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Radar-Altimeter Inertial Vertical Loop—Multisensor Estimation of Vertical Parameters for Autonomous Vertical Landing †

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Abstract: The design, key functionalities, and performance requirements placed on modern aircraft navigation systems must adhere to the needs imposed by the progressively growing UAS/UAM and eVTOL segments, especially for terminal area operations in urban areas. This paper describes the design, implementation, and real-time validation of Honeywell's Kalman filter-based radar-altimeter inertial vertical loop (RIVL) prototype. Inspired by the legacy of barometric altimeter-based technology, the RIVL prototype aims to provide high accuracy and integrity estimates of vertical parameters (altitude/height above ground and vertical velocity). The results from simulation tests, flight tests, and crane tests demonstrate that the vertical parameters estimated by the prototype satisfy vertical performance requirements across different terrains and scenarios.

Keywords: radar altimeter; Kalman filter; altitude/height above ground; vertical velocity; estimation; UAM; UAS; terrain detection

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1. Introduction

The radar-altimeter inertial vertical loop (RIVL) provides vertical parameters—altitude above ground and vertical velocity—with increased accuracy and integrity compared to currently available systems. These are very important parameters for autonomous operation, including the vertical landing of uncrewed aircraft systems (UAS)/UAM vehicles. The rapid growth of the segment and new challenges related to landing procedures in urban areas drives the demand for high-accuracy systems enabling high-precision and autonomous landing operations. The currently available sensors—radar altimeters, radars, light detection and ranging (LIDAR) technologies, cameras, and barometers—are either not able to satisfy landing-zone requirements or represent a significant cost. Radar-altimeter sensors are standard avionics equipment that can satisfy the landing operation requirements only up to certain accuracy. Considering, for example, accuracy requirements of 95% for an altitude above ground of 0.5 m and a vertical velocity of 0.2 m/s, new systems and approaches are necessary.

The basic idea of the RIVL system is to blend radar-altimeter measurements with inertial-based vehicle vertical-acceleration outputs in the navigation frame, usually provided by an attitude and heading reference system (AHRS) or an inertial reference system (IRS), to estimate altitude and vertical velocity statistics with higher accuracy than standard onboard navigation systems [1,2]. A similar algorithm—barometric altimeter inertial vertical loop (BIVL)—is a widely known solution used in inertial navigation systems [3,4]. The naturally unstable vertical channel of the inertial solution is stabilized using vertical

measurements from an independent source and third-order complementary-filter blending measurements from the altitude source; in this case, a barometric altimeter, with inertial vertical acceleration [5,6]. The BIVL is globally available without any specific restrictions. The disadvantage of this method is the achievable performance, which cannot satisfy the requirements for UAS/UAM and eVTOL landing procedures. The accuracy and integrity requirements are achievable with radar altimeters (or other radar technologies) with accurate range-to-ground measurements. When a radar altimeter is used as the altitude source, the altitude measurements are influenced by terrain variations, but the inertial vertical acceleration does not capture these terrain variations. This terrain inconsistency limits the standard mechanization approach, and finding the solution to this issue while satisfying vertical navigation requirements is one of the key motivating factors for updating the vertical loop system design.

The Kalman filter was chosen as the estimation building block for the updated RIVL design. The main advantages of the updated vertical loop design as compared to the standard third-order loop approach [3–5] (frequency domain) are the ability to incorporate the effects of altitude changes due to terrain through state-space selection and design, to estimate the variance of the vertical parameters, and to assure the integrity of the estimated vertical parameters. This approach does not use terrain elevation information stored in a database. One example of a design using the map of the terrain surface is covered in [7]. The trade-offs of state-space designs with respect to the terrain changes are:

- Mechanization considering terrain variations (a dedicated state in the state space to estimate terrain changes): higher estimated variance, as a general terrain model adds uncertainty to the filter's estimates of the vertical statistics.
- Mechanization neglecting terrain variation in + detection of the terrain utilizing radar-measurement innovation tests and reinitializing the filter when terrain changes are detected: relies on the selection of thresholds to detect unknown terrain variations, and reinitializing the filter during critical vehicle operations leaves the vehicle without a vertical navigation solution that satisfies requirements.

The disadvantage of the proposed design is based on the measurements that are of different kinematic parameters, i.e., the vehicle's vertical acceleration and the range-to-ground measurements depend on vehicle motion and terrain variations. The goal is to select the state-space model and design the filter to use measurements of different parameters to estimate the vertical parameters. Therefore, the terrain-detection and convergence capabilities of the nominal state space and Kalman filter design for a vertical loop had to be modified and augmented to satisfy vertical navigation requirements.

The state-space design and Kalman filter-based solution were modified and tested in various design options. A bank of Kalman filters based on the pre-defined number of filters operating in parallel for fixed time intervals processing the same data was chosen as the design implementation. This solution is the evolution of the moving-window Kalman filter approach. After terrain variance occurs, the moving-window implementation enables the filter to satisfy the convergence time requirements.

This paper is organized as follows. In Section 2, we describe the design of the RIVL system. In Section 3, we outline the tests conducted to assess the performance of the RIVL. In Section 4, we assess the performance of the RIVL system using different scenarios. In Section 5, we conclude the paper and include suggestions for future research.

2. RIVL Algorithm—Bank of Parallel Filters

The following block diagram (Figure 1) summarizes the basic logic adopted for the RIVL system combining the BIVL and RIVL using Kalman filter-based solutions. Since the proposed solution uses the Kalman filter algorithm, the state vector for both BIVL and

RIVL consists of altitude (radar or barometric), vertical velocity, accelerometer bias, and altimeter (radar or barometric) bias.

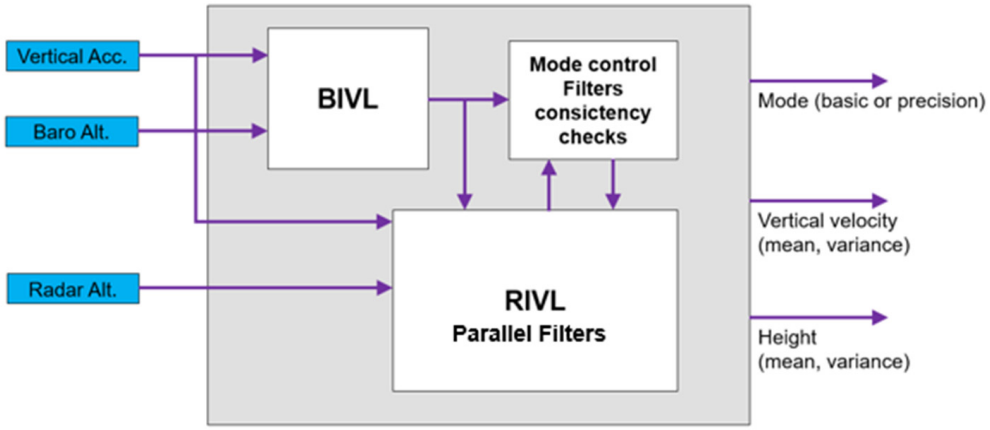


Figure 1. The block diagram of the RIVL system.

The RIVL system consists of two subsystems, the BIVL filter and RIVL parallel filters. The BIVL filter is implemented as a Kalman filter, fusing inertial vertical-acceleration statistics with barometric altimeter measurement statistics. The RIVL parallel-filter subsystem is implemented as a bank of parallel Kalman filters. Each RIVL Kalman filter uses the same state-space system, and they fuse inertial vertical-acceleration statistics with radar-altimeter measurement statistics.

The primary objective of the BIVL is to initialize vertical velocity in the bank of parallel filters of the RIVL system. The radar-altimeter output is used for initialization of altitude above ground. The baseline component of the system is Kalman filter blending radar-altimeter measurement statistics and inertial vertical-acceleration statistics to provide altitude-above-ground and vertical-velocity statistics. To address the issue of inconsistency caused by terrain variation, the Kalman filter is designed to operate only on a limited history of input data. The principle is implemented using a bank of Kalman filter slots, where in each slot there is one instance of the baseline Kalman filter. This results in a bank of filters running in parallel, each operating on slightly different intervals of input data. There is one special instance of the BIVL filter (Kalman filter equivalent of legacy BIVL algorithm) for the initialization of certain states of the baseline Kalman filter. Each filter in the slot is first initialized using the BIVL (vertical velocity and accelerometer bias) and radar altimeter (altitude above ground). In each iteration, the RIVL system output can be selected based on various criteria focusing on the best accuracy or integrity (filter with the longest duration, the mean of all filters, filter with the lowest normalized sum of innovations, etc.). The filter slot can be restarted based on various criteria (maximal duration time reached, innovation monitoring, etc.). Time loading, accuracy, and convergence can be controlled by three parameters—number of filter slots, filter density, and maximal duration of filters. The single slot is reinitialized due to time expiration (slot duration) or Kalman filter innovation monitoring. The innovation statistics are compared to the thresholds based on the probability of false alerts [8].

The simplified principle of the RIVL design based on parallel filters is depicted in Figure 2. This figure defines the bank of filters (1 to N) running in parallel for the pre-defined time (slot duration). Each filter operates with a pre-defined range of input data and the operational time lag is defined by the filter density value.

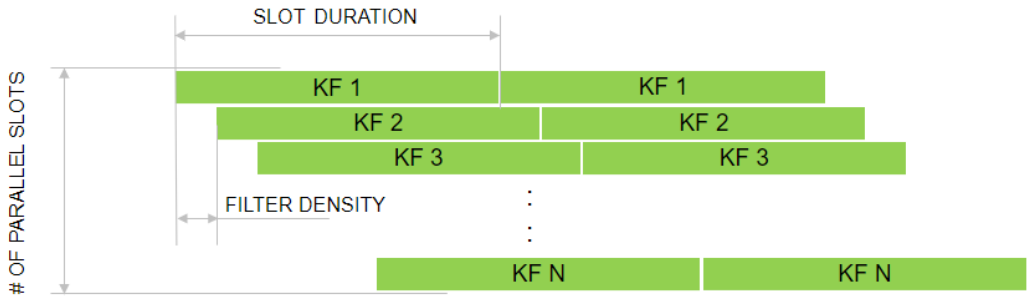


Figure 2. The slot duration enables achieving the steady-state estimation covariance and combined with the filter density value influences the smoothness of the RIVL solution. The slot-duration value divided by filter density leads to the optimal number of parallel slots ('# of parallel slots' in the picture).

3. Simulations and Real-Time Tests

The performance of the RIVL system was tested using three different experiments. First, the RIVL system was evaluated using extensive simulation tests with flat and variating terrains. These simulation tests enable the RIVL system to be tested using terrain variations that are difficult to replicate during flight tests. Second, the RIVL system was evaluated using fixed-wing flight tests on board the Evektor EV-55 (manufactured by Evektor Aerotechnik, Kunovice, Czech Republic). These flight tests were used to test the proof-of-concept in a real flight environment focusing on the functionality and robustness of the RIVL design. Third, the RIVL system was evaluated using crane tests. These crane tests were used as a substitute for the real flight environment and vertical take-off and landing maneuvers.

3.1. Nominal and Terrain Variation Simulations

The collection of the nominal scenarios aims to test the RIVL system with the vehicle operating over flat terrain. These scenarios are used to evaluate the sensitivity of the RIVL system to input parameters. The RIVL system uses a user-selected number of parallel Kalman filters (# of slots) with a mutual time shift (KF density), each running for a predefined period (slot duration). Each filter can be terminated by innovation monitoring, which identifies measurement inconsistencies.

The collection of terrain variation scenarios aims to test the RIVL system's ability to detect terrain changes, minimize the effect of the terrain change on the system's output, and ensure the RIVL system satisfies convergence time and performance requirements. Terrain variations can be approximated by steps and ramps. Terrain variations with ramp profiles with low "terrain-induced" vertical velocity (or small slopes) are the most critical types of terrain variations. This scenario of the slowly growing error is hard to detect with the expected radar-altimeter performance. This scenario, if undetected, can cause a miscalibration of the filter, leading to a downgraded performance. The miscalibrated filter is not able to provide vertical information meeting the desired accuracy and integrity level and thus not able to meet the potentially stringent requirements.

The credibility of the simulation-based testing and verification is based on the variation in the terrain profiles, configuration parameters, and statistical independence of the sensor-error models. Figure 3 depicts the block diagram of the simulation framework created for this purpose.

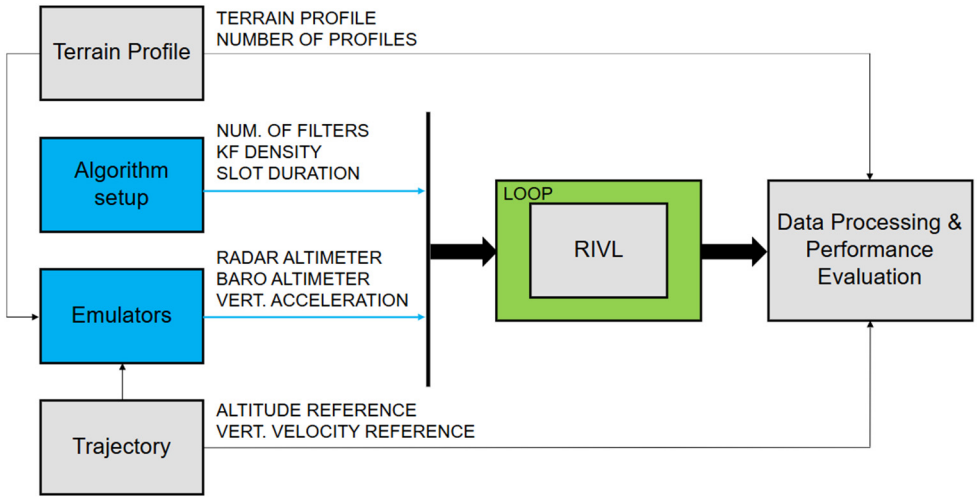


Figure 3. The simulation framework prepared for Monte Carlo analysis of the RIVL algorithm including sensor emulators, trajectory, terrain profiles, and performance evaluation block.

3.2. Evektor EV55 Flight Tests (Fixed Wing CS-23 Type of Aircraft)

The Evektor EV55 (Figure 4) flight tests were aimed as a proof-of-concept of the RIVL system in a representative environment onboard a fixed-wing aircraft. The robustness of the vertical navigation solution in representative environments was tested on three flights.



Figure 4. Evektor EV55 commuter aircraft.

The data gathering was performed around Kunovice Airport in the Czech Republic. The first flight test was focused on maneuvers at low altitudes over the runway. The second flight test consisted of a touch-and-go procedure to test the RIVL system in zero ground clearance during touchdown. The third flight test was dedicated to extensive attitude maneuvers at low altitudes to test the robustness of the algorithm and validity of attitude thresholds used to exclude radar-altimeter measurements at excessive vehicle attitudes.

The Novatel GNSS receiver and a Novatel IMU-LCI fiber-optic gyro-based inertial measurement unit were installed onboard the aircraft to provide high-precision navigation reference measurements (both from the Czech Novatel/HEXAGON dealer: Geoobchod, s.r.o., Gen. Svobody, Pardubice, Czech Republic). The GNSS ground station was located near the runway, gathering open-sky GNSS data, and was later used during post-processing to improve the hybrid Novatel solution. This upgraded hybrid solution was used as a reference for the evaluation of the RIVL vertical velocity.

3.3. Crane Tests

The crane tests were based on a hardware prototype built for software performance testing in a target environment. The most straightforward tests would require installation onboard the rotary-wing aircraft, performing predefined vertical scenarios simulating UAM

profiles. Due to the quick development strategy, direct helicopter tests were substituted using crane tests. The crane enables the testing of the prototype in the expected range of vertical scenarios, leading to a credible set of results in the representative (or semi-representative) environment (see Figure 5 below).



Figure 5. The custom hardware prototype built for the RIVL crane test secured and prepared on the crane mechanism.

The hardware prototype hosted two main groups of devices:

- Core hardware prototype: the devices, custom hardware blocks, and cables creating hardware unit necessary for the testing of the RIVL functionality.
- References: Novatel PowerPak 7, Novatel SPAN SE with Novatel IMU LCI, Honeywell IRU LaseRefVI, and Laser Range Finder (LRF) provide reference navigation data for further performance evaluation.

The test processor was a National Instruments cRIO hosting the RIVL System and a MEMS IMU-based AHRS providing vertical-acceleration statistics. The simple implementation and the proposed design were demonstrated through the scenarios summarized in Table 1.

Table 1. The list of crane test scenarios.

Scenario	Repetitions	Vertical Velocity	Notes
UP and DOWN Motion	30	0.5 m/s	-/-
UP and DOWN Motion	30	1 m/s	-/-
Horizontal Maneuver + Descent	10 (for each 10, 15, and 20 m of ground clearance)	1 m/s	Simulation of horizontal flight above the terrain with random obstacles, followed by descent above the landing area
Sensitivity Analysis	10	-/-	-/-

The sensitivity analysis scenarios are dedicated to evaluating different algorithm configurations in terms of parallel filters' settings and their impact on the computational demands in the cRIO platform, as well as their impact on vertical estimation performance. The sensitivity test has the following algorithm configurations:

- Fifty slots (Kalman filters), slot duration 10 s, circular motion 15 m above ground, 10 repetitions above static terrain obstacle;

- One hundred slots (Kalman filters), slot duration 10 s, circular motion 15 m above ground, 10 repetitions above static terrain obstacle;
- Two hundred slots (Kalman filters), slot duration 10 s, circular motion 15 m above ground, 10 repetitions above static terrain obstacle;
- One hundred slots (Kalman filters), slot duration 5 s, circular motion 15 m above ground, 10 repetitions above static terrain obstacle; and
- One hundred slots (Kalman filters), slot duration 20 s, circular motion 15 m above ground, 10 repetitions above static terrain obstacle.

4. Results and Discussion

This section summarizes the performance results of the RIVL system achieved during the simulation and real-time tests for all stages of the software testing outlined in Section 3.

4.1. Nominal and Terrain Simulations

The following Tables 2 and 3 summarize the achieved estimation performance of both altitude-above-ground and vertical-velocity parameters computed by the RIVL system. In Tables 2–4, the symbol "#" is an abbreviation of the word "number".

Table 2. The simulation setup and achieved performance for nominal simulations.

Scenario	# of Simulations	# of Slots	KF Density [s]	Slot Duration [s]	Altitude Above Ground 95% Accuracy [m]	Vertical Velocity 95% Accuracy [m/s]
#1	100	100	0.1	10	0.39	0.09
#2	100	125	0.08	10	0.39	0.09
#3	100	25	0.4	10	0.39	0.09
#4	100	100	0.15	15	0.39	0.09
#5	100	100	0.07	7	0.4	0.1
#6	100	150	0.08	12	0.39	0.09
#7	100	125	0.1	12.5	0.39	0.09
#8	100	25	0.28	7	0.4	0.1
#9	100	100	0.1	10	0.39	0.14

Table 3. The simulation setup and achieved performance for terrain simulations.

Scenario	# of Simulations	Terrain	Terrain Change Occurrence [s]	Terrain Magnitude [m]	Altitude Above Ground 95% Accuracy [m]	Vertical Velocity 95% Accuracy [m/s]
#1	100	Slope	5	3–4	0.39	0.14
#2	100	Slope	10	3–4	0.39	0.12
#3	100	Slope	15	3–4	0.39	0.11
#4	100	Slope	20	3–4	0.39	0.1
#5	100	Slope	20	2–3	0.39	0.09
#6	100	Slope	10	4–5	0.39	0.13
#7	100	Step	-/-	0.3–0.4	0.39	0.09
#8	100	Step	-/-	0.4–0.5	0.39	0.09

Table 4. The vertical-velocity performance achieved during the EV55 flight test.

Flight	BIVL 95% Accuracy [m/s]	RIVL 95% Accuracy [m/s]
#1	0.18	0.13
#2	0.31	0.14
#3	0.22	0.11

The following observations can be made regarding the flat terrain assumption:

- The number of filters combined with slot duration drives the ability to satisfy requirements (mainly in vertical velocity);
- If the number of filters is more than 100, then the improvement of accuracy is minimal;
- A significant reduction in filters negatively influences the ability to satisfy the requirements;
- There is an expected improvement in accuracy achieved by the longer convergence time of the filters; and
- Lowering the thresholds for innovation monitoring increases false alert rates, leading to decreased performance. Strict thresholds may impact the ability of RIVL to satisfy requirements due to frequent restarts of parallel filters.

The setup of 100 filters with a filter density of 100 ms and a slot duration of 10 s can be identified as the optimal setup, providing sufficient accuracy and keeping the trade-off between convergence time and accuracy on an acceptable level. Consequently, these are key observations related to the terrain simulations:

- The performance of the altitude-above-ground estimation is driven by the measurement grade of the radar altimeter (beam width, effect of terrain material, delay, etc.); and
- Vertical performance can be partially influenced by terrain detection causing reinitialization of all filters, i.e., convergence time following re-initialization from the BIVL/radar-altimeter solution influencing the performance.

4.2. Evektor EV55 Flight Test

These flight tests aimed to test the RIVL system's proof-of-concept implemented in the cRIO platform in a representative flight environment. Although the purpose of those tests was mainly the proof-of-concept, there was also a possibility to evaluate the achieved performance of the vertical velocity. The Novatel hybrid solution was used as the reference for vertical velocity and the following Table 4 summarizes the achieved performance for both BIVL and RIVL solutions.

The RIVL system uses the BIVL vertical-velocity information to initialize the RIVL filters. The Kalman filter-based BIVL vertical velocity was outperformed in every flight test when compared with its RIVL counterpart.

4.3. Crane Test

These crane tests fulfilled the expected set of scenarios in a UAS/UAM vehicle's environment, closely simulating the vertiport approach, approach to landing, and landing phases of flight. The repetitive vertical and horizontal maneuvers were approximated as rotary-wing maneuvers. There are the following observations related to the overall test activity:

- The data processing was focused on the VTOL (vertical take-off and landing) segments. Those intervals were also characterized by the RIVL system operating in full-performance mode.
- A total of 78 VTOL segments were identified and processed.

- Weather conditions were stable, and barometric measurements were more accurate than expected or compared to the helicopter/UAM test environment.
- The tests did not approximate rotor downwash, which is present in real flight conditions. Thus, the performance of the BIVL vertical velocity is probably more accurate than it would be in a real helicopter/UAM flight test.

Table 5 summarizes the overall crane-test performance of the RIVL system evaluated using the above-mentioned reference systems. The improved performance compared to the simulation tests is caused by the conservative overbounding of the sensor-error models during the simulations.

Table 5. The overall crane-test RIVL performance.

	Altitude Above Ground [m]	**Vertical Velocity [m/s]**
95% Accuracy	0.16 m	0.05 m/s

5. Conclusions

This article summarizes the research, development, and testing of the Kalman filter-based radar-altimeter inertial vertical loop (RIVL) system enabling a highly accurate estimation of vertical parameters—altitude above ground and vertical velocity. These vertical parameters are crucial for the final phase of flight and autoland operation in growing UAM, UAS, and eVTOL segments. The main idea is to provide mean and variance estimates of vertical parameters based on the fusion of radar-altimeter measurement statistics and vehicle inertial vertical-acceleration statistics. Consequently, several algorithm candidates were considered, and these possible approaches were analyzed against requirements. The most straightforward solution—the Kalman filter—is based on the principle of a third-order loop complementary filter of barometric altitude measurements and inertial vertical acceleration used for decades as stabilization of inertial vertical channels. The bank of parallel filters initialized using the radar-altimeter measurements and BIVL-based vertical velocity was used in the RIVL system design to overcome inconsistencies induced by terrain variations under the vehicle. The key outcomes of the RIVL design and tests are:

- Nominal and terrain simulations were performed with various setup options (number of filters, slot duration, innovation monitoring thresholds, terrain geometry, etc.) to identify the ability of RIVL to satisfy requirements.
- The EV55 flight tests with RIVL system hosted on a test processor platform (National Instruments cRIO) provided valuable feedback for RIVL design, including a basic debugging of the proposed implementation and proof-of-concept with indicative performance in the flight conditions.
- The crane tests tested the RIVL system using vertical and horizontal maneuvers for the approach and landing phases over different terrain. The crane-test results demonstrate that the RIVL system satisfies convergence time and vertical performance requirements over the different test scenarios and that the RIVL system performance is comparable with the simulation tests.

The future work related to the RIVL system includes flight tests on rotary-wing aircraft. These flight tests with challenging scenarios (urban areas, terrain obstacles, rooftop landings, etc.) will bring other valuable data sets and create proof-of-concept tests in the target environment.

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