COMPARISON OF MULTI-SOURCE DATA, INTEGRATED SURVEY FOR COMPLEX ARCHITECTURE DOCUMENTATION

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ABSTRACT:

The metric documentation of architectural complexes requires today the use of several integrated survey methodologies. This need is an answer to the morphology of the object such as dimension, geometry, inaccessible areas and urban context. These properties inhibit the use of single surveying techniques and force the integration of Geomatics tools. In addition, the metric documentation of Cultural heritage objects not always requires uniform accuracy and resolution, therefore the integration of different surveying methodologies and techniques become the only effective solution both from a technical and economic point of view. The integration, that is today adopted as normal strategy, allows also the better understanding of the benefits which can arise to speed up the metric documentation of Cultural Heritage objects and the benefits that each of the possible surveying techniques can have thanks to the integration of the different potentialities. This study starting from an integrated survey, performed whit a combined use of Mobile Mapping System (MMS), Unmanned Aerial Vehicles (UAV) and Terrestrial Laser Scanner (TLS) and show the results of the comparisons between the possible achievable accuracies by using a correct integration between the different used technologies and the ones achievable by using the same techniques as independent tools.
The case study is the architectural complex of the Ducal Palace in Gubbio (Italy), located upstream of the most important town square facing the cathedral in a very complex but realistic urban context.

1. INTRODUCTION

The metric survey of complex architectural structures always requires the integration of different geomatics techniques.
The metric survey is never an end in itself but is always carried out in support of specific analyses and planning of conservation and restoration interventions as well as the planning of management interventions.
Each of these actions requires metric surveys of a different nature and metric and descriptive content. This differentiation may also be necessary in different parts of the same complex and therefore the use of integrations of more than one metric survey technique is especially acceptable from an economic point of view.
Another reason that justifies the current trend towards the integration of different measurement techniques, lies in the fact that each technique (aerial and terrestrial photogrammetry, laser scanner, SLAM, etc.) has limits both of achievable accuracy and of possible degree of detail.
Finally, as a third reason that justifies the now commonly accepted recourse to the integration of different metric survey techniques in one or the same complex, we can consider the limits of applicability of each of the techniques due to both environmental limits (necessary spaces, lighting, etc.) and limits in the times of accessibility possible in the complex itself.
Integration, first presented as a contingent necessity due to the limitations of the different techniques or to the properties to which the metric survey must answer in different situations, must not however be seen as a limit or even a complication to which the surveyor must submit.
The evolution of geomatics techniques has shown in the past how, from the integration of different technologies, undoubted advantages can often be obtained for the technologies themselves.
In the 90s of the last century the integration between laser scanner techniques and digital photogrammetry brought undoubted advantages to both techniques. The interpretation of point clouds obtained with laser scanning techniques would not have been possible as easily as we can appreciate today without the use of oriented digital images. At the same time, the production of orthophotos and the search for homologous points on stereoscopic images has been greatly facilitated by the ease of having shape models (DSM) quickly and with more than acceptable accuracy in all applications.
Today the techniques that are most used in an integrated approach in the survey of complex architectures are digital photogrammetry (both aerial and terrestrial), terrestrial and aerial scanning techniques and, recently, also SLAM (Simultaneous Localization And Mapping) based techniques. The introduction of this last technology in the metric survey has been facilitated by the development of increasingly performing and easy-to-use equipment during the acquisition of primary data.
It is now an incontrovertible fact that the SLAM based instruments allows rapid acquisition times of point clouds in spaces where photogrammetric and laser scanner techniques would find many difficulties both in terms of feasibility and in terms of primary data acquisition speed.
The main purpose of the work described below is to evaluate the advantages that the SLAM technique can obtain from an integration with photogrammetric and laser scanning techniques in terms of accuracy of the measured data.
However, it is also known that the levels of accuracy that can be achieved with SLAM techniques are in many cases lower than those that the other two techniques mentioned above can guarantee.
Some researchers published some interesting results about the different accuracies reached by using automatic digital photogrammetric tools compared with laser scanner performances (Torres et al., 2014) by showing that, at that time, the existing gap between laser scanner and automatic digital

photogrammetry to produce DSM (Digital Surface Model) was recovered. Using a cloud-to-cloud comparison they showed discrepancies lower than 3 cm between the two point clouds.
One of the first comparisons between laser scanner, photogrammetry and SLAM systems were presented some years later (Chiabrando et al., 2016) more concentrated on the density of the different obtainable point clouds and a possible integration of them into a unique set of primary data useful to speed up the acquisition in dangerous area. They showed that the integration of the two point clouds could give enough information to generate profiles useful to assess the structure stability of ruined building after an earthquake by reducing the risk for surveyor thanks to the speed of acquisition of the SLAM based instruments.
Some of the first results in assessing the metric performances of SLAM systems were obtained by using a cloud-to-cloud comparison of pint clouds obtained by using terrestrial laser scanners and SLAM systems (Masiero et al., 2017; Malinverni et al., 2018). Discrepancies of about 30÷40 cm were established as maximum metric differences of the two measuring systems.
The possibility to register SLAM based point clouds by using the more precise information coming out form laser scanner point clouds showed a great increasing of the accuracy of SLAM results. By using a set of distances measured on the surveyed object and the corresponding on the point clouds obtained by using a SLAM system showed discrepancies less than 1 cm (Russhakim et al., 2019).
The results that will be presented in the next paragraphs add new experiences in managing a full integration of the three above mentioned technologies and the increase of accuracy that this approach could give to the metric quality of SLAM based point clouds.
The analysed data were acquired to perform the survey of the Palazzo Ducale in Gubbio (Italy) a morphologically complex building were the integration of laser scanner, photogrammetry and SLAM systems was a must by considering the dimension of the internal connections between the different floors and the accessibility limitation due to the surrounding buildings (Patrucco et al., 2019).

2. THE PALAZZO DUCALE IN GUBBIO (ITALY)

The architectural complex of the Palazzo Ducale, located upstream of the most important town square, faces the cathedral of Gubbio (province of Perugia) in a very complex urban context (see Figure 1).

Figure 1. Aerial view of the Palazzo Ducale

The palace was built by the will of the Duke of Urbino Federico da Montefeltro, on a pre-existing medieval buildings. The complex, probably designed by the architect Francesco di Giorgio Martini, is divided into two buildings joined by a central courtyard, and was certainly built at the end of XV century, when the pre-existing buildings, owned by the municipality of Gubbio, were donated in 1480 to the Montefeltro family.
Therefore, the complex represents the result of an evolutionary process consolidated over time that describes a unique historical testimony.
As it could be observed today, it is made up of multiple historical stratifications. Originally the first municipal building, a tower and a guard room were located at the Northern part of the current complex. The guard's palace was later built along the side facing the valley and the "platea communis" was located in the centre of these complex. Below this space there are two underground levels characterized by pre-existing walls dating back to X and XIV century. Today the palace hosts the Palazzo Ducale museum.

3. SURVEY STRATEGIES

The survey methodology used in this work tries to favour the integrated use of different sensor to obtain a dataset as complete as possible by considering the specific needs of the future users of the metric survey.
The choice of where and when different technologies can be used strongly depends on the requirement by the end user of the resulting 3D model. In the example used in this work, some parts of the complex do not require a high metric accuracy because recently restored and full equipped with technological devices, while other part require (inner spaces, roofs, facades) accuracies at 1:100 scale (e.g. ±2 cm) because they are used for temporary events and therefore need a continuous re-planning of interior spaces and technological installations (inner spaces) or are under restoration and continuous rehabilitation due to deteriorations problems.
Therefore, a LiDAR (Light Detection and Ranging) survey has been executed in all accessible outdoor and indoor spaces that require the maximum accuracy.
Automatic digital photogrammetry, by using images acquired by UAV, was considered to survey the inaccessible part of the complex, like roofs and the main facades of the building.
Finally, the Mobile mapping system, based on a SLAM (Simultaneous Localization and Mapping) algorithm, was used to survey spaces where lower accuracy can be accepted. Figure 2 shows the different parts of the complex acquired by each of the above mentioned techniques.

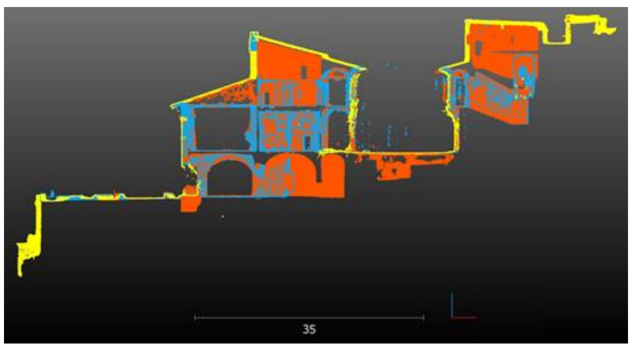

Figure 2. Primary data acquisition: photogrammetric images (yellow), TLS point clouds (red), and SLAM point clouds (blue)

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3.1 Used instruments and recorded primary data

The general overview of the acquired primary data is summarized in Table 1. Each survey techniques requires different procedures for data acquisition and each technique is characterized by different precision and resolution.

Systems	Sensor	Dataset
UAV	DJI Mavic Pro	1658 images
TLS	FARO Focus^{3D} S120	78 scans
TLS	FARO Focus^{3D} X330	64 scans
MMS	GeoSLAM ZEB Revo RT	12 scans
TS	Geomax manual TS	45 vertices, 412 targets

Table 1. General overview of sensor employed, and data collected

The UAV image acquisition has been carried out using a drone DJI Mavic Pro, equipped whit a DJI FC220 camera. Six flights (see Table 2) have been executed to collected data of the selected outer area; only the first three flights were acquired whit a pre-planned mode, while the last three flights were acquired in manual mode to obtain more appropriate acquisition and to avoid the lack of GNSS connection due to the urban complexity around the complex.

Flight	# images	Flight	Taken distance
1	261	PLANNED	≈ 68m
2	234	PLANNED	≈ 68m
3	32	PLANNED	≈ 68m
4	366	MANUAL	≈ 16m
5	316	MANUAL	≈ 10m
6	449	MANUAL	≈ 10m

Table 2. Detail of UAV dataset

The data sets were acquired with a nadir and oblique camera configuration. The first three flights have been integrated together in a single photogrammetric project to obtain a complete aerial model of the area (fig. 3).
The LiDAR survey was performed whit a ToF TLS Faro Focus^{3D} S120 and a Faro Focus^{3D} X330, the error in distance measurement of these system is ± 2mm; 142 scans were acquired to cover the test area, and all of them have been acquired whit a quality 4x and a resolution of 1/5. These values correspond to 1 point every 8 mm at a distance of about10 m (see Table 3 and Figure 4).

Figure 3. Photogrammetric point cloud

Block	# scans	Acquisition time [min]	# points
1	10	85,4	261.249.664
2	11	93,4	259.340.637
3	13	111,5	285.393.037
4	8	68,3	195.121.169
5	5	42,7	103.175.709
6	15	128,1	386.310.833
7	3	25,6	83.847.583
8	22	188,3	309.064.477
9	5	42,7	89.278.854
10	13	111,7	121.448.450
11	10	68,3	359.773.558
12	22	188,3	613.107.688
13	5	42,7	140.525.202

Table 3. TLS acquired dataset

Figure 4. TLS point cloud

The Mobile Mapping System used to survey the test area was the ZEB Revo Real Time (RT). This instrument is an MMS based on a SLAM algorithm and is equipped whit a handheld laser scanner and a RGB camera. ZEB Revo Real time RT represent a rapid mapping solution: the survey of the entire architectural complex required only about 125 minutes. This system has been adopted to survey the most difficult areas of the building to reach through the use of TLS and characterized by little lighting so as not to allow perfect photogrammetric acquisition, such as the underground rooms of the buildings.

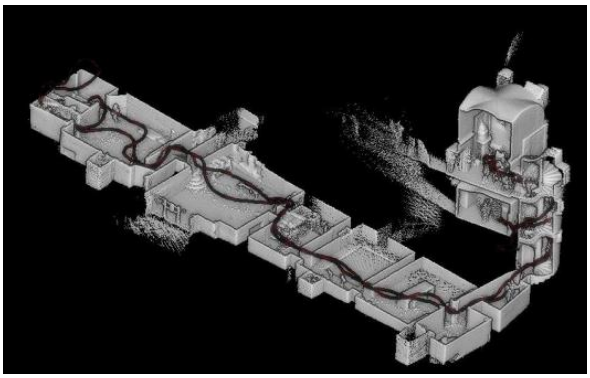

Figure 5. MMS point cloud. The paths are shown by dark line

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# scan	Acquisition time [min]	# points
1	7,15	15.302.472
2	11,5	23.851.663
3	8,6	18.420.264
4	12	24.918.629
5	12,1	28.176.481
6	9,2	20.162.581
7	11,3	22.349.861
8	9,2	19.636.188
9	10,1	22.173.975
10	12,2	30.639.964
11	12,1	24.225.364
12	9,3	20.050.087

Table 4. MMS datasets

The scanning procedure to be followed by MMS systems is very important because it inevitably affects the quality of the data; consequently, the adopted acquisition method was the execution of the loops, that is the closed path in the same starting position (see Figure 5). This scanning strategy facilitates the SLAM based software in 3D reconstruction by minimizing errors along the trajectory and increasing the rigidity of the system. Table 4 shows the summary of the data acquired by using the MMS.

3.2 MMS accuracy assessment

Due the high speed of acquisition of the SLAM based system, the entire building was surveyed by using this technique to allow a comparison of different achievable accuracies by considering different possible treatment of SLAM data.
As usual, the coordinate system, where all the collected data are referred to, has been fixed by means of traditional topographic methods.
To allow the accuracy assessment, some pre-signalized points have been placed and surveyed by using a total station with redundant survey methods from the different vertex of the control network to be able to estimate their precision and accuracy with the least square adjustment approach.
For those points a precision of about 2 mm was reached: this allow one to assume those points as more precise that the ones obtained by using automatic digital photogrammetry and TLS, and therefore able to allow a rigorous assessment of the different accuracies achieved by MMS data.
Table 5 shows the discrepancies between the coordinates of the check points (CPs) estimated by using Total Station measurements and the ones obtained from the point clouds generated by terrestrial laser scanner (TLS), automatic digital photogrammetry (ADP), and the GeoSLAM ZEB Revo RT point clouds without any elaboration after the first adjustment (MMS1).

#	TS			TLS - TS			ADP - TS			MMS1 - TS		
	X [m]	Y [m]	Z [m]	ΔX [m]	ΔY [m]	ΔZ [m]	ΔX [m]	ΔY [m]	ΔZ [m]	ΔX [m]	ΔY [m]	ΔZ [m]
1	66,321	112,445	92,494	-0,001	0,008	0,023	0,001	-0,002	0,019	-0,250	-0,007	0,192
2	69,154	113,965	91,214	0,001	0,003	0,006	-0,001	0,011	0,005	-0,197	0,058	0,193
3	68,009	119,291	91,38	-0,003	-0,007	-0,001	-0,003	0,005	0,004	-0,282	0,089	0,319
4	69,019	123,72	92,848	-0,010	-0,002	-0,004	-0,001	-0,010	0,002	-0,297	0,102	0,315
5	72,118	127,687	92,94	-0,009	-0,009	0,009	-0,002	-0,020	0,000	0,448	-0,005	-0,174
6	71,901	135,971	91,422	-0,012	0,009	-0,014	0,015	0,009	-0,021	-0,243	0,075	0,424
7	74,812	138,475	92,978	-0,005	-0,012	0,002	-0,009	-0,009	-0,015	-0,419	0,026	0,131
8	75,398	140,801	91,102	0,000	-0,008	-0,004	-0,028	-0,016	-0,005	-0,138	-0,005	0,007
9	116,126	107,756	103,178	-0,004	0,004	-0,016	-0,014	-0,015	0,001	-0,016	-0,292	0,186
10	110,296	108,522	100,203	-0,006	-0,014	-0,041	-0,015	-0,022	0,006	-0,014	-0,160	0,105
11	104,437	109,143	100,18	-0,012	-0,002	-0,011	0,008	0,005	0,001	-0,026	-0,077	0,050
12	101,494	109,517	98,293	-0,009	-0,007	-0,035	0,008	-0,002	-0,017	0,016	-0,348	0,227
13	96,704	110,137	100,131	-0,005	-0,009	-0,022	-0,004	0,009	0,001	-0,024	-0,001	0,008
14	85,784	151,59	98,415	0,005	0,013	-0,004	0,016	0,011	0,001	-0,019	0,057	0,018
15	84,945	147,204	99,17	-0,002	-0,007	0,003	0,005	0,001	0,001	-0,032	0,042	0,009
16	80,795	146,994	97,851	-0,007	-0,003	0,000	-0,003	-0,003	-0,002	-0,019	0,040	0,045
Mean [m]				**-0,005**	**-0,003**	**-0,007**	**-0,002**	**-0,003**	**-0,001**	**-0,094**	**-0,025**	**0,128**
St. Dev. [m]				**0,005**	**0,008**	**0,016**	**0,011**	**0,011**	**0,010**	**0,197**	**0,132**	**0,151**

Table 5. Residuals of 3D coordinates on a set of signalized points

A second comparison has been done by using a set of distances measured on well recognizable points in the different point clouds generated by Automatic Digital Photogrammetry, Terrestrial Laser Scanning and ZEB Revo Real Time (RT): for the last one on the original point clouds of each ring the radiometry has been re-projected by using the radiometry of the images used for the photogrammetric survey. Table 6 shows the obtained discrepancies.
By analysing the means and standard deviations of the obtained residuals shown in Tables 5 and 6 it is possible to observe, as it is well known, the almost similar accuracy of Digital Automatic Photogrammetry and Terrestrial Laser Scanning techniques and

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a big gap of the data acquired by using the SLAM based system without any further arrangements.

#	ADP [m]	TLS-ADP [m]	MM1-ADP[m]
1	3,473	-0,008	0,059
2	7,147	-0,019	0,058
3	11,590	-0,004	0,108
4	16,295	-0,001	0,275
5	24,218	-0,015	0,072
6	27,374	-0,010	-0,011
7	29,785	0,007	0,066
8	5,445	-0,004	0,059
9	9,871	0,015	0,087
10	14,113	0,017	0,080
11	22,178	0,005	0,011
12	25,194	0,007	-0,062
13	27,521	0,022	-0,014
14	4,760	0,016	0,022
15	9,454	0,019	0,214
16	17,136	0,006	-0,011
17	20,401	0,012	-0,102
18	22,718	0,028	-0,008
19	5,026	0,003	0,436
20	12,691	-0,013	-0,008
21	15,850	-0,005	-0,113
22	18,302	0,012	0,003
23	8,457	-0,009	0,053
24	11,128	-0,010	-0,151
25	13,641	0,007	-0,151
26	4,118	0,023	-0,100
27	5,925	0,038	0,048
28	3,030	0,022	0,135
29	5,187	-0,018	-0,002
30	7,809	-0,020	-0,004
31	13,681	0,006	0,037
32	19,797	0,006	0,079
33	3,525	0,002	-0,156
34	9,047	0,017	-0,058
35	15,513	0,022	-0,036
36	5,873	0,026	0,041
37	12,128	0,023	0,089
38	6,587	0,013	0,054
39	4,541	0,009	0,005
40	6,830	-0,004	0,002
41	4,368	-0,002	-0,020
Mean [m]		**0,006**	**0,027**
St. Dev. [m]		**0,014**	**0,110**

Table 6. Distance residuals

The software of the SLAM based system, ZEB Revo Real Time (RT), allows the adjustment of the acquired rings in a unique solution by using the overlapping parts of the different rings. The same comparison between 3D coordinates and distances, thanks to the re-projection of the radiometry extracted from the photogrammetric and terrestrial laser scanning point clouds, has been done and Tables 7 and 8 show the obtained results after the re-adjustments of the MMS rings (MMS2).

By comparing the simple statistical parameters (e.g. means and standard deviations) of the obtained residuals in the two different adjustments of the MMS data it is possible to observe that in the final situation the accuracy of MMS data reaches a standard deviation of about 2 cm if compared with photogrammetric data.

#	TS			MMS2 - TS		
	X [m]	Y [m]	Z [m]	ΔX [m]	ΔY [m]	ΔZ [m]
1	66,321	112,445	92,494	0,008	0,002	-0,014
2	69,154	113,965	91,214	-0,024	0,018	0,026
3	68,009	119,291	91,38	-0,010	0,001	0,007
4	69,019	123,72	92,848	-0,010	-0,006	-0,002
5	72,118	127,687	92,94	-0,010	-0,025	-0,009
6	71,901	135,971	91,422	-0,035	0,023	-0,002
7	74,812	138,475	92,978	-0,042	-0,011	0,002
8	75,398	140,801	91,102	-0,033	-0,008	0,001
9	116,126	107,756	103,178	-0,012	-0,020	-0,018
10	110,296	108,522	100,203	-0,013	-0,031	0,014
11	104,437	109,143	100,18	0,003	-0,021	-0,007
12	101,494	109,517	98,293	0,014	-0,031	-0,042
13	96,704	110,137	100,131	-0,016	-0,007	0,008
14	85,784	151,59	98,415	-0,029	0,001	-0,001
15	84,945	147,204	99,17	-0,034	0,041	0,008
16	80,795	146,994	97,851	0,009	0,031	0,006
Mean [m]				**-0,015**	**-0,003**	**-0,001**
St. Dev. [m]				**0,017**	**0,022**	**0,015**

Table 7. 3D coordinate residuals after the second adjustment of MMS data

#	ADP [m]	MM2-ADP [m]
1	3,473	-0,047
2	7,147	-0,017
3	11,590	-0,003
4	16,295	-0,013
5	24,218	-0,006
6	27,374	-0,017
7	29,785	-0,001
8	5,445	-0,015
9	9,871	-0,007
10	14,113	-0,012
11	22,178	0,004
12	25,194	-0,011
13	27,521	0,006
14	4,760	0,005
15	9,454	-0,003
16	17,136	0,008
17	20,401	-0,006
18	22,718	0,013
19	5,026	-0,006
20	12,691	-0,003
21	15,850	-0,014
22	18,302	0,005
23	8,457	0,014
24	11,128	-0,004
25	13,641	0,011
26	4,118	0,001
27	5,925	0,023
28	3,030	0,020
29	5,187	0,029
30	7,809	0,008
31	13,681	0,012
32	19,797	0,008
33	3,525	0,000
34	9,047	0,001
35	15,513	-0,005

#	ADP [m]	MM2-ADP [m]
36	5,873	0,005
37	12,128	0,001
38	6,587	-0,012
39	4,541	-0,048
40	6,830	-0,072
41	4,368	-0,047
Mean [m]		**-0,005**
St. Dev. [m]		**0,020**

Table 8. Distance residuals after the second adjustment of MMS data

4. CONCLUSIONS

The results described above, represent a contribution to those already obtained by other authors and may allow us to affirm how the use of MMS is today a reality to be considered with due attention when dealing with the metric survey of a morphologically complex building.
Moreover, we must not forget the different density of the point clouds that systems based on SLAM technology can provide and the limits in some cases still present of the impossibility of acquiring radiometric information together with the geometric information.
The results obtained from this work confirm that the new points acquired with the MMS offer an excellent integration and even a real possibility of replacing data that can also be acquired with other technologies (such as for example Photogrammetry and Terrestrial Laser Scanning).
Realistically it must be considered that accuracies of a few centimetres, such as those obtained in the case described with the MMS, are more than sufficient in any type of documentation.
It is also clear that the correct integration of different techniques in any case and always required a correct design and execution of a control network of sufficient reliability.
The control network must be designed and built in such a way as to ensure the necessary precision requirements throughout the 3D space of the object to be surveyed.
Finally, it should always be emphasized that a 3D metric survey without the necessary documentation describing the procedures used cannot be considered usable for restoration, conservation and management projects. This concept, which is also the basis of the London Charter, must be increasingly considered as an obligation to make the metric survey "transparent" and professional, which constitutes one of the fundamental pillars of the documentation of cultural heritage.

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