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A Mixed Reality-enhanced Rapid Prototyping Approach for Industrial Articulated Products

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Abstract

The design of industrial articulated products is challenging due to the consideration of multiple poses, movements, and especially in-field constraints, such as the design of a personalized robot arm or the layout of articulated hoists. Traditionally, depicting 2D sketches from multiple perspectives and poses of the product is tedious. Meanwhile, on-site evaluation after fabricating the physical prototype is costly and time-consuming. In order to assist in context-aware decision-making at the early design stage, this research proposes a mixed reality-enhanced rapid prototyping approach for industrial articulated products. In a 3D mixed reality environment that incorporates the surroundings, designers can depict key joints and rough shapes through intuitive gesture-based interaction. After a quick prototype creation, the kinematics preview is provided to designers for preliminary functional verification. Finally, a user study shows that the proposed approach can help designers rapidly complete the MR prototype of articulated products at the early design stage, provide a better understanding of the product movement, assist in-field solution generation and facilitate communication. It is hoped this explorative study can offer insightful ideas with effective toolkits for assisting the new product design process more intuitively and interactively.

Keywords: Mixed reality; Rapid prototyping; Articulated objects; Kinematics; Augmented reality;

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1. Introduction

In industry, articulated objects with multiple moving parts perform various poses during usage, such as robot arms, tower cranes, or articulating boom lifts. Compared with a static entity, designing an articulated product that perfectly fulfilled functional requirement is more complicated due to the linkage of moving parts, the transition between different poses, user interaction, and the constraints of the actual workspace [1].

The traditional design process is time-consuming and costly. To depict multiple movement patterns and poses of articulated products, designers usually start by sketching from different angles. However, drawing 3D poses on a 2D plane not only requires the strong spatial sense and expertise of designers but is also repetitive and tedious. After the conceptual design, more detailed and accurate 3D models are created in CAD systems. Finally, physical prototypes are fabricated and used for functional testing. Nevertheless, once the performance is different than expected, designers must modify the design iteratively.

In view of the above limitations, we present a mixed reality (MR)-enhanced rapid prototyping approach for industrial articulated products to accelerate the prototyping and validation process, in the hope of assisting designers in and on-site decision-making at the early design stage. Instead of creating detailed and precise 3D models like in CAD systems, this workflow concentrates on the rapid and rough description in an MR environment, an interactive 3D prototyping experience combining reality and user-generated virtual content. The key joints and geometry can be defined using intuitive gestures with the kinematics preview generated by a simple click. Therefore, designers can create, visualize and interact with the real-scale 3D structure of articulated products and validate the movement directly on-site.

In the following sections, the related works are introduced in Section 2. Then, the motivation is presented in Section 3. Next, the design workflow, system design, and implementation are elaborated in Sections 4 and 5. The user study, discussions, and conclusions are included in the final sections.

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2. Related works

2.1. MR prototyping for on-site design

MR prototyping is an immersive and interactive experience combining the physical world and virtual information to construct design prototypes, facilitating multiple dimensions of design [2]. Designers can visualize and interact with the virtual prototype [3] for better communication and collaboration. More importantly, MR can be a suitable medium to facilitate context-aware solution generation in on-site design. MixFab [4] and RoMA [5] were two representative MR-based applications which use physical objects as references in new product design. Moreover, Reipschläger and Dachselt presented the DesignAR [6] system, letting designers draw on tablets but visualize the real-scale models within the surrounding environment through AR glasses. Immersive functional analysis that needs ambience information as input [7] can also be integrated into MR.

While more studies have elaborated on static product design, few papers concentrate on kinematics modelling and verification based on MR prototyping. Exploration for moving objects is relatively inadequate.

2.2. Immersive 3D sketching and modeling techniques

Immersive 3D sketching and modelling, which means drawing directly in mid-air, have made significant improvements due to the advancement of AR and Virtual Reality (VR) technologies. In an AR environment, some applications [8] aim to create simple freeform sketches to support conceptual design or content authoring. Meanwhile, more accurate point-determined lines are also considered by researchers like [9]. Regular or freeform surfaces [10] have been realized to support more delicate 3D sketching. In VR, controllers provide more accurate and far-reaching objection selections and various button-based orders. Research works include CAD-like modelling platforms [11] and 3D sketching systems [12]. In industry, mature applications such as *Gravity sketch* and *Google Tilt Brush* have become more and more popular.

While most research is trying to make 3D modelling and sketching more aesthetic and accurate, this research focuses more on quickly and roughly depicting the geometry and motion of articulated products in a 3D environment.

2.3. Kinematics prototyping

Traditional kinematics movement preview is realized by adding animation in CAD systems or professional softwares. At the conceptual design stage, Lee et al. [1, 13] focused on creating the moving and multi-pose 3D sketches of the products on tablets, significantly reducing the 2D depicting or 3D animation time. In addition, Jeong et al. [14] proposed Perfboard to support linkage prototyping and fabrication in engineering education. However, among the existing related works, the kinematic model lacks depth perception or interaction with physical environments.

3. MR-enhanced rapid prototyping

In view of the above, the design of articulated products is more challenging in both depiction and verification. A more intuitive way is needed for kinematic prototyping. Moreover, if designers could conduct kinematic behaviour verification more efficiently before the detailed component design begins, unnecessary parameter and layout modification could be avoided largely. Facing the current problems of long product design cycles, difficult iterations, and high trial-and-error costs, this research aims to build kinematics prototypes for articulated products rapidly at the early design stage to instantiate concepts, identify design problems and facilitate decision-making in advance.

Considering that MR prototyping inherited the advantages of both physical and virtual prototyping, which is cost-effective, repetitive, flexible, and with a certain validation ability [2], MR can be a suitable approach for early-stage rapid prototyping. On the one hand, MR can integrate environmental information into the design process, which brings huge benefits. Real circumstance, also referred to as "context", forms the setting, inspiration, or physical reference for the product design. Designing in context *"encourges designers to consider contextual elements, is more inspiring, and makes ideas more memorable [15]."* In the MR environment, a more reliable motion design, collision avoidance, and reachability testing could be realized by manipulating the virtual articulated prototype for kinematic preview, thus further determining or optimizing the size or structure parameters. Hence, designing in MR based on the actual conditions and ambient information is considered context-aware. On the other hand, MR supports diverse and intuitive interaction methods for designers to create virtual content in 3D space. Immersive 3D modelling in unconstrained mid-air brings significant benefits for product depiction, especially depth perception[10], which is in line with the requirements of the kinematics preview. While plenty of research has been conducted to improve the accuracy or delicacy of 3D sketching, investigations on kinematics modelling have so far been scanty. To be more specific, adopting the most intuitive bare-hand gestures to quickly grab the kinematic structure, rather than achieving an aesthetic sketch, is the focus of present research.

In conclusion, this research sets out to explore the methodology of generating kinematic models of articulated products rapidly in the MR environment, integrating human intelligence in the design loop via intuitive interactions [16].

4. The proposed workflow

4.1. Articulated products composition and hierarchy

The key components of an articulated product consist of exterior geometry, joints, and kinetic movement. To simplify the research question, this work currently targets at products only containing one articulated arm. Fig. 1 (a) shows a 4-axis robot arm as an example. The *Base joint* of the base layer, which is connected to the pedestal, is the parent node. Two child nodes *Bone 1* and *Joint 1* are in the next layer. The translation and rotation of the parent node are simultaneously passed to the children nodes. The last layer includes the end effector and the endpoint. Fig. 1 (b) illustrates the general hierarchy, which can be easily generalized to more complex articulated products, such as folding furniture or quadruped robots with multiple articulated arms.

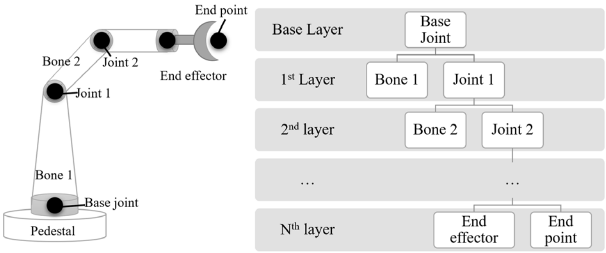

Fig. 1. (a) Robot arm components. (b) The defined hierarchy.

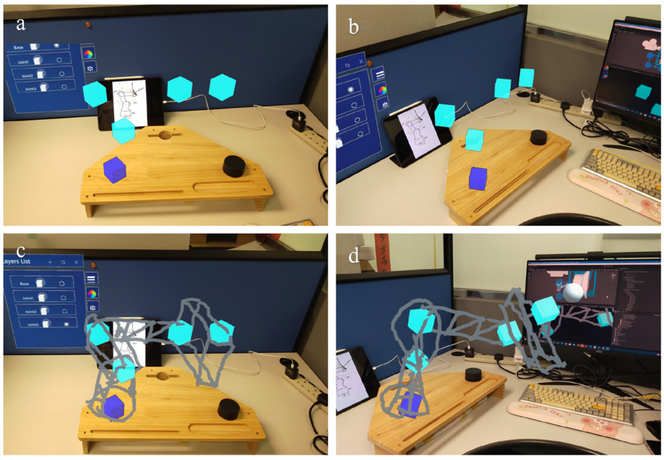

Fig. 2. (a) Determine the position of all joints. (b) Another perspective of all joints. (c) Add shape geometry, using freeform 3D curves as an instance. (d) Change the posture of the prototype and visualize it from another perspective.

4.2. *Design workflow*

According to the hierarchy of an articulated product prototype, the design workflow is composed of three steps: create joints, create geometry layer by layer, and make it move! The creations of geometry and joints are separate, aiming to allow product designers to focus more on motion design. The whole workflow is illustrated in Fig. 2.

Create joints - First, users determine the position of all deciding joints by hand gestures in the MR environment, as shown in Fig. 2 (a). The default type of each joint is a ball joint. The position, type, and constraints of each joint can be modified. Fig. 2 (b) shows another perspective of the created joints.

Create geometry layer by layer - Second, users create exterior shapes of each bone layer by layer in the MR environment. Users should proactively choose the target layer before drawing the corresponding geometry according to the hierarchy. They can draw various shapes to describe the geometry, including freeform 3D curves, cubes, spheres, cylinders, and capsules. The size and position of depicted shapes can also be modified by hand gestures.

Make it move! - Finally, users conduct the kinematics preview for an on-site evaluation. When users finish all the depictions of key joints and rough geometry, the inverse kinematics can be added with a simple one-click. As the endpoint follows the user's hand, the articulated prototype subsequently changes its posture as the user wants. The geometry can be seen as a "bounding box" which is essential for functional testing. Therefore, the users can visualize and evaluate the prototype on-site for reachability verification or collision detection before the detailed design. The position of the prototype can be changed by moving the base joint. Fig. 2 (c) and (d) show the different poses of an articulated arm with a computer monitor as the end effector.

5. System design and implementation

To verify the feasibility of the proposed approach, an MR-enhanced rapid prototyping system is developed based on Unity and Microsoft HoloLens 2. The MR environment and PC complement each. Through HoloLens 2, the deciding structure and shapes can be identified rapidly by hand gestures. The designers can modify the details on the PC simultaneously, such as changing the constraints of a joint. The inverse kinematics and movement preview are realized by integrating Final IK [17]. Finally, the prototype can be exported to CAD systems in *.fbx* format for further use. The precise dimension is not involved in this paper considering the ease and efficiency of interaction.

5.1. *Menu design*

The main menu contains two parts: Layers List and Hand Menu. When users enter the system, they will find the always-hovering window, *Layers List*, that shows the currently created joints and corresponding layers, as shown in Fig. 3 (a). The radio button represents whether the geometry is being created at the layer where the joint is located. Then, users can start by *raising arm and palm up* to trigger another *Hand Manu* like Fig. 3 (b). Users can tap each button using their index finger and trigger the function.

5.2. *Bare-hand gestures*

Hand gestures provide diverse, natural, and intuitive interactions in MR. There are three gestures defined in our system.

Air tap and hold - Hold your hand straight out in front of you in a loose fist, point your index finger straight up toward the ceiling, tap your finger down and keep like Fig. 4 (a). This gesture is designed especially for sketching freeform 3D curves.

Grasp - Place your hand straight in front of you, open it with your palm facing forward, then make a fist and release it. The gesture can be used for creating a joint or a primitive, as illustrated in Fig. 4 (b).

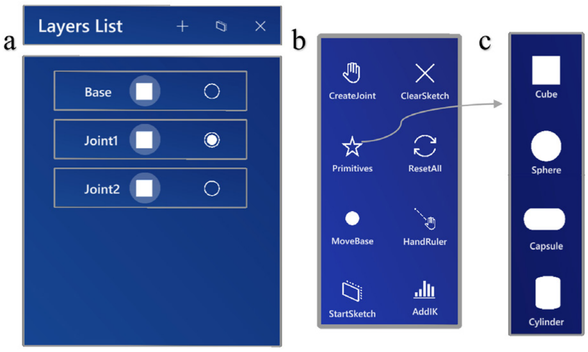

Fig. 3. Menu design in Unity. (a) Layers list. (b) Hand Menu. CreateJoint – Create joints; Primitives – Trigger another UI Menu; MoveBase – Move the base joint; StartSketch – Draw freeform 3D curves; ClearSketch – Clear all the curves; ResetAll – Clear all; HandRuler – Measure the distance between two hands; AddIK – Add kinematics to the prototype. (c) Primitive types - Create a cube, sphere, capsule or cylinder.

Two-handed air tap and hold - Two hands conduct air tap and hold first. As the distance between the two hands lengthens, a straight line will be displayed between the fingertips, with the actual distance marked. This effect is shown in Fig. 4 (c).

Also, other default gestures defined by HoloLens 2 are integrated, including two-handed manipulation, one-handed manipulation, one-finger tap, and raise arm and palm up. The overview of all gestures and the supporting interactions is listed in Table 1.

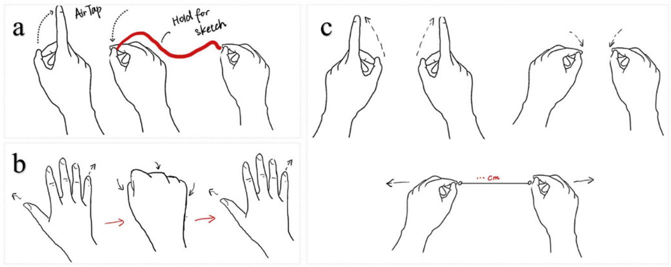

Fig. 4. Self-defined hand gestures. (a) Air tap and hold. (b) Grasp. (c) Two-handed air tap and hold.

Table 1. An overview of gestures and the supporting interactions

Hand gesture	User interaction
Air tap and hold	Sketching freeform 3D curves
Grasp	Create joints and primitives
Two-handed air tap and hold	Hand ruler
Two-handed manipulation	Move, scale and rotate primitives
One-handed manipulation	Move joints and primitives
One-finger tap	Select button on Hand Menu
Raise arm and palm up	Trigger Hand Menu

5.3. *Key joints creation*

The proposed system covers two kinds of joints: the hinge joint and the ball joint. A joint is created by a grasping gesture after triggering the button “CreateJoint” on the hand menu. When a joint is created, it is set to a ball joint by default as shown in Fig. 5 (a) with a 360 degree of freedom. Currently, designers can only change the joint to a hinge and modify the rotation axis or angle limit, like Fig. 5 (b), on the PC. The users can change the position of each joint in the MR environment before the geometry is depicted.

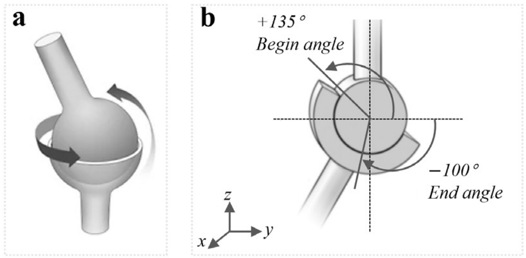

Fig. 5. (a) Ball joint with 360° rotation. (b) Hinge joint with rotation axes x, begin angle +135°, and end angle −100° as an example.

5.4. *Rough geometry depiction*

Users can depict rough geometry in the MR environment by hand gestures. There are two kinds of geometry: Freeform 3D curves and primitives.

Freeform 3D curves - Freeform 3D curves sketching is triggered by “StartSketch” button on the hand menu. The drawing starts with an air tap and hold gesture as shown in Fig. 4 (a) and ends until the designers raise the index finger again.

Primitives - There are four types of primitives: cube, sphere, cylinder, and capsule. Users can create one using a grasp gesture. As mentioned in section 5.2, designers can move, rotate, and scale the primitives by two or one-handed manipulation.

5.5. *Kinematics set up and preview*

Final IK [17] is integrated to equip the articulated object with inverse kinematics computational ability. After tapping the “AddIK” button, designers can drag the endpoint by air tap and hold gestures and change the movements of the product. The articulated object will follow the position of the user’s hand.

6. User study

In order to evaluate the usefulness of the proposed approach and system, eleven participants (4 males) were recruited to join the user experiment.

Participants -The participants were undergraduate and graduate students coming from the fields of product design (P1-3), robotics (P4-6), mechanical engineering (P7-9), and user interaction (P10-11). Seven participants (P1, P2, P4-6, P9 and P11) had VR or AR using experience.

Procedure - The experiment started with a 5-minute motivation introduction. For participants without professional AR using experience, the authors took another 10 minutes to get them familiar with the gesture interactions of HoloLens 2. After watching a video demonstrating the basic operations, the users try to create an articulated product prototype as they want. Finally, each participant filled out a questionnaire and discussed the strength and limits of the system from their perspectives.

Case studies - Fig. 6 and Fig. 7 show two representative cases depicted by P5 and P2. P5 is a robot engineer with 2-year experience using HoloLens 2. First, he created a prototype with almost the same mechanical structure and shape as the actual KUKA robot arm. Then, he moved the virtual robot to the new workspace and verify whether it could cover all the target points the robot was required to reach. P2 is a 3-year-experience industrial designer but has no experience with AR. She completed a concept design for a personalized rehabilitation robot leg by identifying all the joints according to the actual dimension of the volunteer. She wanted to use this prototype to discuss with the other colleagues of her team. She also used the “HandRuler” function to measure the size of the volunteer’s leg.

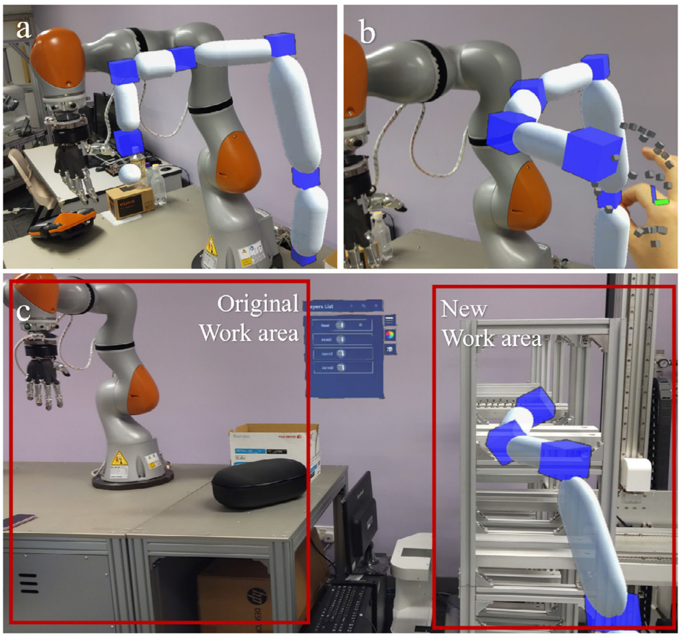

Fig. 6. The robot arm prototype created by P5. (a) Reconstruction the robot arm. (b) Movement preview. (c) Moving it the new work area and testing the function.

Fig. 7. Conceptual design of a rehabilitation robot leg from P2. (a) Posture in sitting position. (b) Posture in standing position.

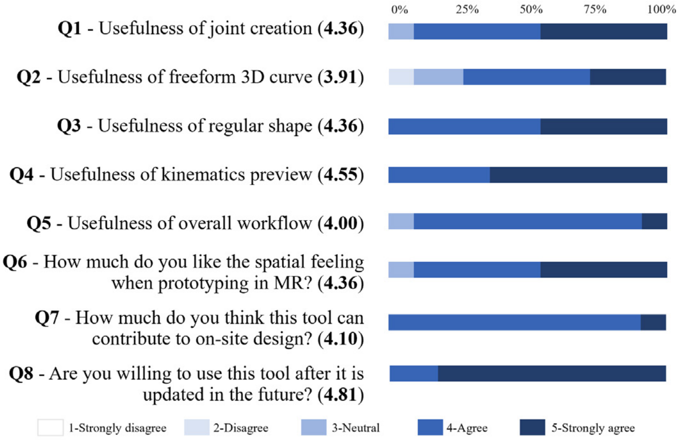

Fig. 8. Questionaire results (5-point Likert scale, average in parentheses).

7. Discussion

To better understand the strength and limitations of the proposed approach, we analyzed the recorded audio, questionnaire results, and interviews. The questionnaire results are shown in Fig. 8. The overall usefulness of the proposed workflow ($u = 4.00$) was positively rated. In particular, the kinematics preview function ($u = 4.55$) got highly evaluated. Moreover, almost all of the participants were strongly willing to reuse this tool in the future ($u = 4.81$). This result showed the feasibility and promising potential of the proposed system. Other valuable observations are listed as follows:

Help create kinematics prototype rapidly - After the experiment, 8 of 11 participants (72.73%) succeed in creating a prototype within half an hour. Based on this result, a preliminary observation can be concluded that the system can rapidly help users generate virtual prototypes with a kinematics preview at the early design stage. *“Compared to using CAD software, this tool can help me quickly grab the structure and preview the movements (P8).”*

Improve spatial awareness and kinematic understanding - *“Designing in the 3D environment is beneficial for people who are not that good at sketching or spatial imagination. This tool can help them express and evaluate their ideas more clearly (P2).”* Furthermore, P5 noted that this system could be applied to STEM education, *“allowing students to design their own mechanisms and understand movement more intuitively with depth perception. ”*

Assist context-aware solution generation and validation - MR technology provides a 3D design space that integrates the physical world, so that spatial dimensions and constraints can be naturally converted into design parameters, reducing manual measurements. Designers can obtain feedback based on the actual environment to optimize parameters before detailed design. *“It will be definitely helpful if we can design a welding robot arm exactly within the real factory and get some preliminary on-site evaluation (P8).”* P9 also believed that this tool can be used in ergonomics verification, such as preliminarily testing the user comfort with different angles and heights of a monitor arm model. Moreover, the generated model can be imported into CAD software (such as 3d Max or Rhino) for subsequent detailed design, which is positively agreed useful by P2, P9 and P10 during the interview.

Facilitate communication in the initial co-design stage - Compared with the traditional 2D sketch or CAD model, a kinematic prototype can be generated rapidly for visualization and discussion through the proposed system. P2 and P10 also believed that the system can facilitate communication during the conceptual design phase, especially among people with different backgrounds, such as industrial designers, mechanical designers, and programmers.

Limitations - Participants also pointed out some limitations. First, most participants complained about the annoying gesture recognition failure or misidentification. In addition, while the system improves the spatial awareness of the users, the total freedom and lack of constraints make users *"feel overwhelmed when determining the positions of joints (P2)"*. Lacking constraints makes freeform 3D curves look messy, and that is why Q2 got the lowest score ($u = 3.91$). Finally, more customized shapes and colours (P1, P4 and P10), and more convenient design modifications (P2, P9, and P10) should be provided as recommended by the participants.

8. Conclusion

This research proposes an MR-enhanced rapid prototyping approach for industrial articulated products. At the early design stage, users can grab the key kinetic joints and rough external shapes rapidly by intuitive gestures in the MR environment. Then, the embodied spatial structure and kinematics can be previewed. A user study with eleven participants proved the usefulness of the developed system. The system can assist designers in completing the prototype rapidly, improving spatial awareness and kinetic understanding, generating context-aware solutions and facilitating communication in the initial stage of co-design.

In the future, we aim to bring forth new MR-based solutions for a more immersive and interactive design process. Firstly, the system performance should be improved with more features added as the participants suggested. Moreover, dynamics information should be considered in the proposed system, such as payload. Finally, MR prototyping or modelling technology can be extended to other scenarios. For example, in redesign or interactive fabrication, engineers can make MR-based modification marks on existing products or even guide the manufacturing machines directly to modify the product on site.

Acknowledgements

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