COMBINED 3D SURVEYING TECHNIQUES FOR STRUCTURAL ANALYSIS APPLICATIONS

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ABSTRACT

The plenty of works presented in last two years about the use of 3D models in the field of Cultural Heritage witness the great interest of surveyors, engineers, architects and archaeologists towards the laser scanning technique as an invaluable surveying mean for as-built documentation, digital archiving and restoration of important elements belonging to our historical and cultural heritage. Usually, the end products are represented by VR models (Vrml, Flash), suited to be shared among different user across the Internet, stunning movies (Avi, Mpeg, Divx), showing the 3D geometry of various objects, even phisically located in remote sites, embedded in a unique virtual environment, textured DSMs (Digital Surface Models) of both large and small size artistical pieces (e.g. churches, ancient buildings, statues, basrelieves, etc.) and orthophotos. Beside these products, Virtual Restoration applications should be taken into account so as, lately, the Solid Image, a new way for the interactive exploration of 3D models. Such wide variety of applications demonstrate that 3D models allow the user to retrieve different information contents from a unique digital representation of the reality, what is a topic not yet fully investigated.
As contribute to the topic of information retrivial from laser scanning-based 3D models, in this paper we will show how a 3D model can be used even for structural analysis applications. To this aim the walls surrounding Montagnana, an ancient little city located 35 km south west of Padua, have been surveyed with combined techniques: reflectorless total station and GPS for establishing a local network, Leica HDS 3000 laser scanner for the generation of a 3D model of the walls. Acquired point clouds were then registered in Cyclone employing retroreflective target to strength the alignment results, which were compared with the ones obtained by the application of Procustes Analysis algorithms, in order to verify the effectiveness of such registration method. Afterthat cross sections have been extracted from the global 3D model, where wall tickness and shape variation were clearly visib le, for the FEM based structural analysis.

1. INTRODUCTION

Since early '90s terrestrial laser scanners (TLS) have been increasingly spreading out on the market as an efficient alternative 3D measurement system respect with to photogrammetry and/or geodetic methods. Given their capability of measuring millions of points within relatively short time periods, complete and detailed 3D model of objects could be efficiently and easily created from acquired point clouds. These features allowed laser scanning technology to start to dominate the market in a variety of applications such as automotive and mining industry, mechanical engineering, as-built documentation for both industrial plants and historical buildings, archaeology and architecture. In this context, the interest of surveyors, engineers, architects and archaeologists towards the laser scanning technique as an invaluable surveying mean for 3D modeling of sites and artifacts of cultural heritage has increased remarkably in recent years. A wide variety of objects, e.g., small pieces of pottery, statues, buildings, and large areas of archaeological sites, have been scanned and modeled for such purposes as preservation, reconstruction, study, and museum exhibitions.
However, in most of the works presented in last two years about the use of 3D models in the field of Cultural Heritage, the end products have been limited to visually pleasant representations of surveyed objects, while only few ones addressed the problem of a metric analysis of such models. In this sense we can account for papers reporting the generation of VR models (Vrml, Flash), suited to be shared among different user across the Internet, stunning movies (Avi, Mpeg, Divx), showing the 3D geometry of various objects, even phisically located in remote sites, embedded in a unique virtual environment, textured DSMs (Digital Surface Models) of both large and small size artistical pieces (e.g. churches, ancient buildings, statues, basrelieves, etc.) and orthophotos. Beside these products, Virtual Restoration applications should be considered as well (Beraldin et al., 2003), so as, lately, the Solid Image, a new way for the interactive exploration of 3D models (Bornaz et al., 2004). Despite the limited end product typology, such wide variety of applications demonstrate that 3D models allow the user to retrieve different information contents from a unique digital representation of the reality, what is a topic not yet fully investigated.
As contribute to the topic of information retrivial from laser scanning-based 3D models, in this paper we will show how a 3D model can be used even for structural analysis applications. To this aim the walls surrounding Montagnana (Fig. 1), an ancient little city located 35 km south west of Padua, have been surveyed with combined techniques: reflectorless total station and GPS for establishing a local network, Leica HDS 3000 laser scanner for the generation of a 3D model of the walls. Acquired point clouds were then registered in Cyclone software employing retroreflective target to strength the global alignment. Results of this modeling stage were compared with the ones obtained through the application of Procustes Analysis algorithms, in order to verify the effectiveness of such

registration method when applied to TLS-based 3D models. Afterthat cross sections have been extracted from the global 3D model, where wall tickness and shape variation were clearly visible, to conduct a FEM- based structural analysis.This study was aimed to detect the areas of the walls requiring consolidation works of the structure.
The paper is structured as follows. In section 2 we describe the instruments and procedures adopted to survey a 200 m segment along both sides of the walls of Montagnana. Then in section 3 results of the scan global alignment, performed both with Cyclone software and with the Procrustes Analysis, are presented, while preliminary results of the FEM-based structural analysis are exposed in section 4. Finally, conclusions are discussed in section 5.

Figure 1: Partial view of the walls surrounding Montagnana

2. INSTRUMENTS

In order to build a unique 3D model comprising both outer and inner side of the walls surrounding the city of Montagnana, the laser scanning survey had to be supported by the establishment of a local network along the profile of the walls. Indeed, linking together the outer side with the inner one would have required to fully scan the pedestrian crossings available along the walls. However this solution would have led to following negative outcomes: a) increasing the number of required surveying stations and consequently the global time needed to carry out the work; b) getting a low level of scan registration accuracy, given the very limited number of crossings available along the 200 m of the walls to be surveyed. Furthermore, limiting the survey to a little segment of the walls (200 m) would have led to the modeling of a structure with "open" geometry, mainly expanded along the east-west direction only. In this sense establishing a local network could make more robust the alignment by georeferencing the scans on such network.
Since the structure geometry prevented the intervisibility between measuring stations located on both sides of the walls, the local network was defined by combining together total station and GPS survey. Network stations located along the outer side of the walls were surveyed with a Leica TC 2003 reflectorless total station, getting a global accuracy (RMS) for the adjusted coordinates (North, East and Up) of 2 mm (Fig. 2).
After this first stage, a GPS survey was undertaken using 4 double frequency receivers (two Leica 200 series, one Leica 500 and one Novatel DL4), performing static observations with a time window of 30 min. per session. Two receivers were kept in fixed positions coincident with two network stations measured with the total station, in order to transform adjusted GPS coordinates in a common reference system defined by the local network. Altogether 4 new stations were surveyed with the GPS along the inner side of the walls and then added to such network. Average accuracy (RMS) of transformed GPS coordinates was about 4.5 mm, the worstening is due to the intrinsic higher error in the measured GPS height.

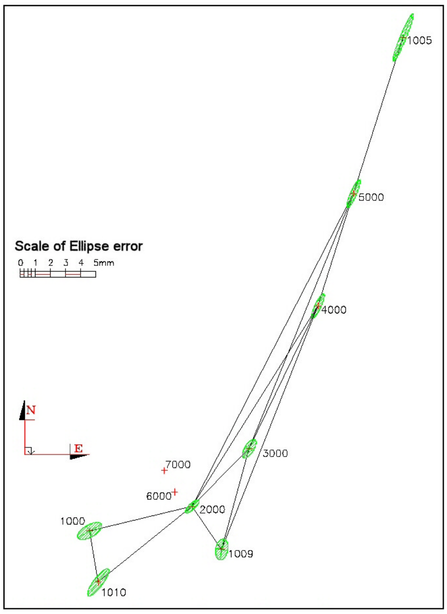


Figure 2: The local network surveyed with the total station

In the third stage of the survey, a number of retroreflective targets were placed along both sides of the wall (Fig. 3) and measured with the reflectorless total station: coordinates of corresponding target center have been then used during modeling process for laser point cloud alignment and georeferencing. Target positions were distributed along the walls in such a way that at least four of them were captured on each scan.

Figure 3: Example of retroreflective target used for laser scan registration and georeferencing

Finally, during the fourth stage, both sides of 200 m walls were surveyed with a Leica HDS 3000 laser scanner, the newest high precision Leica HDS family product (Fig. 4). This scanning system allows for a larger Field of View (360^o H x 270^o V) thanks to the adoption of a dual-window, ensuring in the same time a low beam divergence (< 6 mm @ 50 m) and a good measuirng accuracy (6 mm @ 50 m), as in previous laser system (formerly Cyrax) 2500. Furthermore, beside intensity of reflected beam the HDS 3000 is able to acquire RGB data at different user selectable pixel resolutions (low, mid, high), through the 1 Megapixel built-in CCD camera. A summary of the most important features of the HDS 3000 are reported in table 1, more details can be found in (Leica Geosystems, 2004).

Figure 4: The Leica HDS 3000 laser scanner

Table 1: Technical specifications for the HDS 3000

Leica HDS3000

SYSTEM PERFORMANCE	
RANGE	
Optimal effective range	1m-100m
To 10% reflectivity targets	Up to 100m (typical)
SINGLE POINT ACCURACY*	
Position	6mm
Distance	4mm
Angle (horizontal)	60 micro-radians
Angle (vertical)	60 micro-radians
SCAN RATE	Up to 1800 points/second*
** Maximum scan rate dependent on scan resolution and selected field-of-view*	
COLOR	Green
LASER CLASS	Class 3R (IEC 60825-1)
FIELD-OF-VIEW (PER SCAN)	
Horizontal	360° (maximum)
Vertical	270° (maximum)
SCAN DENSITY (RESOLUTION)	
Spot size	≤ 6mm from 0 - 50 meters
Maximum Sample Density	1.2mm

Despite the large Field of View of the laser allowed to survey the 200 m wall segment with few scans, in order to limit as much as possible the meaurement noise, due to the beam tilting respect with the wall surface, 16 point clouds were acquired with a 2 cm resolution on average. This relatively high scan step was choosen considering that a high level of detail was not required for this work and that Cyclone software still not provides an optimized memory (RAM) management with large datasets composed by several scans.

3. BUILDING THE 3D MODEL

3.1.1 Scan registration with Cyclone software

Acquired point clouds were processed in Cyclone software vs. 5.1, according to following scheme: in a first step, scans related to outer and inner side of the walls were registered separately, building in this way two different models, then in a second stage they were unified trough target-based georeferencing. It should be noted that this approach was required not only to overcome the problem of merging together the models of both sides of the walls, as discussed in previous section, but also to perform a sort of global registration of the scans. This operation represents indeed the final step of the registration phase, typically adopted by most of the 3D modeling software available on the market (e.g. Polyworks , Rapidform, Geomagic Studio). As described in several works (Besl et al., 1992; Bergevin et al. 1996; Pulli, 1999; Stoddart et al. 1996) the global alignment allows to distribute the residual registration error more uniformly across the scans, respect with a simple pairwise approach. Cyclone provides an easy way to perform this latter kind of alignment, through a matrix-based structure involving all possible relationships among loaded scans: of course it is up to the user to select the right correspondence by simply marking the checkbox relating the scan pair to be registered each other (Fig. 5).

On the other hand, surprisingly, such software doesn't provide any tool for the global alignment of all pairwise registered point clouds, however it tries to overcome this lack, allowing the user to somehow strength the full set of computed pairwise transformations through a target-based registration. Therefore, all 16 scans were firstly pairwise aligned, obtaining a 6 mm RMS on average (fig. 6): slightly higher values have been noticed where the overlap between adjiacent scans was less than 20% because of the structure geometry (wall apertures) and the viewing angle from the station position. Then the resulting models, one for the outside and one for the inside part of the 200 m wall segment, were furtherly registered and in the same time georeferenced in the local network using the retroreflective targets surveyed both with the total station and the laser scanner. This last operation allowed to join together in a unique model the two wall sides, as shown in figure 7c.

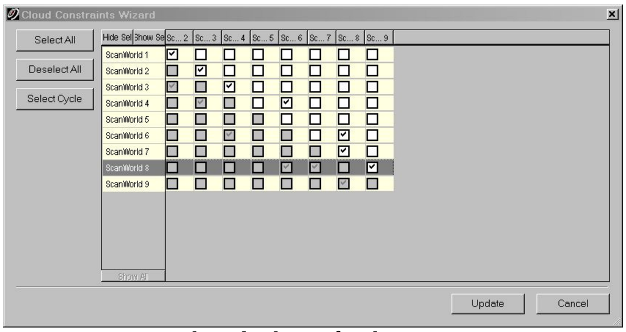


Figure 5: Matrix-based scheme for the pairwise registration

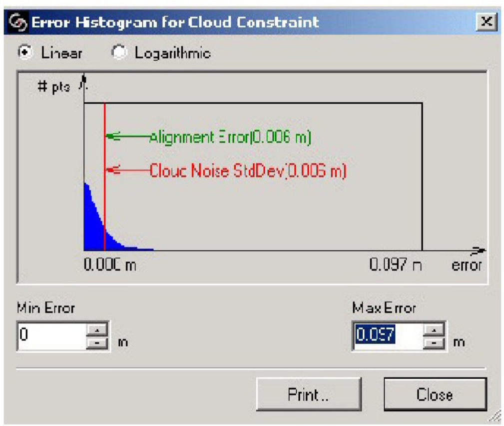
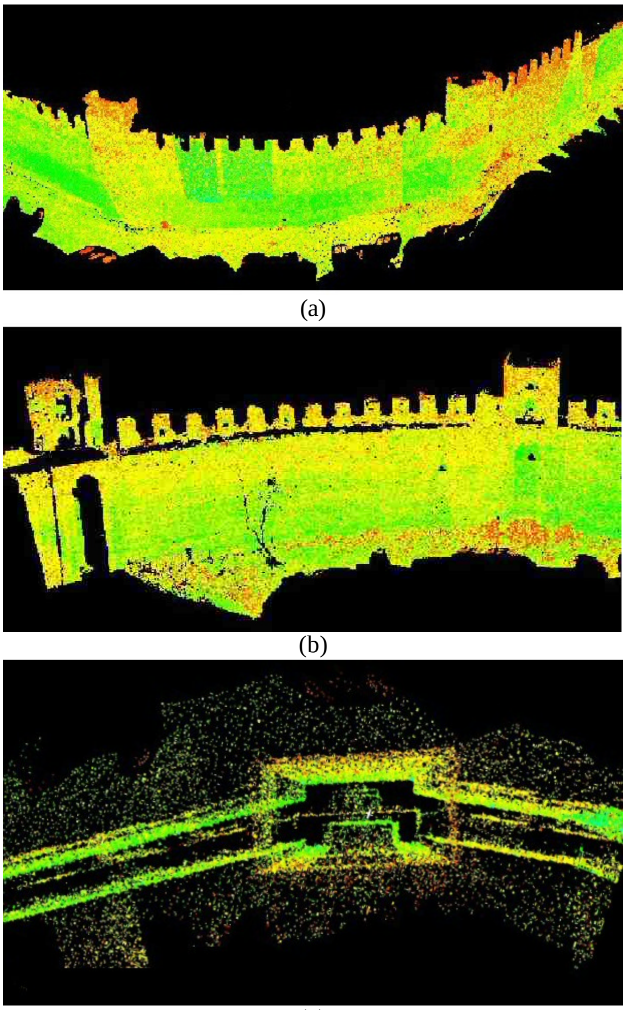


Figure 6: Example of the RMS of a pairwise registration



(a)

(b)

(c)

Figure 7: Views of the aligned scans of the outside (a) and inside walls (b); unified global model (c)

3.1.2 Procustes -based global alignment

In the context of point cloud and surface global registration, various approaches can be recognized, like for instance:

- ICP algorithm (Besl and McKay, 1992) and its multiple variants. It requires only approximations for the corresponding points but does not provide any statistical analysis tool for the results. It can converge to a wrong solution due to its closest point (or tangent plane) scheme and it cannot handle multi-scale range data. It is the most common algorithm implemented in reverse engineering software.
- Least squares 3D surface matching (Gruen et al., 2004): it is a generalization of the least squares 2D image matching concept; it can handle any kind of 3D surface and it has good tools for accuracy and reliability checks. As non-linear estimation model, it requires good approximations of the unknowns.

Beside such solutions, an alternative procedure to perform the least squares global registration of a set of range views is represented by the Generalised Procrustes Analysis (Beinat et al., 2001). This method is based on a set of mathematical least squares tools to directly estimate and perform simultaneous similarity transformations among model point coordinates matrices up to their maximal agreement. To this aim it requires identical corresponding points for the alignment. The singular value decomposition (SVD) of matrices of order 3 x 3 that characterises the Procrustes procedure avoids the need for linearisation of equation systems and large matrix inversions, thus determining a fast and easy software implementation. Moreover no prior information is requested for the geometrical relationship existing among the different model objects components. Therefore they can be expressed independently into their own reference system as a consequence, for instance, of the particular different point of view established to survey the object parts.

Being a linear estimation model, the Procrustes Analysis algorithm performs good registration when target are used during the scanning process. It lacks of reliability criterium to detect blunders and gross errors but it can handle global and simultaneous registrations and not only simple pairwise registrations.

The Generalised Procrustes Analysis is an extension to the multiview registration problem of the least square method originally developed by (Schoenemann, 1966) for the estimate of the rotation between two datasets, named as Orthogonal Procrustes Analysis (OPA). The first generalization was given by Schoenemann and Carroll (1970) which presented an algorithm to compute in a least square sense not only the unknown rotation, but also the translation and scale factor of the transformation. This method is often identified in statistics and psychometry as Extended Orthogonal Procrustes (EOPA) problem. Further generalization in the stochastic model is called Weighted Orthogonal Procrustes Analysis (WOPA), which allows for the different weighting across columns (Lissitz et al., 1976) or across rows (Koschat and Swayne, 1991) of a matrix configuration, in the case of the rotation estimate. Finally the Weighted Extended Orthoginal Procrustes Analysis (WEOPA) represents the extension of the EOPA procedure allowing for the different weighting of matrix elements.

In order to verify the effectiveness of the Procrustes Analyisis for the alignment of terrestrial laser scanning data, a test was undertaken by comparing the results of the target-based global registration performed in Cyclone software with the ones obtained from the EOPA method, applied to the 16 scans of the outside and inside walls surrounding Montagnana. The EOPA procedure was chosen in place of the Generalized Procrustes algorithm in order to use a limited number of tie points (retroreflective targets), though the latter method allowed for the global registration of all our scans. Therefore we applied the EOPA to the matching points represented by the target coordinates, related both to the local network and the laser scanner reference systems of the two models resulting from the pairwise alignments. As shown in Table 2, which summarizes the results of this comparison test, both methods provided the same level of magnitude for the RMS. This should demonstrate that even the Procrustes Analysis performs well in the case of laser scanner data registration. However further investigations are required in order to assess how good is the alignment of a set of cloud points using target-based registration algorithms if compared to range view-based softwares like Polyworks or Geomagic Studio. The key point is to establish if a limited number of tie points, as the ones provided by retroreflective targets, can provide the same results of global registration procedures, which operate directly on the whole scans and therefore on a much larger number of corresponding points.

Total # of Targets	RMS Cyclone	RMS - EOPA (outer walls)	RMS - EOPA (inner walls)
63	6 mm (63 targets)	5.3 mm (35 targets)	5.8 mm (28 targets)

4. 3D MODEL STRUCTURAL ANALYSIS

As mentioned at the beginning of this paper, 3D models of cultural heritage objects have been mainly considered so far in terms of data sources for as-built documentation, archiving and restoration purposes. However in our opinion, they comprise a larger information content, allowing them to be profitably used in a wider number of application fields. In order to demonstrate the validity of this assertion, in this section we report the preliminary results of a FEM-based structural analysis performed on a short track of the 200 m wall segment surveyed with HDS 3000 laser scanner.

The advantage of the use of a laser scanner-based 3D model for structural analysis investigations is mainly represented by the availability of a high detailed representation of the object's geometry, which allows for a better estimate of the stressing states. Tipically, structural investigation tools can be related to the following two main groups: traditional static analysis and Finite Element Methods (FEM). The latter seems to be more suited for complex structures, as it provides several advantages, among which we recall the option to work in a 3D space, to perform different kind of analysis (linear, non-linear, dynamic, etc.) and to test specific features of the structure with a stepwise approach. On the other hand FEM analysis doesn't allow to estimate the plausible response in the case of elements that are non-stressing resistant.

A few cross-sections extracted from the unified 3D model of the walls were importated as DXF in the Straus software, considering a 1 m section depth, subdivided according to a series of 4-node elements (Plate) of 20 cm each. A linear static analysis was performed on such cross-sections, aimed to study the response of the wall structure to three different effects: the own weight, the wind and the off-plumb line. Corresponding results related to a cross-section sample are shown in figures 8, 9 and 10 respectively.

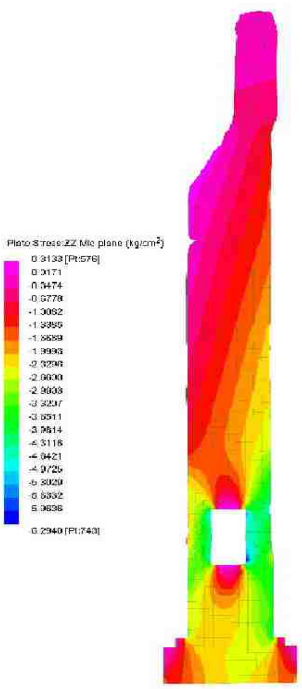


Figure 8: Color map showing the effect of the vertical stresses due to the weigth of the cross-section

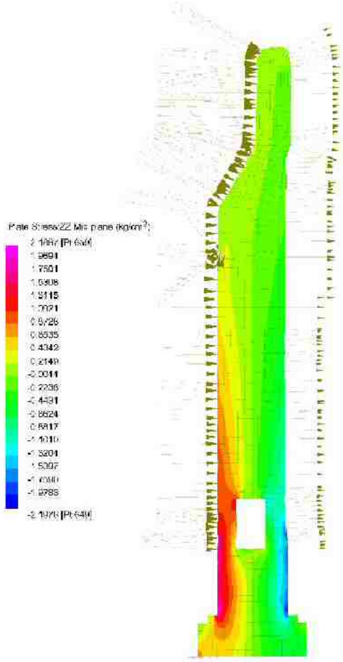


Figure 9: Color map showing the effect of the vertical stresses due to the wind

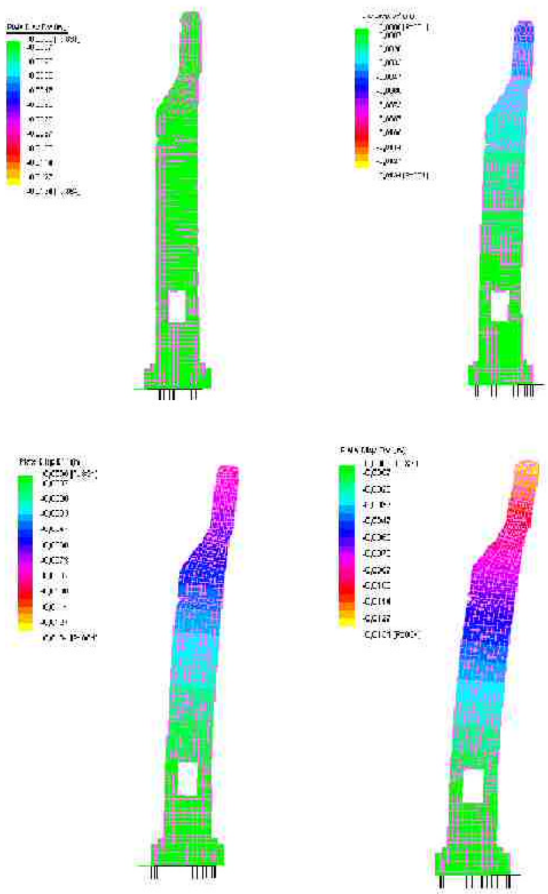


Figure 10: Plumb line displacements due to the increasing applied loads

5. CONCLUSIONS

In this paper a work related to 3D model-based structural analysis on a structure belonging to the Cultural Heritage has been presented. Namely, the outer and inner side of the walls of of Montagnana, an ancient little city near Padua, were surveyed with combined procedures: reflectorless total station, double frequency GPS receivers and high precision terrestrial laser scanner. During the modeling stage, a global alignment of acquired scans was performed employing two different methods: through the registration tool provided by Cyclone modeling software and by application of the Procrustes Analysis algorithm. Result comparison showed that even this registration method performs well when applied to TLS-based 3D data. However further investigations are required in order to assess the accuracy of target-based alignment of a point cloud set if compared to range view-based softwares like Polyworks or Geomagic Studio, which operate directly on the whole scans and therefore on a much larger number of matching points.
Preliminary results related to the structural analysis of the surveyed walls have been presented, as well. The study is current under development and it is aimed to detect the areas of the wall requiring most important consolidation works of the impressive structure enclosing the ancient city of Montagnana.

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