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Automation of Agricultural Grain Unloading-on-the-go

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Abstract: This paper describes the development and experimental validation of a novel grain unloading-on-the-go automation system (automatic offloading) for agricultural combine harvesters. Unloading-on-the-go is desirable during harvest, but it requires highly-skilled and exhausting labor because the combine operator must fulfill multiple tasks simultaneously. The automatic offloading system can unburden the combine operator by automatically monitoring the grain cart fill status, determining the appropriate auger location, and controlling the relative vehicle position and auger on/off. An automation architecture is proposed and experimentally demonstrated to automate the unloading-on-the-go process. To allow for different operator-selected unloading scenarios, the automatic offloading controller has three fill strategies and two movement control options, "open-loop" and "closed-loop". The automatic offloading controller was implemented on a dSPACE MicroAutoBox II and integrated into a combine harvester. In addition, a stereo-camera-based perception system was connected to the automatic offloading controller via an Ethernet cable for grain fill profile measurement during unloading. In-field testing demonstrated that the automatic offloading system can effectively automate the unloading-on-the-go of a combine harvester to fill a grain cart to the desired level under nominal harvesting conditions.

Keywords: Autonomous vehicle, Vehicle control, Driver assistance systems, Perception, Off-road vehicle automation,

1. INTRODUCTION

The availability of skilled labor in the agriculture industry in the US has been declining for decades while the demand stays relatively constant. As a result, the US has seen farm labor shortages for many years Hertz and Zahniser (2013); Taylor et al. (2012). In the meantime, the Food and Agriculture Organization (FAO) of the United Nations has reported that the world is facing a 70 % higher demand for food as the population is expected to grow to 9.1 billion by 2050 Alexandratos and Bruinsma (2012). However, this staggering growth in demand is counter to the available arable land Bringezu et al. (2010).

These trends altogether reveal the importance of improving productivity while reducing the requirements for skilled labor in farming operations. Agricultural machinery feature automation is a key step to achieve these goals as proposed in "Agriculture 4.0" De Clercq et al. (2018); Charania and Li (2020).

Grain harvest involves coordination between multiple machines and is one of the most time-sensitive operations. Unloading is the process of transferring grain from the onboard grain hopper of a combine harvester to a tractor-towed grain cart, ideally as the combine continues to move while harvesting grain. Grain unloading-on-the-go is a desirable operation that improves productivity but requires skilled labor and attentive operation throughout a day of grain harvesting. During unloading-on-the-go, the combine continues to harvest while unloading grain to a grain cart moving alongside, allowing the combine to reduce unproductive time Reinecke et al. (2013). Delchev et. al. showed that on-the-go unloading can provide up to 30% time reduction per unit area in harvesting Delchev et al. (2016). However, unloading-on-the-go also requires high-skill labor for both combine and tractor drivers. In particular, the combine operator must carry out multiple tasks simultaneously:

(1) Monitor the filling status inside the grain cart
(2) Determine the appropriate location for the auger to unload
(3) Communicate with the tractor operator to move the auger to the desired location by changing the speed and heading of both vehicles
(4) Watch for the clearance between two vehicles and react to obstacles, terrain change, and waterways in the traveling path
(5) Monitor crop harvesting conditions and accordingly adjust harvester settings or vehicle movement

A system to automate the unloading process can unburden the combine operator of tasks 1-3. Considering the productivity and labor impact of the unloading process, a system to fully automate the unloading-on-the-go process can help to:

- **Improve operator experience and performance.** Besides the user experience improvement from automation, Bashiri and Mann (2015) also demonstrated that the automation on agricultural machinery could improve driving performance.
- **Lower the demand for skilled labor.** By reducing the number of required tasks for both the combine and tractor operators, the system can reduce the unloading operation complexity and thus the demand for operator skills.
- **Improve productivity.** Consistently monitoring the grain profile can reduce the chances of spillage during unloading, one source of harvest loss.

To assist operators during unloading-on-the-go,agricultural machinery companies have developed various products to automate or assist parts of the unloading operations (e.g., Ag Leader CartACE Yegerlehner (2017); Gunbatar (2020), John Deere Machine Sync Metzler et al. (2009); Peters et al. (2014), and Case IH V2V Morselli and Posselius (2012)). Some researchers have built combine harvester unloading-on-the-go automation systems Kurita et al. (2014, 2012); Potter (2012); Jennett (2012), but their limited performance (e.g., tracking performance, fillable region in cart), strict constraints (e.g., grain cart size, use of fiducial patterns), high cost, and the remaining burden on the combine operator curb their impact on productivity improvement or adaption for commercialization. Several companies have released products to automate the forage harvester unloading, a similar application to combine unloading. However, the difference between forage harvester and combine harvester unloading system design is still too large to allow direct replication of forage harvester technology.

To the best of our knowledge, no existing system can fully automate the unloading-on-the-go operation of a combine harvester. A system to accomplish this is outlined and demonstrated in this paper. This automatic offloading system automatically monitors grain fill status, determines preferred auger location to achieve prescribed fill strategy, and controls the auger status and location to achieve the desired fill with intervention, as required, from either the combine or the tractor operator.

2. AUTOMATIC OFFLOADING ARCHITECTURE

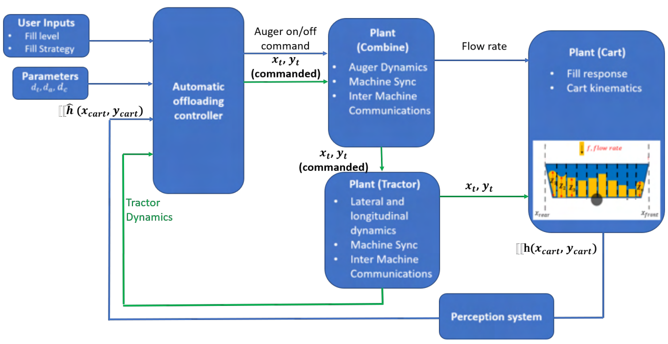


Fig. 1. High-level automatic offloading system architecture

Figure. 1 shows the high-level architecture of the automatic offloading system. The automatic offloading system is built by integrating an automatic offloading controller and a perception system. The automatic offloading system incorporates Machine Sync, a machine-to-machine communication, and control technology, that is an option on current John Deere vehicles. Meanwhile, AutoTrac, another technology available for John Deere vehicles, is also used in this system to keep combine moving in a straight line during unloading-on-the-go.

The entire automatic offloading system runs on the combine harvester. It automatically calculates the desired vehicle locations and auger on/off status to achieve the target fill specified by the operator based on the current grain fill profile inside the grain cart. After that, it sends the desired location and auger on/off command to other control systems on the combine harvester, namely Machine Sync and the auger control system. Ultimately, the relative tractor location determines the combine auger location relative to the grain cart, and together with the auger flow rate, affects how grain piles in the grain cart. Finally, the perception system measures the grain profile inside the grain cart and provides the fill level feedback to the automatic offloading controller, closing the automatic offloading control loop.

3. CONTROLLER DESIGN AND SIMULATION

3.1 Fill strategy

The automatic offloading controller calculates the desired location and auger on/off based on the current fill status, current impact location, and user-desired behavior. Because a grain cart is usually longer than it is wide, the relative vehicle movement in the longitudinal direction has a more crucial impact on the fill quality. Therefore, to reduce the system complexity, the automatic offloading controller keeps the auger at the center in the lateral location and only controls the auger movement in the longitudinal direction.

To automatically determine the desired auger location, the automatic offloading controller first partitions the grain profile, which is a 2D array $h(x, y)$, in the longitudinal direction into R rows. Within each row, the fullness of the cart can be calculated based on the average height of all the grids in this row (other fullness methods can also/instead be used). The algorithm compares the average fill level in each row with the desired fill level specified by the operator to binarize the fullness within each cart into "full" or "not full". The first and last rows are always be marked as "full" to prevent spillage.

$$F_i = \begin{cases} 1, & \overline{h_i\,(x, y)} > h_{des} \quad or \quad i = 1, R \\ 0, & Otherwise \end{cases} \tag{1}$$

where F_i is the binary fullness of the i-th row, $\overline{h_i\,(x, y)}$ is the average grain height in the i-th row, R is the number of rows, and h_{des} is the desired grain height based on the target fill level specified by the operator.

The desired location from the automatic offloading controller is determined by the binary row fullness and the fill strategy specified by the operator. Three commonly-used strategies were implemented in the automatic offloading controller:

- Front to back fill strategy (F2B): Filling the grain cart from front to back.
- Back to front fill strategy (B2F): Filling the grain cart from back to front.
- Front to back to front fill strategy (F2B2F): Filling the grain cart from front to back and then top off the cart to the desired fill level from back to front.

In addition to turning the auger off according to the Fill strategy, the automatic offloading controller turns it off, if, for any reason, the auger moves too close to any cart edge to prevent spillage.

3.2 Movement controls

Two different options were considered for generating the position command for the Machine Sync system: "open-loop" movement controls and "closed-loop" movement controls. Figure 2 shows the block diagram of open-loop control. Figure 3 shows the block diagram of the closed-loop movement controller.

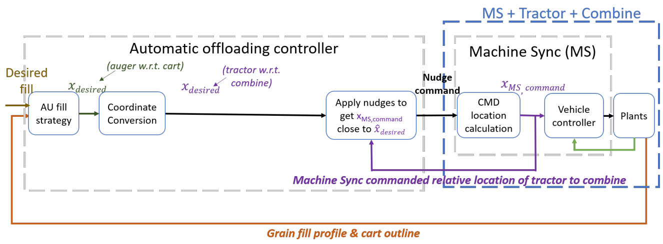


Fig. 2. automatic offloading controller block diagram with open-loop movement controls. Note: the automatic offloading system also includes the perception system, but it is not explicitly included in this figure.

The open-loop control approach sends nudges to the Machine Sync system solely based on the desired location from the automatic offloading fill strategy $x_{desired}$. Because the Machine Sync location is defined between the tractor and the combine, the automatic offloading controller first converts the desired location from the auger-grain cart coordinate system to the tractor-combine coordinate system based on the vehicle geometry. After that, since Machine Sync takes nudge commands to update its target location by a fixed distance, the automatic offloading controller translates the desired location to nudge commands with a nudge handler. The nudge handler commands nudges to get the target location in Machine Sync $x_{MS,commanded}$ as close to the desired location $x_{desired}$ as possible.

One underlying assumption of the open-loop controller is that the Machine Sync system will successfully control the relative location between the two vehicles. However, in practice, external disturbance or plant uncertainty could result in a tracking error of the Machine Sync system and the assumption would no longer hold. Consequently, open-loop controls are not expected to be as robust to disturbance or plant uncertainty.

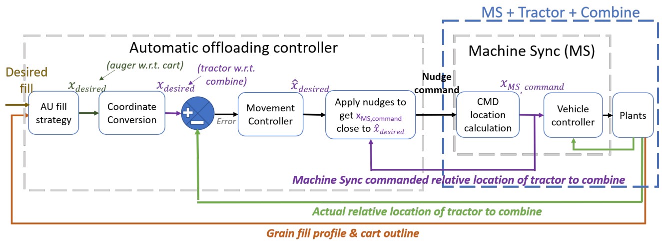


Fig. 3. automatic offloading controller block diagram with closed-loop movement controls.

As a result, another movement control strategy was proposed and developed: the closed-loop movement control strategy shown in Fig. 3. The closed-loop controller does not directly command nudges based on the desired location from automatic offloading fill strategy $x_{desired}$. Instead, it calculates an adjusted desired location $\widehat{x}_{desired}$ based on the tracking error, which is the difference between the desired location $x_{desired}$ and the actual location x_{actual}. By tracking the error, the closed-loop controller is expected to be more robust than the open-loop controller.

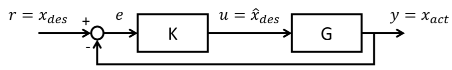


Fig. 4. SISO controller design for small nudge plant.

The closed-loop movement controller was synthesized based on the Machine Sync dynamic model identified from in-field testing. In summary, the dynamics of Machine Sync only depend on the nudge size but do not seem to change with nudge direction, combine speed, or grain cart loading. When the nudge size is greater than one meter, Machine Sync can be modeled as an overdamped second-order system with a six-second settling time.

$$G_L = \frac{0.0453s + 0.4942}{s^2 + 1.315s + 0.4942} \tag{2}$$

When nudge size is smaller than one meter, Machine Sync can be modeled as a second-order system with a settling time of 18 seconds and 20% overshoot.

$$G_S = \frac{0.6049s + 0.1021}{s^2 + 0.5458s + 0.1021} \tag{3}$$

Given that during an unloading process most auger movements are shorter than one meter, the small nudge plant of Machine Sync was treated as the nominal plant to design the controller. Additionally, because the smallest nudge size of the Machine Sync is six inches, the discretization error from the nudge handler is negligible. Consequently, the movement controller design for the Machine Sync system can be described as a classic single-input-single-output (SISO) system as shown in Fig. 4. In Fig. 4, K is the controller to be synthesized, G is the Machine Sync small nudge plant, the reference input r is the desired location x_{des}, the control effort u is the adjusted desired location $\widehat{x}_{desired}$, and the system output y is the actual relative location x_{act}. After defining the variables, the following transfer functions related to the system can be defined as

$$
\begin{aligned}
S &= (1+KG)^{-1} = \frac{E}{R} \\
T &= 1 - S = \frac{Y}{R} \\
KS &= \frac{U}{R}
\end{aligned} \tag{4}
$$

where S is the sensitivity function and the transfer function from the reference input r to tracking error e, T is the complementary sensitivity function and the transfer function from reference input r to system output y, and KS is the transfer function from reference input r to control effort u.

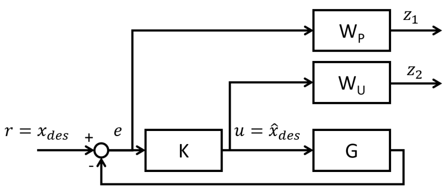


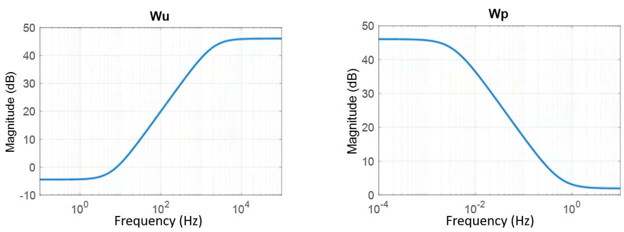
Fig. 5. Augmented block diagram for H_∞ mixed-sensitivity loop shaping.

The controller was synthesized with H_∞ mixed-sensitivity loop shaping technique Kwakernaak (1993) because it allows to design the system performance in frequency domain. First, two weighting functions W_P and W_U were formulated to penalize the tracking error and control effort respectively as shown in Fig. 5. As a result, the transfer function M for the augmented plant from r to z can be described as

$$
M = \begin{bmatrix} W_P S \\ W_U KS \end{bmatrix} = \frac{Z}{R} \tag{5}
$$

and the overall system requirement for controller synthesis is

$$
\|M\|_\infty = \max_\omega \sqrt{|W_P S|^2 + |W_U KS|^2} < 1 \tag{6}
$$



(a) (b)

Fig. 6. System specification for controller synthesis. (a) weighting function for control effort; (b) weighting function for tracking error.

Figure 6(a) shows the specification to limit the controller control effort magnitude. In this way, Machine Sync is less likely to switch from the small nudge plant to the large nudge plant, and the high-frequency cut-off on W_U is designed to prevent the abrupt change of the Machine Sync command to avoid large vehicle acceleration or jerk.

Figure 6(b) shows the controller specification on tracking error. The large penalty on low frequency reduces the steady-state error, and the cut-off frequency of 0.7 Hz maintains the responsiveness of the controller.

With this specification of W_P and W_U, the H_∞ optimal controller is obtained by solving the following optimization with methods proposed in Glover and Doyle (1988) and Doyle et al. (1988)

$$
\min_K \|M(K)\|_\infty \tag{7}
$$

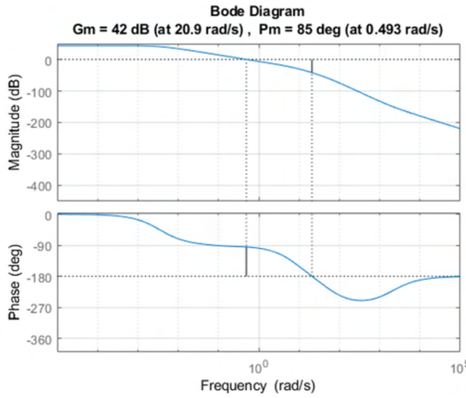


Fig. 7. Bode plot of system loop transfer function with H_∞ controller.

Figure 7 shows the Bode plot of the loop transfer function $L = KG$, which reflects the frequency response of the closed-loop system. The closed-loop system has a high phase margin of 85^o while maintaining a grain-crossover frequency of 0.49 rad/s.

4. SYSTEM INTEGRATION

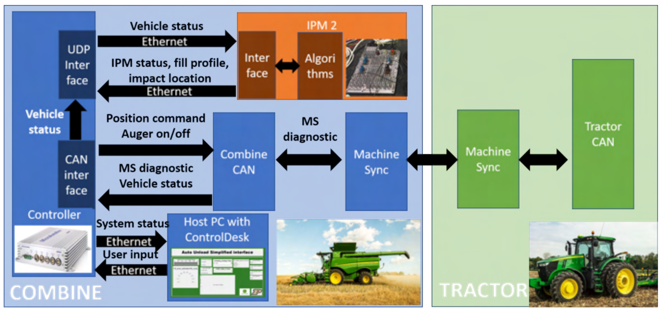


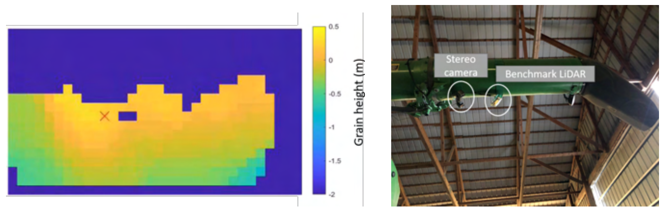
Fig. 8. automatic offloading hardware diagram

Figure 8 shows the hardware configuration of the automatic offloading system. The automatic offloading controller is implemented in a Rapid Control Prototyping (RCP) system (model: dSPACE MicroAutoBox II). The controller is placed on the combine harvester. The automatic offloading controller has 3 interfaces running simultaneously:

(1) Controller interfaces with the combine harvester via on-combine CAN bus. The CAN communication between the controller and the combine harvester not only provides the vehicle status to the controller for feedback control but also allows the controller to automatically send positional commands to Machine Sync and auger on/off commands to the auger controller on the combine.

(2) Controller communicates with the perception system (IPM2) via an Ethernet cable. The perception system receives the vehicle status from the Ethernet for its detection algorithms. While simultaneously, the perception system transmits the cart filling status and perception algorithm status to the controller.
(3) Controller also communicates with a user interface implemented on the host PC of the dSPACE MicroAutoBox via an Ethernet cable. The controller sends the current system status to the UI for visualization and receives the user-specified automatic offloading configurations from the UI.

The automatic offloading system uses a stereo-camera-based perception system IPM (Image Processing Module) to monitor the fill status of the grain cart Herman et al. (2016). As shown in Fig. 9(b), the stereo camera is placed on the combine auger. IPM provides perception feedback for the automatic offloading system. Figure 9(a) shows an example data from the IPM, discretizing the grain cart via a 32×18 matrix. Each grid in the matrix represents the measured grain height relative to the grain cart edge nearest the combine. The height value was provided at 5 cm increments. Additionally, the perception system also estimated the impact location of the grain. The grain impact location data was provided as a coordinate in the matrix.



(a) (b)

Fig. 9. Perception system (IPM) (a) An example data returned from perception system. The heat map shows the grain height relative to the edge, and the red cross shows the estimated grain impact location; (b) Placement of perception system and benchmark perception system.

5. AUTOMATIC OFFLOADING IN-FIELD TESTING

The automatic offloading system was validated with a John Deere S790 combine, and a John Deere 8R340 tractor towing a Brandt 1020 XR grain cart.During the automatic offloading testing, the combine operator began harvesting and adjusted the hydro-handle to set the combine harvester at a constant cruising speed. AutoTrac system was used to keep the combine harvester on a straight line. When the combine hopper was full and ready to unload, the tractor operator drove the tractor near the combine.

After Machine Sync was engaged, the combine operator started the automatic offloading system from the user interface. The automatic offloading system then automatically moved the grain cart to the first desired location based on the specified fill strategy. When the grain cart arrived at the desired location, the automatic offloading system indicated on the user interface that the automatic offloading system was ready. The combine operator used the combine handle to manually enable the auger. The automatic offloading system automatically filled the grain cart by controlling the relative position of the vehicles and stopped the auger when the desired fill level was achieved.

The automatic offloading system was tested at a nominal combine harvester speed of four mph, executed on flat terrain with no end-of-row turning. The testing covered different fill strategies, initial fill profiles, and desired fill levels to validate the performance of the system under different conditions.

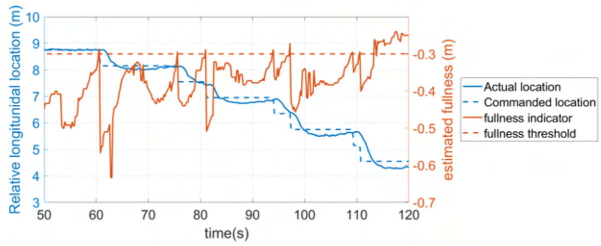
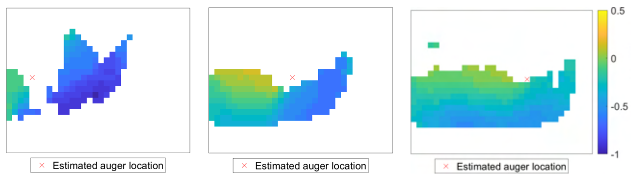


Fig. 10. Relative location between vehicles and fill level metrics during automatic offloading testing scenario A. Fill strategy: Back to Front. Desired fill level: $h_{edge,i} = -0.3m$. Initial profile: half-full. Combine speed: four mph. Open-loop movement control.

Fig. 11. Unload scenario of automatic offloading testing scenario A. Associated with in-cabin video recording in Visualization 1



(a) (b) (c)

Fig. 12. Grain profile change during automatic offloading testing scenario A, associated with Visualization 2 (a) t = 55.8s; (b) t = 84.0s; (c) t = 105.2s.

Figures 10-12 show automatic offloading testing scenario A in which the unloading started from a half-full grain cart, front to back strategy, and an open-loop movement controller. The desired fill level was $h_{edge,i} = -0.3m$ as based on the metrics defined by how close the grain profile is to the cart edge. The grain cart was divided into 0.6-meter rows.

The left axis in Fig. 10 shows the relative movement in the longitudinal direction (vehicle moving direction) between the two vehicles represented by the relative distance between the combine GPS globe and the tractor GPS globe. The right axis in Fig. 10 shows the fill metrics indicator at the current row that the auger was operating in. Visualization 2 shows the unloading process recorded by a camera in the combine cabin.

At the start of the test in Visualization 2, the auger boot is at the back of the grain cart. After it stabilized at the first unloading row, the automatic offloading controller informed the operator to turn on the auger via the user interface. At around 55s of the experimental log, the grain started to pile up on the grain cart, so the fullness metrics started to increase. Once the fullness at the current section had reached the desired fill level set by the operator (at around 60 s), the automatic offloading controller commanded a nudge and moved the auger to the next section. The controller followed a similar pattern to fill up the grain cart from the back to the front. At around 114 s, the last section was filled so the automatic offloading controller did not continue to nudge the tractor, but turned off the auger automatically instead. The final fill level in the last section (at t=115s in Fig. 10) was slightly higher than the specified threshold because of the delay in turning off the auger. Besides F2B strategy, in-field testing has also demonstrated the capability of the F2B and M2B2F strategies to fill up the grain cart automatically in nominal conditions.

6. CONCLUSION

The design and validation of an automatic grain unloading system for combine harvester unloading-on-the-go were described in this paper. To simulate the automatic offloading process, system models for grain fill dynamics and vehicle dynamics were developed and verified with in-field testing. The automatic offloading controller provided three different fill strategies and two movement control options, both of which were simulated to validate the unloading performance. A stereo-camera-based perception system was integrated into the automatic offloading system to provide feedback to the controller. Perception data augmentation algorithms were proposed to accommodate the characteristics of the perception system. The automatic offloading system was implemented on a combine harvester and a tractor-driven grain cart. The system was tested with different scenarios to demonstrate successful automatic offloading under nominal harvesting conditions with different configurations.

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