

LINEAR FEATURES IN PHOTOGRAMMETRIC ACTIVITIES

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ABSTRACT:

Photogrammetric manipulation of imagery has been, for the major part, a point-based operation. The utilization of points remains to be convenient since few manually digitized points can be accurately obtained to carry out various photogrammetric orientation procedures (e.g., relative and absolute orientation as well as photogrammetric triangulation). On the other hand, the constant evolution of digital photogrammetry calls for the use of other primitives since distinct points fall short when attempting to derive higher level/semantic information from the input imagery. As a result, there has been a tremendous interest by photogrammetric researchers in utilizing linear features in various photogrammetric activities. This interest is attributed to the fact that the extraction of linear features from the image space is easier to automate than distinct points. On the other hand, object space linear features can be directly derived from terrestrial Mobile Mapping Systems (MMS), GIS databases, and/or existing maps. Moreover, automatic matching of linear features, either within overlapping images or between image and object space, is easier than that of distinct points. Finally, linear features possess more semantic information than distinct points since they likely correspond to object boundaries. Such semantics can be automatically identified in the input imagery to facilitate higher-level tasks (e.g., surface reconstruction and object recognition). This paper summarizes the authors' prior research using linear features, which might be represented by analytical functions (e.g., straight-line segments) or irregular (free-form) shapes, in photogrammetric activities such as automatic space resection, photogrammetric triangulation, camera calibration, image matching, surface reconstruction, image registration, and absolute orientation as well as in medical applications. Current progress, future expectations, and possible research directions are discussed as well.

1. INTRODUCTION

The majority of manual orientation as well as map compilation processes rely heavily on point-based features, which are well determined in two-dimensional imagery. For these features, the human operator has to store their semantics for later use. After the introduction of softcopy workstations and digital image compilation and analysis, the majority of recent research activities have been focusing on the automation of various point-based procedures in photogrammetry (Förstner, 1986; Haala and Vosselman, 1992; Gülch, 1994; Drewniok and Rohr, 1997). The main difficulty in this type of research is the automatic extraction of useful semantics for the identified point primitives.

Recently, more attention has been focused on using higher-level features (e.g., linear and areal features) in various photogrammetric operations. The emergence of digital images coupled with well-developed image processing tools motivated this direction of research. Also, the research has been propelled by the fact that automatic extraction of linear features is easier than distinct points (Kubik, 1991). The reliability of the extracted features is another factor to be considered. The reliability stems from the relationships among the sub-entities, which yields a robust extraction process that is not susceptible to inherent noise in the input imagery. Moreover, such features increase the system's redundancy and consequently improve the geometric strength and robustness in terms of the ability to detect blunders. Therefore, matching ambiguities can be resolved, occluded areas can be easily predicted, and/or changes can be detected. Moreover, higher-level features, which can be automatically extracted, possess more semantic information

regarding the object space. This constitutes an important factor for facilitating subsequent processes such as surface reconstruction and object recognition. In the object space, linear features can be easily derived from existing maps, GIS databases, or terrestrial Mobile Mapping Systems (MMS).

There has been a substantial body of work dealing with the use of linear features that can be represented by analytical functions (such as straight lines and conic curves) in photogrammetric orientation (Mulawa and Mikhail, 1988; Heuvel, 2000). On the other hand, few research attempts have addressed the use of free-form linear features (Smith and Park, 2000). The main objective of the presented research in this paper is to establish a model capable of incorporating linear features, whether represented by analytical functions or free-form shapes, in images captured by frame cameras as well as scenes acquired by linear array scanners (line cameras). The implementation should allow for possible incorporation of these features in multi-sensor photogrammetric triangulation and other photogrammetric and medical activities (such as single photo resection, camera calibration, relative orientation, scene/image registration, and absolute orientation).

In the next section, a short discussion regarding the motivation for using linear features is introduced. Section 3 deals with various alternatives for image and object space representation of linear features as well as the corresponding perspective transformation. The main applications of these primitives in various photogrammetric operations are briefly discussed in Section 4. Finally, conclusions and recommendations for future work are presented in Section 5.

2. FEATURE TYPES

Features can be defined as discerned objects of interest that can be extracted in the working space. Therefore, features in a photogrammetric environment can be classified into image and object space features. The following subsections discuss the various types of features that can be found in the image and object space.

2.1 Image Space Features

Image space is two-dimensional. Therefore, primitives that can be extracted from this space are either point, linear, or areal features. It can be argued that areal features are the most general features, because the image space can be classified into homogeneous areal features/regions without leaving any part of the space unclassified. Linear and point features can be considered as a subset of areal features whose dimension in one or two directions is negligible because of scale or application requirements.

2.2 Object Space Features

Object space is a three-dimensional space. Following the same line of thought in the previous section, one can consider volumetric features as the basis and most general primitives capable of representing the entire object space. However, appropriate object space features have to be based on the photogrammetric procedure of object space reconstruction. In photogrammetry, observing conjugate primitives in overlapping images is utilized to derive corresponding object space elements. The process usually starts by the extraction of image space primitives, either manually or automatically. Then, corresponding primitives need to be identified in overlapping images. Finally, geometric attributes of the imaging system, represented by the Interior and Exterior Orientation Parameters (IOP & EOP), as well as matched primitives are used in an intersection procedure to generate the corresponding object space. Therefore, suitable object space primitives are those that can be reliably extracted and matched in the input imagery. So far, photogrammetric object space reconstruction has been solely based on utilizing point and linear features. In other words, there has not been an established procedure for object space reconstruction using image space areal features. This leads us to conclude that point and linear features are the most suitable primitives for object space reconstruction from imagery and consequently they should be the chosen primitives. However, it should be noted that 3-D areal features (sometimes called surface patches) could be considered when implementing its dual representation, the bounding linear features.

2.3 Linear Features for Photogrammetric Activities: Why?

With the introduction and continuous evolution of digital photogrammetry as a result of the availability of high-resolution scanners and advances in digital image processing, automated procedures are becoming popular. However, most of these procedures are still point-based. Image processing techniques allow for the extraction of numerous points with lower quality than those selected manually. Moreover, automatic matching of the extracted points in overlapping images is complicated and often unreliable procedure due to variations in the imaging system's point of view and relief displacements in the image space. Due to the above limitations, recent photogrammetric research has been focusing on the use of linear features. This line of research has been motivated by the following facts:

- Image space linear features are easier to extract when compared to distinct points. This is attributed to the nature of linear features since they represent discontinuities in the grey value function in one direction. On the other hand, point features represent discontinuity in all directions.
- Linear features in the image space can be extracted with sub-pixel accuracy across the direction of the edge.
- Images of man-made environments are rich with linear features.
- Linear features allow for the incorporation of areal features through the use of their boundaries. Moreover, linear features are easier to use in change detection applications than areal features. The superiority of linear features stems from the possibility of dividing them into smaller subsets. On the other hand, breaking areal features into smaller subsets is not a trivial task.
- Mobile Mapping Systems (MMS) can economically provide accurate and current object space linear features in real time.
- Linear features possess higher semantic information, which are desirable for subsequent processes (such as DEM generation, map compilation, and object recognition). On the other hand, it is hard to derive useful semantic information regarding the real world from distinct points. Moreover, geometric constraints are more likely to exist among linear features than points. This will facilitate subsequent automatic matching and object recognition activities.
- Linear features increase the redundancy and improve the robustness and the geometric strength of various photogrammetric adjustment activities.

Image space linear features can be either represented by an analytical function (e.g., straight-lines and conic sections) or by an irregular (free-form) shape. Among these representation alternatives, one can argue that straight-line features are appropriate for photogrammetric activities for the following reasons:

- Man-made environments are rich with straight lines.
- Straight lines are easier to detect and the correspondence problem between overlapping images as well as between the image and object space becomes easier.
- Straight-line parameters can be obtained with sub-pixel accuracy.
- Free-form linear features can be represented with sufficient accuracy as a sequence of straight-line segments (poly-lines).
- Straight lines are valuable for the recovery of the IOP of frame cameras, where object space straight lines should appear as straight lines in the image space in the absence of distortions. Therefore, deviation from straightness in the image space can be attributed to distortions (e.g., radial and de-centring lens distortions).
- Straight lines are valuable for the recovery of the EOP of linear array scanners, where object space straight lines will not appear as straight lines in the image space due to perturbations (changes in the EOP) along the flight trajectory.

3. UTILIZING STRAIGHT-LINE FEATURES IN PHOTOGRAMMETRIC ACTIVITIES

Incorporating linear features in photogrammetric applications has to address two key issues. First, one should determine the most convenient alternative for representing straight-line features in the image and object space. Then, a mathematical model has to be derived to incorporate the geometric attributes of these primitives to solve the photogrammetric problem in question.

3.1 Object Space Representation of Straight Line Features

The authors' prior research showed that a straight line in the object space is properly represented using two points (X_1, Y_1, Z_1) and (X_2, Y_2, Z_2) along the line, which can be the beginning and end points of that segment, Figure 1. Therefore, we will end up with well-defined line segments in space, which can be directly incorporated in GIS databases. In addition, such representation will have no singularity (i.e., it is capable of representing all line segments in space). Moreover, free-form linear features can be represented with sufficient accuracy by a set of connected finite straight-line segments. Finally, such representation would lead to a straightforward perspective transformation between the image and object space features. Such transformation functions can be easily incorporated in existing bundle adjustment procedures. Comparison between this representation and other representations can be found in (Habib and Morgan, 2003).

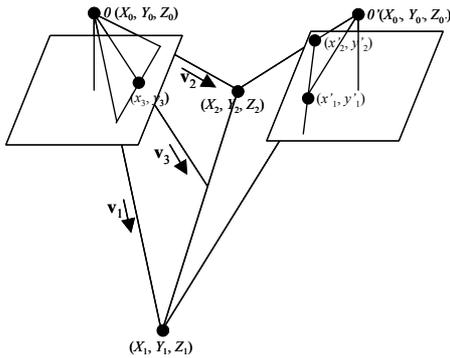


Figure 1. Object line representation and the mathematical model - the coplanarity condition

3.2 Image Space Representation of Straight Line Features

After representing the object space line, one has to consider its representation in the image space. As discussed in the previous section, two points define the object line. These points can be selected in one or two images within which this line appears, but they need not be visible in other images, Figure 2. On the other hand, corresponding linear features in overlapping images will be defined by a sequence of intermediate points along these features. The measured intermediate points need not to be conjugate. Figure 2 illustrates two scenarios for the measurement of the end and intermediate points. The end points can be either identified in a single image (Figure 2-a) or in two different images (Figure 2-b).

This representation can handle raw images captured by frame cameras in the presence of distortions (i.e., it allows for possible deviations from straightness in the image space features). Therefore, such a representation can be incorporated in a bundle adjustment with self-calibration procedure to solve for the IOP

of the implemented camera. Moreover, it is suitable for dealing with linear features in scenes captured by linear array scanners since perturbations in the flight trajectory would cause deviations from straightness in the acquired images of these features.

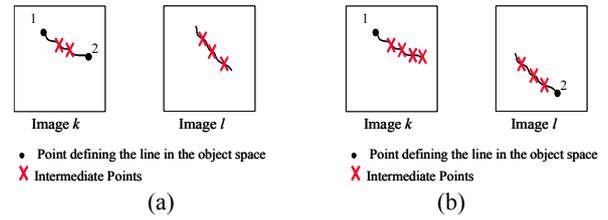


Figure 2. End points can be measured in one image (a) or in two different images (b) while the intermediate points are measured in all images within which the line appears

3.3 Perspective Transformation of Straight Line Features

In this section, we will discuss a method for image-to-object space perspective transformation of straight-lines. The relationship between the measured end points and the corresponding ground coordinates, (X_1, Y_1, Z_1) and (X_2, Y_2, Z_2) , is established through the collinearity equations. For every intermediate point, a constraint has to be introduced to ensure that the two ground points, the intermediate image point, and the corresponding perspective centre are coplanar. This constraint can be expressed as the triple product in Equation 1, Figure 1.

$$(\mathbf{v}_1 \times \mathbf{v}_2) \cdot \mathbf{v}_3 = 0 \quad (1)$$

where:

- $\mathbf{v}_1, \mathbf{v}_2$ are the vectors connecting the perspective centre and the two object points (the end points), and
- \mathbf{v}_3 is the vector connecting the intermediate point and the perspective centre, rotated into the ground coordinate system.

The constraint in Equation 1 incorporates the ground coordinates of the points defining the object line, the IOP of the camera, the image coordinates of the intermediate point, and the EOP of the image. Thus, it does not introduce new parameters. Control lines can be also considered. In such a case, there is no need to measure the end points in the imagery since the control line already defines them. The depicted constraint in Equation 1 is suitable for the estimation of distortion parameters associated with frame cameras. Moreover, for scenes captured by linear array scanners, it can be used to estimate variations in the EOP of the scanner along the flight trajectory. Such capability is attributed to measuring numerous intermediate points along the linear feature in the image space. Furthermore, the constraint in Equation 1 can be easily incorporated in existing bundle adjustment programs.

3.4 Straight-Lines in Other Photogrammetric and Medical Applications

In this section, we will investigate the use of linear features in other photogrammetric and medical applications; namely, image-to-image registration (using 2-D line segments) and surface-to-surface registration (i.e., absolute orientation using 3-D line segments). For these applications, the line segments will be represented by their end points, which need not be conjugate.

The correspondence of the line segments is described by a mathematical constraint, which ensures the coincidence of conjugate line segments after applying the proper transformation function relating the involved images or surfaces.

To illustrate the concept of the registration procedure using line segments, let us consider Figure 3, where a line segment a , defined by the end points 1 and 2, in the first dataset is known to be conjugate to the line segment b , defined by the end points 3 and 4, in the second dataset. Let us assume that the line segment a' , defined by the end points 1' and 2', is the same line segment a after applying the transformation function relating the two datasets in question. In this case, we need to introduce a mathematical constraint, which guarantees that the end points 1' and 2' lie along line b but not necessarily coincide with points 3 and 4. In other words, the mathematical model should minimize the normal distances between the transformed end points in the first data set, points 1' and 2', and the corresponding line in the second dataset, line b . The implemented transformation function depends on the nature of involved datasets. For example, either 2-D similarity or affine transformations can be used for image-to-image registration. On the other hand, 3-D similarity transformation can be used for surface-to-surface registration applications.

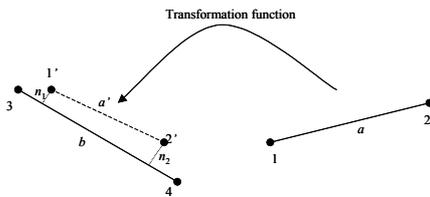


Figure 3. Correspondence of conjugate line segments in two datasets

4. APPLICATIONS

This section briefly outlines the implementation of linear features in various photogrammetric and medical applications such as automatic space resection, photogrammetric triangulation, camera calibration, image matching, surface reconstruction, image-to-image registration, and absolute orientation. We are mainly illustrating the value and the benefits of using linear features. However, detailed analysis of such applications can be found in the provided references.

4.1 Single Photo Resection (SPR)

In single photo resection, the EOP of an image are estimated using control information. Traditionally, the SPR problem has been solved using distinct control points. However, the SPR can be established using control linear features, which can be derived from MMS, existing GIS databases, and/or old maps. Conjugate object and image space straight-line segments can be incorporated in a least squares procedure, utilizing the constraints in Equation 1, to solve for the EOP. A minimum of three non-parallel line segments is needed to solve for the six elements of the EOP. This approach can be expanded to handle free-form linear features, which can be represented by a set of connected straight-line segments, Figure 4. Habib et al. (2003b, c) introduced the Modified Iterated Hough Transform (MIHT) to simultaneously establish the correspondence between object and image space line segments as well as estimate the EOP of an image captured by a frame camera. The MIHT successfully

estimated the EOP while finding the instances of five object space linear features within twenty-one image space features, Figure 4.

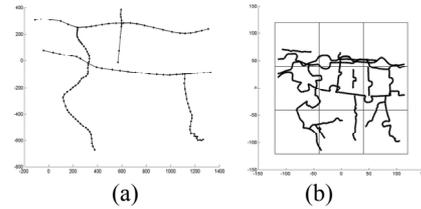


Figure 4. SPR using control linear features (a) while establishing the correspondence with image space features (b)

4.2 Photogrammetric Triangulation

In this application, straight lines can be implemented as tie features, control features, or a combination of both. Habib et al. (1999, 2001a) showed the feasibility of utilizing straight lines in photogrammetric triangulation using straight-line segments in imagery captured by frame cameras and linear array scanners, respectively. It has been proven that the photogrammetric triangulation of scenes captured by linear array scanners incorporating straight-line segments leads to a better recovery of the EOP when compared to those derived using distinct points.

4.3 Digital Camera Calibration

Camera calibration aims at determining the internal characteristics of the involved camera(s). Traditionally, the calibration starts by establishing a test field containing many precisely surveyed point targets, which requires a photogrammetrist or surveyor. On the other hand, the calibration test field incorporating linear features is very easy to establish compared to that containing point targets. In addition, the linear features can be automatically extracted allowing non-photogrammetric users of digital cameras to produce high quality positioning information from imagery. Straight lines could be beneficial for estimating the internal characteristics of frame cameras. Deviations from straightness in the image space are attributed to various distortions (e.g., radial and de-centring lens distortions). Habib and Morgan (2002, 2003) and Habib et al. (2001a; 2002) used object space straight-lines in a calibration test field as tie features for digital camera calibration.

Figure 5-a shows an image of the test field comprised of straight lines, where distortion parameters led to deviations from straightness in the image space. Figure 5-b illustrates the recovery of the straightness property using the estimated IOP from the calibration procedure. Moreover, the calibration results turned out to be almost equivalent to those derived from traditional point-based calibration procedures.

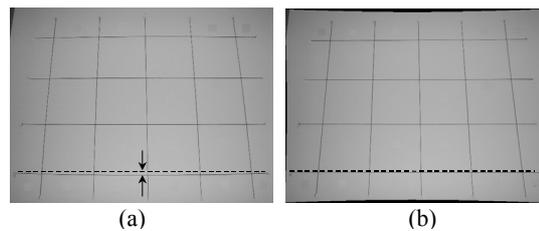


Figure 5. Straight line before calibration (a) and after calibration (b). Straight dotted lines were added to show the recovery of the straightness property

4.4 Image Matching and 3-D Reconstruction

Object space reconstruction is the prime objective of photogrammetry. Traditionally, this process starts by matching points in the image space. However, matching points encounter many problems due to different geometric and radiometric differences between the images as well as repeated signals. It is very hard to reduce or eliminate mismatched automatically – it is up to the human operator to reject them. Apart from points, Habib and Kelley (2001) used the MIHT strategy to estimate the Relative Orientation Parameters (ROP) between stereo-pair of images using linear features. The suggested approach was successful in dealing with large-scale imagery over urban areas, which proved to be difficult when using traditional matching procedures. Habib et al. (2003a) extended this approach to allow for the reconstruction of corresponding 3-D linear features, Figure 6. Such an approach can be expanded to allow for surface reconstruction, ortho-photo generations, and object recognition applications.

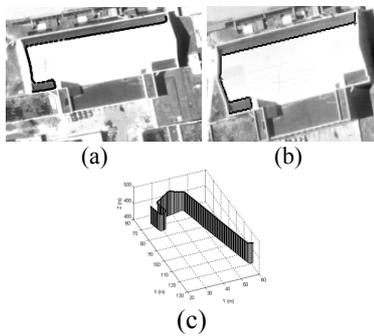


Figure 6: Left (a) and right (b) images containing matched linear features and the reconstructed 3-D linear feature (c)

4.5 Photogrammetric and Medical Image-to-Image Registration

With the enormous increase in earth observing satellites, there has been an urgent need for establishing automatic and accurate registration techniques of multi-source imagery with varying geometric and radiometric properties. Traditional image registration techniques require distinct points, which have to be identified in the imagery. However, identifying conjugate points in imagery with varying geometric and radiometric resolutions is difficult. Habib and Al-Ruzouq (2004) used linear features for the co-registration of scenes captured by space-borne linear array scanners. The MIHT strategy has been implemented to automatically establish the correspondence between conjugate linear features as well as estimate the parameters relating the involved scenes. Figure 7 shows straight-line features digitized in SPOT and IKONOS scenes as well as a mosaic scene generated after establishing the registration.

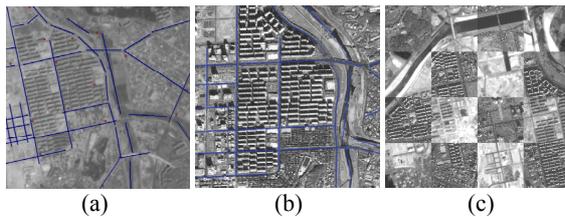


Figure 7. SPOT (a) and IKONOS (b) scenes with digitized linear features, which are used to generate a composite mosaic (c)

Similarly, in medical images, it is often hard to find conjugate points, Figure 8. Linear features, as seen in the same figure, can be used instead to facilitate the registration between the images.

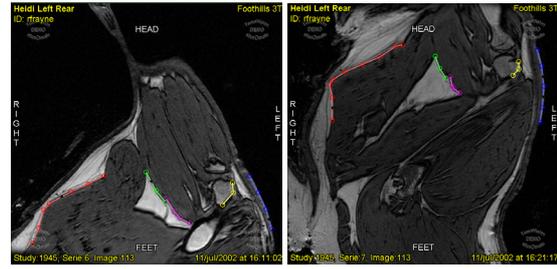


Figure 8. Registration of medical images

4.6 Surface-to-Surface Registration

With the increasing popularity of LIDAR systems, there has been an interest in establishing procedures for surface-to surface registration for change detection applications (e.g., Habib et al., 2001b). Habib et al. (2004) used LIDAR features as control information to establish the absolute orientation of 3-D photogrammetric models. Photogrammetric triangulation incorporating tie linear features has been used to derive 3-D straight-line segments relative to an arbitrary coordinate system, Figure 9-a. On the other hand, LIDAR linear features have been extracted by processing the elevation data, Figure 9-b. Finally, conjugate photogrammetric and LIDAR features were used to determine the parameters relating the photogrammetric coordinate system to the LIDAR reference frame (i.e., solve for the absolute orientation parameters). The approach proved to be successful in detecting discrepancies between the involved surfaces. Such discrepancies can be either attributed to changes in the object space and/or un-accounted systematic biases in the data acquisition systems.

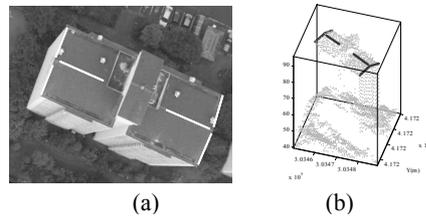


Figure 9. Straight-line features obtained from photogrammetric (a) and LIDAR (b) systems

5. CONCLUSIONS AND RECCOMENDATION FOR FUTURE RESEARCH

This paper discussed key issues related to the incorporation of linear features in photogrammetric applications. First, it has been established that among the possible types of linear features, straight-line segments are the most interesting ones. This can be attributed to the fact that they abundantly exist in imagery of man-made environments. Also, free-form linear features can be represented with sufficient accuracy as a sequence of straight-line segments (poly-lines). Moreover, straight-line segments are valuable for the self-calibration of frame cameras and the recovery of the EOP for linear array scanners.

We introduced a mathematical model for incorporating linear features in photogrammetric and medical problems (e.g., automatic space resection, photogrammetric triangulation,

camera calibration, image matching, surface reconstruction, image-to-image registration, and absolute orientation). For example, straight-line segments from existing GIS databases can be used to estimate the EOP of a single image (SPR). Such integration of object space vector data with aerial imagery would allow for detecting changes and updating applications. Straight lines can be also used either as control or tie features in photogrammetric triangulation procedures involving frame or linear array scanners. For frame cameras, the straight-lines will allow for the recovery of the IOP of the implemented camera. In addition, straight-lines will lead to a reliable recovery of the EOP associated with scenes captured by linear array scanners. In addition, linear features offer a significant advantage in solving image matching and surface reconstruction problems, especially when dealing with large-scale imagery over urban areas.

Finally, we outlined a methodology for incorporating linear features in image-to-image and surface-to-surface registration tasks. Such a methodology is valuable for registering multi-source imagery with varying geometric and radiometric resolutions. Moreover, it can be used as a tool for utilizing LIDAR surfaces as control information for photogrammetric triangulation and the calibration of LIDAR/photogrammetric systems.

Future research will concentrate on automatic extraction of linear features from imagery. Incorporating linear features in approximate sensor models, such as rational functions, direct linear transformation and parallel projection models, will also be investigated. Finally, future work will focus on incorporating linear features in surface reconstruction, object recognition, change detection, and map updating activities.

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