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Geomatics techniques for the 3D survey of the Arno River to support hydraulic studies

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Abstract. This paper presents the geomatic contribution to the hydrographical survey applied to the Arno River in Tuscany (Italy) that has been performed to obtain both underwater cross-sections as well as riverbank height using point cloud data from echo-sounder and terrestrial laser scanner so that water flow storage capability could be further estimated with high accuracy. The control network and ground control points design, measurement and adjustment are presented, describing the solutions adopted to face the specific needs of the project. The overall accuracy assessment is performed considering some known vertices: the results are fully compliant with the requirements for subsequent hydrological analysis.

1. Project introduction and goals

On the occasion of the 50th anniversary of the Flood of Florence (November 4th, 1966), described in detail in [1], it was decided to carry out a complete survey of the entire urban section of the Arno River, to acquire the geometry of the riverbed and banks as completely and accurately as possible. The project is part of the various study, awareness and dissemination activities carried out in the campaign “2016 Progetto Firenze”, an initiative which for three years dealt with floods, particularly those involving cities of art, in all possible facets [2].

The data acquired by this project aims to support both hydrographic and structural studies [3]: on the one hand, they will be used to make analysis and mathematical models suitable to predict the maximum flow rates that the various sections of the river can pass without problems; on the other hand, they will supply the assessment of the condition of the bridges for stability and integrity. These studies require to know the morphology of the underwater and emerged parts and they are traditionally based on classical topographic survey [4].

1.1. The role of geomatics

Thanks to the geomatics techniques, the metric documentation of the territory morphology is becoming more and more widely available and with unprecedented resolution. The potential of 3D mapping is in fact made evident in the applications of photogrammetric surveys by drones, terrestrial surveys with laser scanner, as well as bathymetric surveys with echo-sounder [5] [6]. Remote sensing data with other techniques can provide fast and cost-effective data on large areas that may be flooded, but with a lower resolution [7] [8] [9].

In order to study a mathematical model, it is essential to have a precise and accurate knowledge of the shape of the submerged riverbed, but also of the one of the emerged parts (banks) and of the structures that modify the sections (bridles, piers and bridge abutments), of those that delimit them (parapets and walls) or that overhang them (bridge arches), to have, at every point of the river axis, the possibility of drawing and measuring the shape of the cross-section. Besides, the sections must all refer to a unique system so that the distances and the differences in height measured on the surveyed data and in the real word are immediately comparable.

In order to achieve this aim, a procedure, already applied for the study of maritime and river hydraulic works [10], has been used, which can provide an "almost continuous" survey. The equipment and methods used produce "point clouds" at high density and with homogeneous and controlled accuracy (in the order of a few centimeters) of the entire stretch of the Arno River that runs through the City of Florence - from Varlungo to Ponte a Signa, as shown in Figure 1.

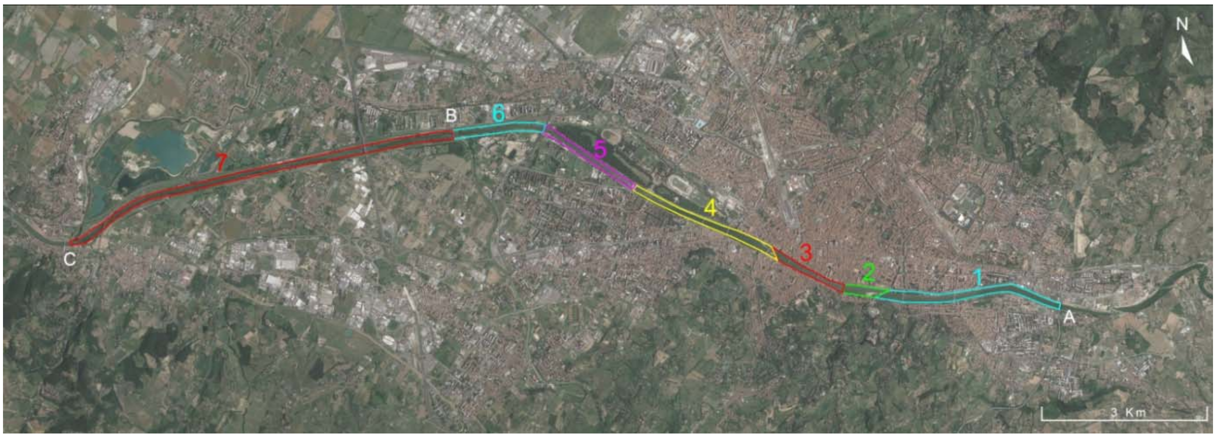

Figure 1. The section of Arno river under investigation (A: Varlungo, B: Greve river mouth, C: Ponte a Signa, Bisenzio river mouth). Numbers refer to the sub-sections defined to manage the survey

A control network based on high precision satellite measurements (GNSS), integrated with traditional topographic measurements and geometric levelling, guarantees the necessary planimetric and altimetric accuracy, while a simultaneous survey of the riverbed (with a multi-beam echosounder, MBES) and of what emerges from the river (with terrestrial laser scanner, TLS) produces a detailed survey consisting of tens of millions points.

In order to reduce the massive amount of data, some multi-resolution digital surface models (DSM) have been interpolated. In the end, hydraulic models are set up based on the provided DSM. Obviously, also conventional graphical elaboration, easy and immediate to read, can be provided, such as cross-sections, as in the case it is needed to compare morphologies that varied – sometimes abruptly.

A "database" made up of the results of a survey is indispensable for those who have to manage and to monitor the river, its parts, the territory in which it flows, the structures built on and around it. In fact, a generalised description of what is existing at a specific date is the basis to be able to carry out new surveys, even partial ones, and to compare immediately old and new data, highlighting changes or the stability of every detail, from the riverbed to the banks, from the structures in the riverbed to those of soil containment.

The 2015 survey's database was delivered to the competent authorities together with a report that allows repeatability of the measurements with procedures able to guarantee the same standards of precision and the absolute identity of the reference system, that is the essential conditions for any automatic overlap between surveys carried out at different times.

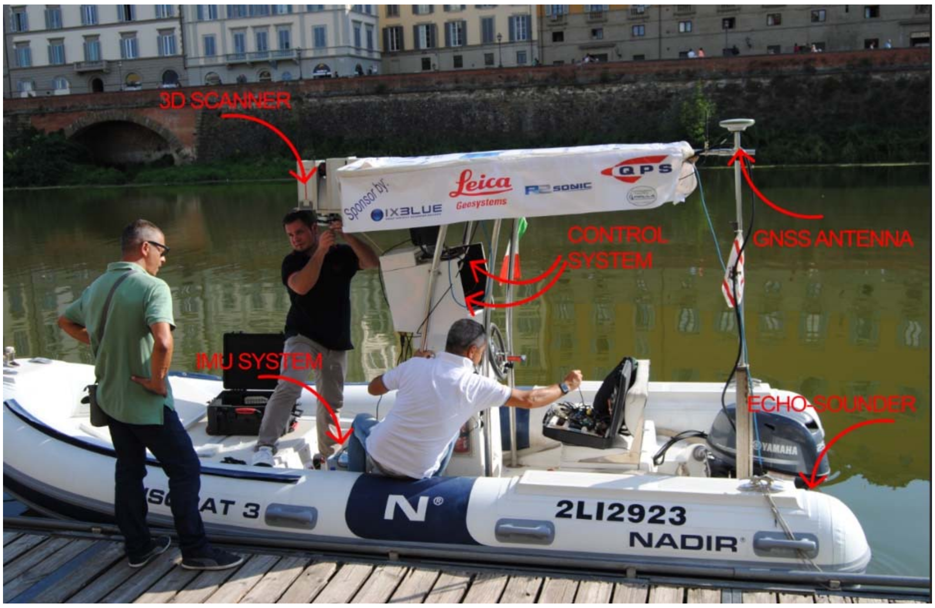

Figure 2. The tender equipped with the echo-sounder and the laser scanner.

2. Data acquisition

The data acquisition started in 2015 along the urban section of the Arno river, for a length of about 17.7 km (11 km across the city of Florence), from the Varlungo Viaduct (A in Figure 1) to the mouth of the Bisenzio river in Ponte a Signa (C in Figure 1). The planning operations and the fieldwork for making the control network and for providing the control points were carried out by the staff of the Civil and Environmental Engineering Department - Geomatics research group, in cooperation with the Research and Advanced Training Centre for Hydrogeological Risk (CERAFRI).

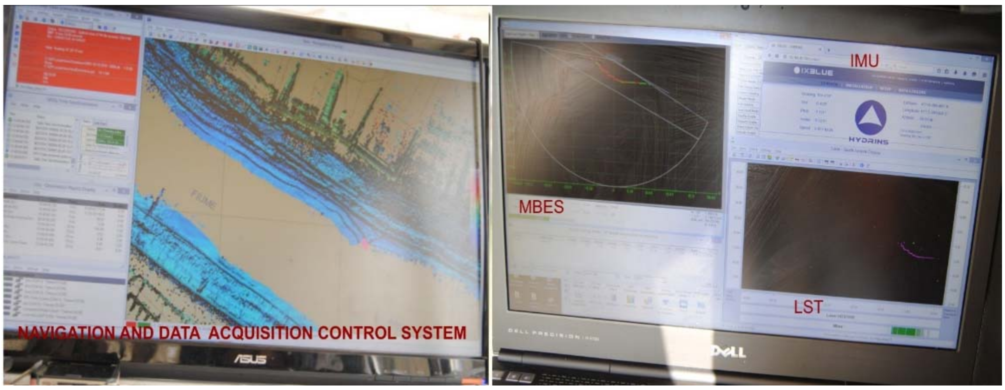

Figure 3. The tender real time control system.

3. Instruments and methods

For the control network, a Leica 530 GPS receiver was used for most of the measurements. A rapid static method was applied, combining high accuracy in positioning and short observation periods (variable between 20 to 10 minutes, according to the presence of obstacles, as building and vegetation). Only in obstacle-free areas (as on some bridges), a "stop-and-go" method was applied: after accomplishing a static initialisation, the vertices were occupied with only a one minute of measurements. The use of at least two permanent stations - most often three - to calculate (in post-processing) the coordinates of all the GNSS vertices made it possible to objectively and punctually verify their accuracy,

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thus revealing that, even on the vertices surveyed with shorter occupation time, precision is suitable and substantially similar to the one obtained on "static" vertices.

Given the characteristics of the Arno River path, that presents relevant tree coverings in the extra-urban areas and notable obstacles made by the high buildings overlooking the waterfront in the historic centre, satellites measures were not enough. Therefore, the control network has been integrated by total station observations, useful also for the positioning of ground control points (GCP). The total station TCRA1202 (by Leica Geosystems) was used, and the vertices were planned considering both their mutual intervisibility and their visibility from the previously determined vertices.

For the geomatic survey of the point clouds describing the submerged riverbed and the banks of the Arno river, the equipped tender shown in Figure 2 from Oikos company was used. It is equipped with a multibeam echo-sounder and a terrestrial laser scanner; it can, therefore, acquire three-dimensional data simultaneously, above water from TLS and underwater from the MBES. Each point acquired by one of these two systems must be "synchronised" and geo-referenced thanks to a control system that continually detects and interpolates the position of the sensors and their angular position [11]. The control system consists of a couple (base – rover) of GNSS RTK receivers (by Leica Geosystems) and an inertial measuring unit (IMU Hydrins), as well as two PCs and a complex system of links; it allows to check on the field in real-time the position and direction of the boat, to monitor the performance of the sensors and the completeness of the survey. A post-processing elaboration integrates point data, from both laser scanner and echo-sounder, computing and adjusting motion orientation and transforming all the results in the same coordinate reference frame.

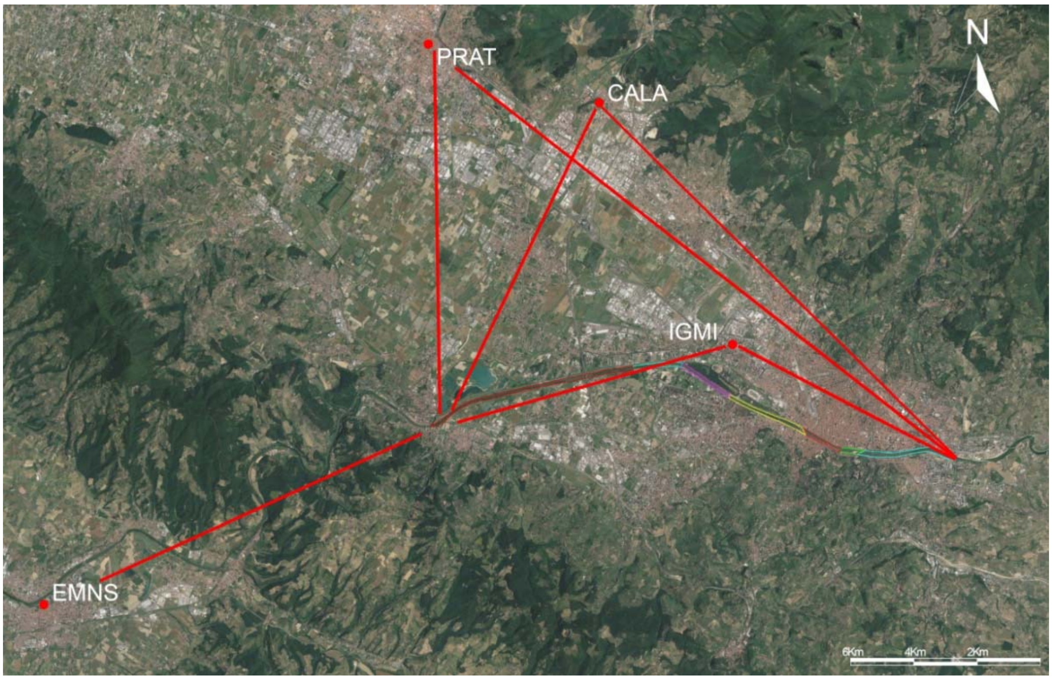

Figure 4. The permanent stations providing GNSS data for the control network arrangement.

3.1. *The control network*

For the survey of such an extensive area, it is essential to design a robust geodetic framework, to guarantee a univocal reference to the large amount of data acquired, especially concerning the altimetric trend of the riverbed, that is the basis for hydraulic runoff analyses.

The sensors used for the point cloud acquisition apply a kind of direct georeferencing of the data, as in any mobile mapping system, thanks to GNSS and IMU. However, control and refinement of the reference system seemed indispensable, especially considering the altimetry, given the relevance of the survey for subsequent hydraulic analysis.

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The coordinates of many vertices materialised by the Mareographic and Hydrographic Office of Pisa through the General Directorate for Environmental Policies, Energy and Climate Change were also acquired. These vertices are carefully materialised along the Arno river and especially in its urban section so they would have been a relevant support for this study; unfortunately, there are, besides the loss of points due to works or vandalism, lacks in their metadata (witness diagrams are missing for many points) and defects in their positioning. In the points we had the opportunity to re-measure, we assessed planimetric (± 35 cm) and altimetric (± 10 cm) standard deviation that is higher than the one required in the present work.

Figure 5. GNSS vertices in the river section passing through the city of Florence.

Thanks to the precious cooperation of the Military Geographic Institute (IGMI), the GNSS observation were computed considering as the main "base" the IGMI Permanent GNSS Station, that is a node of the European (EUREF) and national (RDN, Dynamic National Network) networks and it is located in a barycentric position with respect to the study area (Figure 4). The data coming from others permanent stations were also used: PRAT (Prato), that is a node of the EUREF and RDN networks as well, and two stations of the ItalPos network (managed by Leica Geosystems): CALA (Calenzano), and EMNS (Empoli) for the westernmost part of the survey.

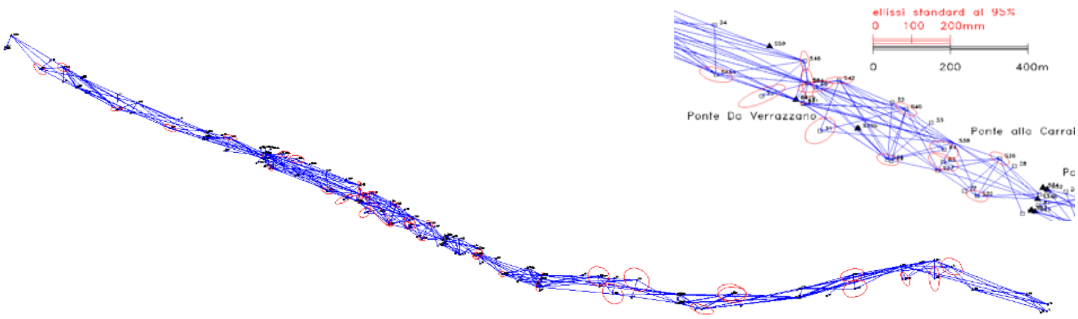

Figure 6. Diagram of the GNNS and TS measurement collected and adjusted.

Control network vertices have been materialised and witness diagrams were carefully sketched; the network design considered to fix some points on all bridges (except on Ponte Vecchio, where buildings blocked most of the satellites), and along the banks, in obstacle-free zones to acquire satellite data with strong geometry. Vertices have a higher density in the central zone, where precision requirements were more demanding. At the same time, they are further apart in the peripheral areas, where rather dense vegetation covers the banks.

3.2. The reference system
The official geodetic datum for geo-referenced information in Italy was proposed by IGMI as the European system ETRS89 - ETRF2000 updated to 2008.0.

GNSS stations are expressed in Cartesian ellipsoidal coordinates (X, Y, Z), that can be easily converted into three-dimensional ellipsoidal coordinates (Φ, λ and H, Ellipsoidal height) and projected into UTM zone 32, in order to make easier to manage distances between points.

As well known, a cartographic projection always induce deformations; the difference between the measured distance and the same distance represented on the cartography, i.e. determined with GNSS techniques, can reach several dm/km. Fortunately, in the area of the survey, the total deformation varies between - 7mm/km (at Varlungo) and + 62 mm/km (at Signa). However, given the extent of the survey, neglecting these deformations would lead to an error of about 50 cm, much higher than the one resulting from position measurements, both satellite and topographic, which are expected to have absolute sub-decimetric accuracies.

Therefore, the "total deformation" have been tabulated for the main points of the survey, particularly in the junction zones between the areas into which the survey has been divided.

In order to perform the geomatic survey, and also for future applications, we transformed the coordinates also in the Gauss-Boaga cartographic system (GB) through the IGMI grids, which allow the transformation of datum minimising errors. The point clouds measured with the scanner and the sounder will then be acquired in the GB system, with orthometric heights.

Since the vertical reference for GNSS observations is the WGS84 ellipsoid, it was necessary to transform the ellipsoidal heights (h) to orthometric heights (H) through a geoid model (Italian Geoid ITALGEOyy, the conventional geoid model defined by IGMI with the collaboration of the Polytechnic of Milan) and the software certified by IGMI, that allow to reach accuracies of ±4 cm. Moreover, quality control was conducted by a high-precision geometric levelling, connecting five vertices with known orthometric height to several vertices of the control network through levelling lines. Vertices directly linked to points with known orthometric height has been considered as “fixed” with regard to the altimetry in the network adjustment; the residuals after the adjustment process are entirely satisfactory.

3.3. Ground control points
The control points - materialised with plastic-coated A4 sheets - are the link between the control network and the point cloud survey, as they can be recognised within the point clouds captured by TLS and recorded for subsequent processing. Points positioned by GNSS technique have been connected with each other and with the ground control points, obtaining a dense and highly hyper-determined network. StarNet software (by MicroSurvey) was used for its adjustment, achieving a satisfactory accuracy.

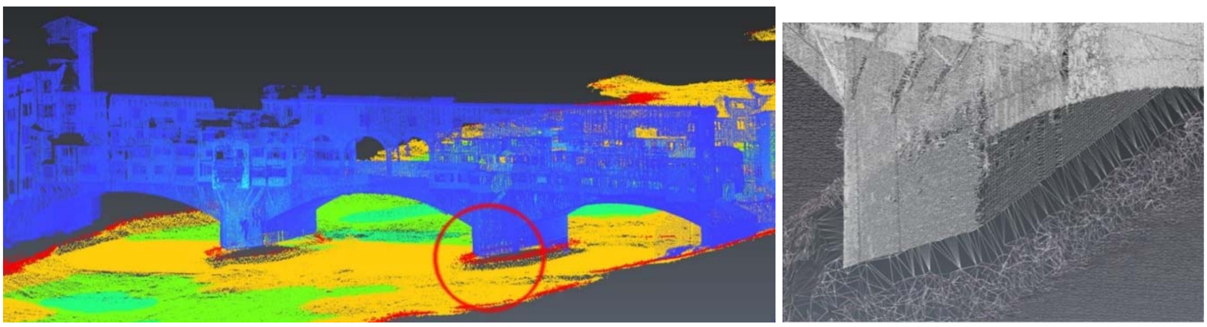

Figure 7. The Ponte Vecchio area: in blue, the emerged structures; the riverbed is represented in colour scale: in red the water surface, in green the deeper surfaces. Data highlighted in the red circle is shown in the right, after a TIN computation.

4. Graphic outputs

The geomatic survey produces clouds of "raw" points of very variable density, which also contain elements external to the survey, such as boats, people, cars. These elements should be removed from the dataset and points should be filtered to remove spikes and outliers. This process, carried out by the Oikos company, allowed to obtain a “clean” database to be used in all subsequent operations. Figure 7 shows a DSM made by a triangular irregular network (TIN) which continuously describes, albeit with variable density, the surfaces detected. Original point clouds are made by scattered data; therefore, a gridding step is used to produce the riverbed DTM used in the hydraulic analysis.

5. Geomatic survey accuracy assessment

Reil [12] investigates the sensitivity of the hydraulic model to different topographic inputs, demonstrating that the geometry of the watercourse and the inundation area is a key element to hydraulic models. As already mentioned, in the project here described, the control network last square adjustment was performed, from time to time, on different sections, considering both GNSS and TLS measurements, assuming as fixed the vertices measured by GNSS and geometric levelling on the bridges. For each unknown point, the actual accuracy is computed, and it is always compliant with the requests, never reaching (at 95% confidence level) ± 0.1 m error in plan and ± 5 cm in height: the RMSE of the GCPs are ± 4 cm (planimetry) and ± 1 cm (altimetry).

Figure 8. Example of the triangular sub-sets of data considered for altimetric adjustment.

GCPs were used to improve the geo-referencing and to control possible deformations in TLS data. Their centre was automatically detected and thus it was possible to assess the residuals respect to the coordinates determined by total station measurements. The residuals in the city area are, in most points, lower than 0.1 m. Considering triangular sub-sets, the point clouds were slightly “deformed” on the basis of bilinear interpolation, to force GCP automatically recognised on the scan data to correspond to topographic measurements (Figure 8).

6. Concluding remarks and perspectives

The result of a 3D metric survey is an accurate representation of reality; the quality of the representation can be assessed considering its accuracy and its resolution. The adoption of rigorous method and the redundant checks performed allow to obtain very remarkable results in terms of accuracy: as testified by the residuals obtained by the adjustment process, the accuracy of the GCPs is about few centimetres, and it can be considered typical also of billions of points measured by TLS. As far as the resolution is concerned, however, Figure 7 shows as is possible to read small details both on the emerged structures, on the riverbed, and the submerged part of the piers.

The acquired database is available for further studies and analysis and the digital model could be assumed as reference for monitoring purposes. Indeed, by repeating measurements at intervals, it is possible to analyse the evolution of the riverbed and banks morphology, highlighting morphological changes that may have several effects on hydraulic structures, infrastructures, and environment. In 2016, due to ground instability, the parapet in the central section budget. After a new survey campaign, limited to that area and again carried out by Oikos company, it was possible to evaluate the deformation occurred to the structure, as shown in Figure 9.

Figure 9. Documentation of wall failure occurred in 2016, and comparison of the update cross-section (in red, 2016) with the previous survey (in blue, 2015).

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