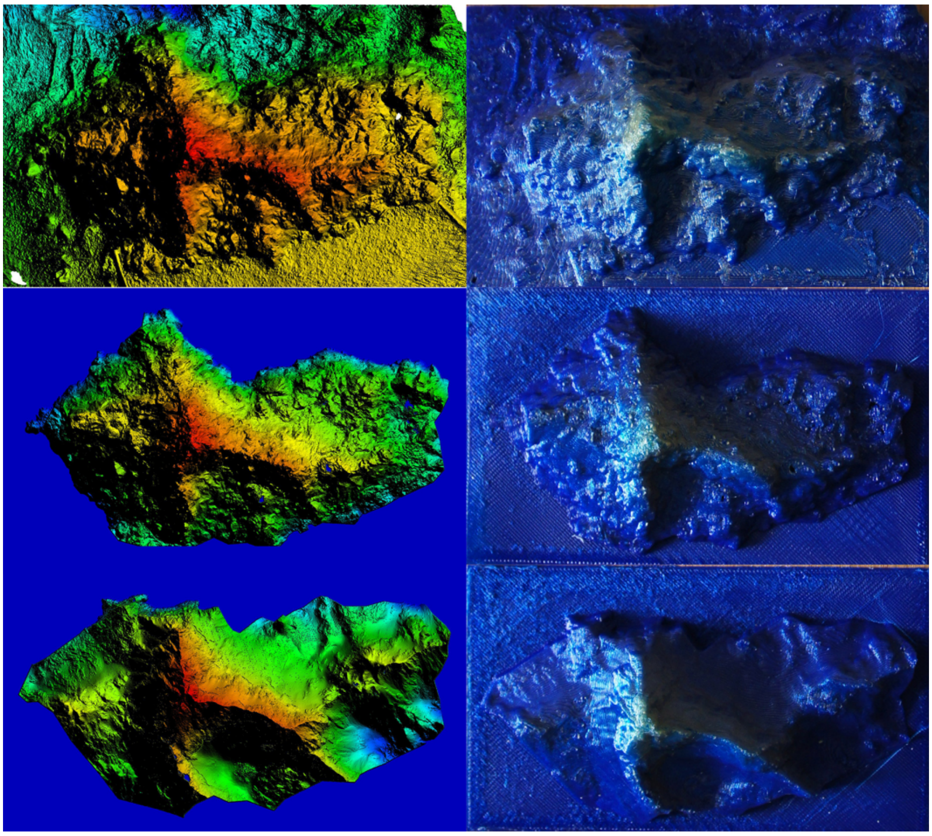
reduced them for this purpose to 14 cm in length. The stone model of Triglav near Lake Bohinj was printed in the approximate scale of 1:53 and the model of the actual shape of the Triglav mountain range in the scale 1:18,570. To facilitate comparison, we also printed a geometrically adjusted reduced stone model (transformed point cloud). Figure 18 shows all three models; in the left column are the shaded and hypsometric tints images of digital data, and on the right are the illuminated 3D prints.

Figure 19 additionally shows the comparison between the outlines of the actual mountain shape and the geometrically adjusted stone model in an oblique view from four different directions.

This visual comparison shows good matching of shapes in the central part and larger deviations at the edges. Above all, it is obvious that the shape of the stone model is rougher, which was surprising at first, as we always thought that the limestone mountains were extremely rough with few smooth slopes. However, with the scale reduction, all apparent recesses and bulges are concealed by the size of the mountain.

5 Conclusions

The stone model of Triglav and its surroundings at Bohinj Lake in Ribčev Laz is a good approximation of the actual shape of the mountain. Visitors and observers

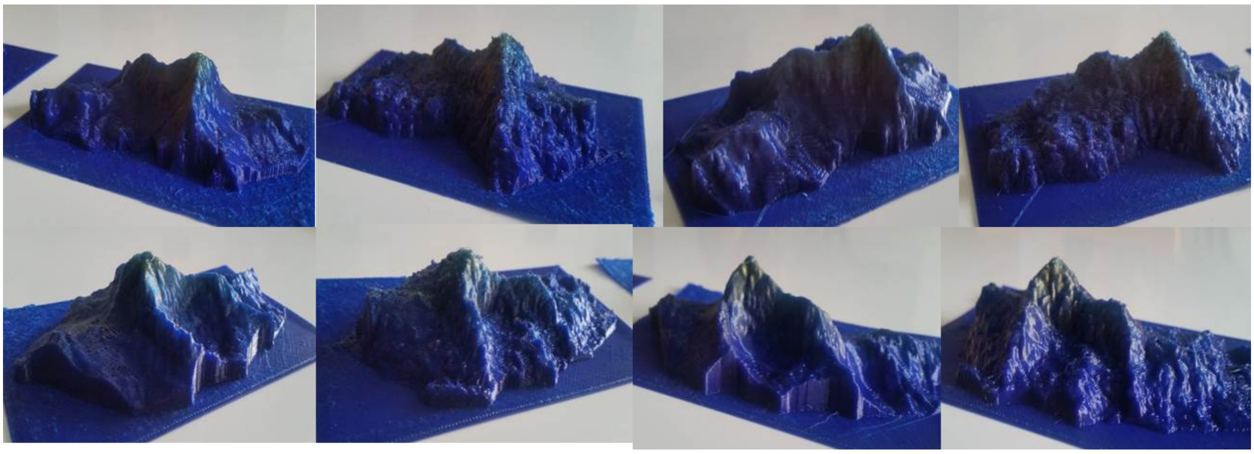


◄ **Fig. 18** Triglav model at Bohinj Lake, scale 1:53; geometrically adjusted Triglav model, Mount Triglav and the surrounding are, scale 1:17,850.

◄ **Slika 18.** Maketa Triglava uz Bohinjsko jezero, mjerilo 1 : 53; geometrijski prilagođen model makete; stvarni oblik Triglava i okoline, mjerilo 1: 17 850.

▼ **Fig. 19** Actual mountain shape model and geometrically adjusted stone-built model in an oblique view from four different directions.

▼ **Slika 19.** Model stvarnog oblika planine i geometrijski prilagođen model kamene makete u kosom pogledu iz četiri različita pravca.



dijelovima, ali su iznosi odstupanja na užem području manji.

Iz usporedbe oblaka točaka kamene makete i stvarnog oblika planine vidi se da je slikar Valentin Hodnik prilično dobro uhvatio stvarni oblik Triglava i uže okoline jer je odstojanje na većem dijelu površine manje od 50 m, što u ocijenjenom mjerilu makete iznosi 7,1 cm. Odstojanja su uočljivija na grebenima. Ti su na maketi po pravilu niži i manje oštri od stvarnih, što bi moglo biti i rezultat fizičkog oštećenja kamene makete nepovoljnim vremenskim uvjetima i penjanjem posjetitelja po maketi. Razlike su najmanje na užem području između Kredarice i vrha Triglava. To je središnji i za veći dio posjetitelja i najatraktivniji dio područja. S udaljenošću se odstupanja uvećavaju. To je uočljivo već na užem području, a pogotovo na rubu kamene makete, gdje odstupanja dosežu i do 200 m. Ocjenjujemo da su razlozi za veća odstupanja na rubovima i u tome što je autor trebao maketu prilagoditi konfiguraciji terena na mjestu postavljanja i da je na rubovima maketu završio uglađenim oblicima.

Ustanovili smo dalje, da su planinarske kuće postavljene samo za grubu orijentaciju jer njihovi položaji na maketi prilično odstupaju od njihovog stvarnog položaja. To smo primijetili već kod određivanja približnog mjerila makete dobivši dosta različite razmjere između planinarskih domova i Aljaževog stupa na vrhu Triglava. Na slici 17 vide se stvarni položaji planinarskih can easily recognize individual peaks, mountain huts, ridges and faces. The exactness of the shape was estimated using a precise geodetic survey. Traditional geodetic measurement methods were suitable for accurate measurements of individual selected points to assess their correctness, but not for the complex shapes of the surfaces as a whole. Using photogrammetric methods, we created a dense point cloud of the stone model from photographs and compared it to the point cloud of the actual Triglav mountain range, acquired from Laser Scanning of Slovenia data. The average absolute distance between the point clouds was 41.8 m (6 cm at a built-model scale) with a standard deviation of 38.0 m (5.4 cm) for the entire area with the additional use of ICP method, while for the central part of the model it was 28 m (4 cm) with a standard deviation of 36.2 m (5 cm). The results of the comparison showed that the stone Triglav model matched the actual mountain shape well close to Triglav Peak, Mali Triglav peak and *Kredarica* hut, while differences arose at the edges of stone model. Peaks and ridges were lower than their real counterparts, but this might be explained by natural erosion and human interference. The model is rougher, since the author was limited by the shapes of the stones he used. We also performed terrestrial laser scanning of the stone model, but the point cloud made from it was less useful for interpretation, less accurate and less complete, so we decided not to use it in later steps.

The Triglav model is a work of art which also has cultural, historical and tourist significance. From the cultural heritage conservation perspective, the data obtained through this project could be used in any future reconstruction of the stone model. For a more accurate presentation of the area around Triglav, a new model based on LSS data could be created and perhaps printed with a large-scale 3D printer, showing mountain paths and the proper positions of the mountain lodges. To summarise, the stone model of Triglav shows the shape of the relief well for orientation and presentation purposes only.

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domova i Aljaževog stupa te njihovi položaji na kamenoj maketi.

4. Tisak s pomoću 3D pisača

Ocjena pravilnosti oblika kamene makete u odnosu na stvarni oblik planine određena je apsolutnim udaljenostima između točaka oba oblaka točaka upotrebom programa CloudCompare. Koristili smo zadane parametre programa Za lakšu vidljivu usporedbu i ocjenu napravili smo 3D printe modela i maketa. Naravno, za tu smo ih namjenu dodatno smanjili. Tako smo natisnuli model kamene makete Triglava uz obalu Bohinjskog jezera u približnom mjerilu 1 : 53, a model stvarnog oblika planine Triglava u mjerilu 1 : 18 570. Za lakšu usporedbu dodatno smo natisnuli geometrijski prilagođen model makete (transformiran oblak točaka). Prikaz oblika tih triju modela s upotrebom sjenčanja i hipsometrijskih boja te vertikalni pogledi 3D printa vide se na slici 18.

Na slici 19. dodatno je prikazana usporedba printa modela stvarnog oblika planine i geometrijski prilagođenog modela kamene makete u kosom pogledu s četirima različitim pravcima.

I ova vizualna usporedba ukazuje na dobro uklapanje oblika na središnjem dijelu te veća odstupanja na rubovima. Ponajviše se vidi da je oblik kamene makete hrapaviji u odnosu na stvarni oblik, što je donekle iznenađujuće, jer imamo uglavnom osjećaj kako su vapnenačke planine izuzetno raspucane i bez glatkih padina. Ipak su se kod smanjivanja sve te neravnine nekako uklopile u ukupnoj veličini planine.

5. Zaključak

Oblik kamene makete Triglava i njegove okoline uz obalu Bohinjskog jezera u Ribčevom Lazu je dobra aproksimacija stvarnom obliku planinskog područja. Posjetitelji i promatrači mogu na njoj jednostavno prepoznati značajne vrhove, planinarske kuće, grebene i lica. Dimenzijsku pravilnost možemo odrediti samo na osnovu dovoljno točne geodetske izmjere. Tradicionalne metode geodetske izmjere omogućavale su točnu izmjeru pojedinih odabranih točaka, što omogućava ocjenu pravilnosti položaja tih točaka, ali ne i ocjene kompleksnog oblika plohe u cjelini. Upotrebom fotogrametrijskih metoda iz fotografija kamene makete izradili smo gusti oblak točaka površine makete i usporedili ga s oblakom točaka stvarnog područja Triglava koji je bio prikupljen kao dio podataka Laserskog skeniranja Slovenije. Poprečna apsolutna udaljenost između točaka oba oblaka točaka iznosi 41,8 m (6 cm u mjerilu makete) sa standardnom devijacijom 38,0 m (5,4 cm) za cijelo područje makete s dodatnim uspoređivanjem pomoću metode ICP, a za uži središnji dio makete iznosi 28 m (4 cm) sa standardnom devijacijom 36,2 m (5 cm). Rezultat usporedbe pokazuje dobro uklapanje oblika kamene makete sa stvarnim oblikom na užem području Triglava s Malim Triglavom i Kredaricom, a veća odstupanja uočljiva su na ostalim dijelovima, pogotovo uz rub kamene makete. Vrhovi i grebeni niži su u odnosu na pravi oblik, što možemo objasniti erozijom i čovjekovim uticajem. Maketa je „hrapavija"jer je autor bio ograničen oblikom kamena koji je imao na raspolaganju. U postupku ocjene maketu smo skenirali i terestričkim laserskim skenirajnem (TLS), ali se pokazalo da je iz toga bio napravljen oblak točaka manje pogodan za interpretaciju, lošije točnosti i nepotpun pa ga stoga u daljnjim postupcima nismo koristili.

Maketa Triglava kao autorov umjetnički rad ima i kulturno–povijesni i turistički značaj. Sa stajališta čuvanja kulturno–povijesne baštine u projektu smo dobili podatke kojima je moguće rekonstruirati kameni model. Za točniji prikaz područja oko Triglava, na osnovu podataka LSS i natiska na 3D printeru većeg formata, može se izraditi novi model, uključujući planinske puteve i planinarske kuće u pravim razmjerima i lokacijama. Dakle, izrađena kamena maketa Triglava dobro prikazuje oblik planina, ali se može koristiti samo za orijentaciju i grubu predstavu.

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