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Development of Master-Slave Manipulator Using Pneumatic Cylinders

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ABSTRACT

Recently, development of instruments for minimally invasive surgery has been considerably required. This surgical procedure, as compared with traditional open surgery, enables the incision smaller, and this result in less patient pain and shorter duration of hospital stays. However, it requires increased skill on the part of the surgeon. To solve this problem, robotic manipulators using electric actuators that have multi-DOFs at the tip of them have been reported as alternative to conventional instruments. These systems, however, has the problem that force sensing is difficult. In this paper, we propose a master-slave manipulator using pneumatic cylinders as actuators that can be useful for laparoscopic surgery. This system can provide force feedback to the surgeon from the differential pressure of the cylinders. We designed a bilateral dynamic control system using neural network for acquisition of the inverse dynamics. The obtained inverse dynamics is used for feedforward and estimation of the external force. Experimental results showed that the developed system successfully display the contact force.

KEY WORDS

Pneumatics, Bilateral Control, Forceps, Neural Network

INTRODUCTION

Minimally invasive laparoscopic surgery has been widely performed in recent years. This surgical procedure enables a smaller incision as compared with traditional open surgery. This result in less patient pain and shorter duration of hospital stays. However, it requires increased skill on the part of the surgeon. This is because surgical instruments in laparoscopic surgery are restricted to the degrees of freedom (DOFs) motion due to trocars. As a result, surgeons have to handle the instruments at the opposite end to the abdominal cavity with respect to the trocar point. This prevents surgeons operating intuitively.

To solve the above problems, robotic manipulators, which have multi-DOFs at their tip, have been reported as alternative to conventional instruments [1]. These manipulators can be divided into two approaches with regard to the operating method. One is the manipulator where some DOFs are added to the tip of the conventional forceps [2][3]. A system of this type is omparatively small, and it is easy to introduce into surgery. However, the problem that the operation is not intuitive still remains. The other is a master-slave type in which the operating portion for the surgeon is separated as master from the forceps [4]. In this type, a surgeon is able to teleoperate the forceps at the master side, as if one handles the forceps at the slave side in the abdominal cavity. Therefore, this master-slave type is useful from the view of intuitiveness. This system, however, has the problem that the sense of force is lost. Some studies have been made on the force display in the master-slave surgery system [5][6], in which the force sensor, that is almost strain gauge, is attached into the tip of forceps manipulator. However, the sensor at the end of manipulator makes sterilizing and downsizing difficult.

In this research, we propose a master-slave system with multi-DOF forceps manipulators that is able to provide a force display to surgeons without a force sensor. This is to realize a bilateral control without force sensors that is quite different from the conventional methods [7]. To achieve this, pneumatic cylinders are used as the actuator, because they are effective for a haptic device due to the facility in measurement and control of their driving force, and enable the estimation of the external force from the driving force and the impedance.

DEVELOPED MANIPULATOR

Structure of the Manipulator

Fig.1 shows the developed forceps manipulator that has 7-DOFs. It has 4-DOFs at the tip, a roll, two bending joints and a holder, and 3-DOFs at the upper part, which is parallel mechanism with three cylinders. The size of the manipulator is about 800mm in height and 300mm in width. It is quite compact compared with daVinci and Zeus that are commercial systems. Moreover, the developed system can provide a force display using pneumatic cylinders not electric motors as the actuators.

Fig.2 shows the tip part of the manipulator. The diameter of the manipulator is 10mm that is useful for laparoscope surgery. The power for two bending joints at the tip of the manipulator is transmitted by a wire rope as shown in Fig. 3. The cylinder made by Airpel was used because it uses a precision fit graphite piston which slides freely - without lubrication - inside a pyrex glass cylinder. Therefore, the friction force is negligible small. The sizes of the cylinder used at the lower and upper part are 9.3mm and 14.9mm in diameter, 3.2mm and 5.0mm in the piston rod diameter and 25mm 75mm for the full stroke. The driving force of the cylinder F_{dr} is given as

$$F_{dr} = A\Delta P \tag{1}$$

where A and ΔP indicate the pressurized area and the differential pressure in the cylinder.

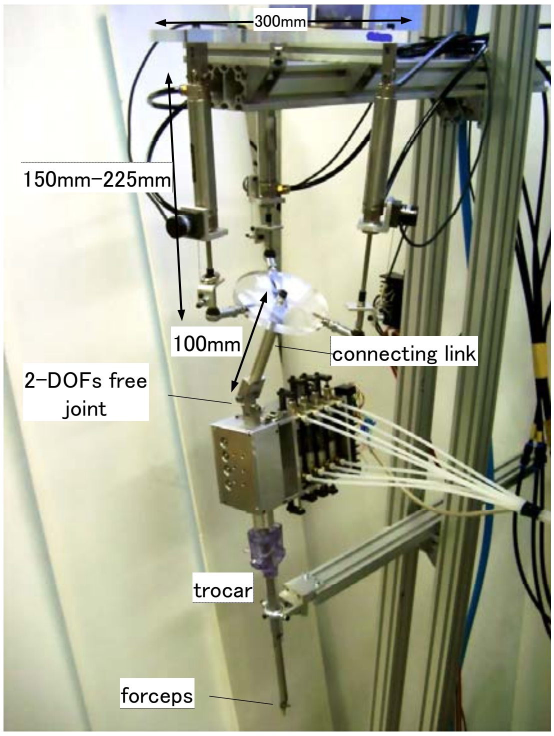

Fig.1 Developed manipulator

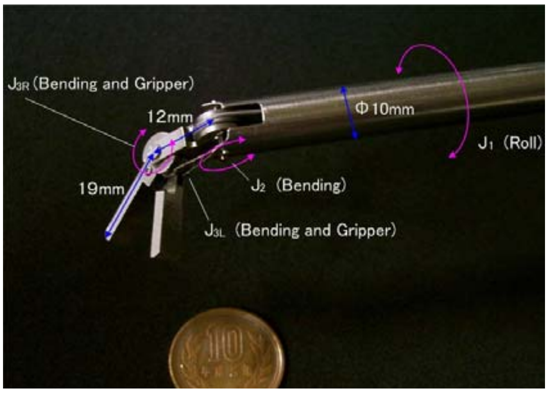

Fig.2 Tip photo of the developed manipulator

The supply pressure was set at 500kPa and a pressure sensor having a resolution of 20Pa was used. Since the pressurized area is 60mm^2, the maximum driving force at the tip becomes 30N which is considered to be enough for driving the manipulator.

The cylinder was controlled by a five ports servo valve made by FESTO. The servo valve receives the voltage signal and controls the flow rate to the cylinder. Pressures in the cylinder are measured with semiconductor type sensors and are used to control the driving force. Position is measured by an encoder having a resolution of 1000Pulse/Rev. We have confirmed in the preliminary experiment that the position error of the cylinder is not more than 0.1mm using a PID controller. Also, we have confirmed that the force control could be achieved with 0.05N accuracy.

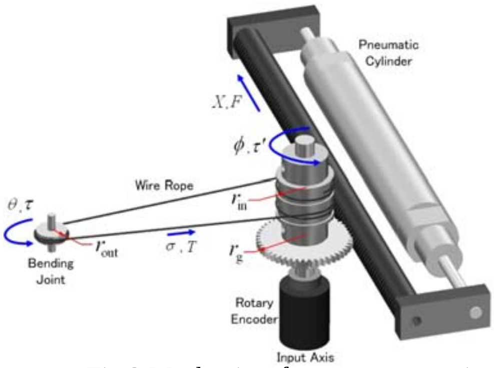

Fig.3 Mechanism for power transmission

At the tip, the displacement of the wire rope *l* shown in Fig.3 is proportional to that of the cylinder *X*.

$$l = r_{in}\phi = \frac{r_{in}}{r_g} X \tag{2}$$

where ϕ is the rotation angle of the pinion gear and the pulley, r_g is the pitch circle radius of the pinion and r_{in} is the radius of the pulley. Then, the angle of bending θ is given as

$$\theta = \frac{l}{r_{out}} = \frac{r_{in}}{r_{out} r_g} X = \frac{X}{R} \tag{3}$$

where r_{out} is the radius of the small pulley at the bending joint. Thus, the angle of bending θ is linear to the displacement of corresponding cylinder. We designed that the wire rope for driving the bending joint J_3 passed through the center of the joint J_2 to prevent interference between the joints. Additionally, the relationship between the torque τ for bending and the driving force of the pneumatic cylinder *F* is also linear and is given by

$$\tau = RF \tag{4}.$$

Where *R* is an equivalent value to reduction ratio. To improve the resolution of the rotation angle at the tip of the manipulator, *R* should be small. However, in contrast, to improve the force sensitivity *R* should be large. In this prototype manipulator, we adopted 8 [mm] as *R* (r_{in} =6.5mm, r_g =13mm, r_{out} =4mm) to reasonably satisfy both of these conditions. As a result, the resolution of the bending angle is considered to be 0.7degree. The weight of the tip part is 20N.

At the upper side, 3-DOFs are realized with parallel mechanism as shown in Fig.4. The maximum angle of

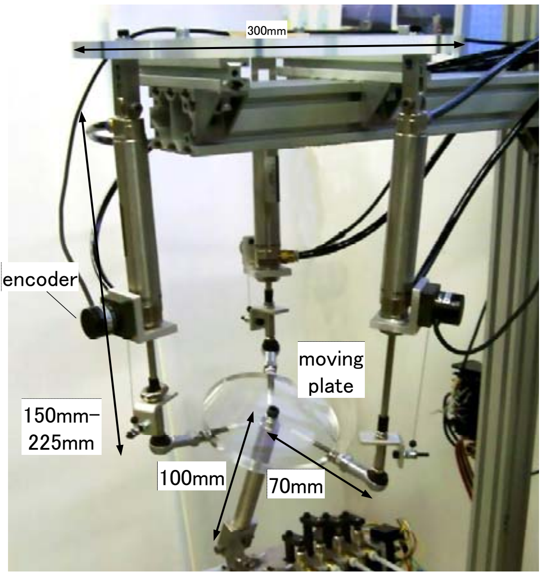

Fig.4 Upper part of the developed manipulator

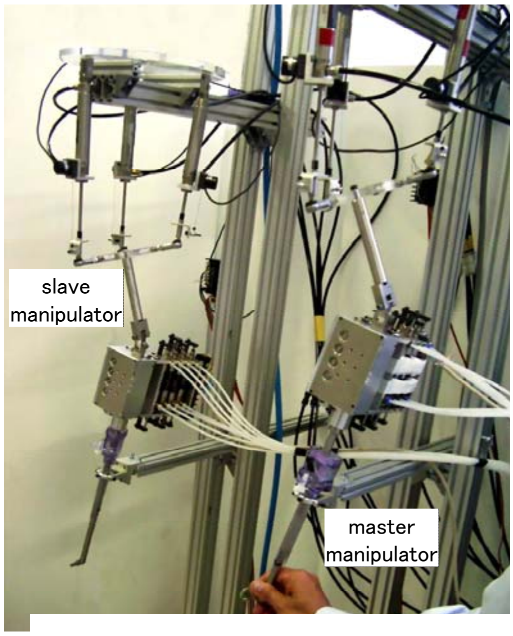

Fig.5 Developed Master-slave system

the moving plate is 30 degrees. The maximum force with the three cylinders is 90N, which is enough to hold the tip part. The tip and upper part were connected with a free joint. The length of the connecting link determines the moving angle at the tip of the manipulator. Therefore, it was designed as 100mm, which realizes the moving range of a circle whose diameter is about 120mm. The manipulator whose structure is the same as that of the slave side is used as the master side for simplification of control as shown in Fig5. Measured position and pressure signals are sent to a computer for control, and the computed voltage signals are provided to the servo valves.

BILATERAL CONTROL

Proposed control method

In this section, we describe the proposed method of bilateral control without force sensors in the master-slave system. Although a bilateral control method called symmetric position servo type needs no sensing of force, the performance is influenced by the dynamics of the manipulator. Therefore, the dynamic control using the impedance and the external force that are estimated by neural network as the driving force of the cylinders has been implemented.

The ideal response of the master-slave system is that both the position and force response in the master and slave side are identical with each other [7]. Consider a teleoperation system with two 7-DOF master and slave manipulator, whose dynamics described as

$$F_{dr}^{s} = Z^{s}(X^{s},\dot{X}^{s},\ddot{X}^{s}) + F_{en} \quad (5)$$

$$F_{dr}^{m} = Z^{m}(X^{m},\dot{X}^{m},\ddot{X}^{m}) - F_{op} \quad (6)$$

where F_{dr}, F_{op}, F_{en}, Z and X are translational vectors of the driving force of the pneumatic cylinders, the force exerted by an operator on the master side, the force applied on the environment, the impedance function of the manipulator and the displacement of the cylinder respectively, and subscript s and m denote slave and master side. The conditions of ideal response in this system can be written as

$$X^{s} = X^{m} \quad (7)$$

$$F_{op} = F_{en} \quad (8).$$

To satisfy Eq.(8), the driving forces of cylinders should be

$$F_{dr}^{s} = Z^{s}(X^{s},\dot{X}^{s},\ddot{X}^{s}) + F_{op} \quad (9)$$

$$F_{dr}^{m} = Z^{m}(X^{m},\dot{X}^{m},\ddot{X}^{m}) - F_{en} \quad (10).$$

There are, however, disturbances due to the uncertainty of impedances, external forces and so on. Therefore, position and velocity feedback has been added to restrain them as follows:

$$F_{dr}^{s} = K_{P}^{s}(X^{m} - X^{s}) + K_{d}^{s}(\dot{X}^{m} - \dot{X}^{s}) + Z^{S}(X^{s},\dot{X}^{s},\ddot{X}^{s}) + F_{op} \quad (11)$$

$$F_{dr}^{m} = K_{P}^{m}(X^{s} - X^{m}) + K_{d}^{m}(\dot{X}^{s} - \dot{X}^{m}) + Z^{m}(X^{m},\dot{X}^{m},\ddot{X}^{m}) - F_{en} \quad (12)$$

where K_p and K_d are gain vectors. Substituting Eq.(11) and (12) to Eq.(5) and (6) yields

$$K_{p}^{s}e + K_{d}^{s}\dot{e} + F_{op} - F_{en} = 0 \quad (13)$$

$$-K_{p}^{m}e - K_{d}^{m}\dot{e} - F_{en} + F_{op} = 0 \quad (14)$$

where

$$e \equiv X^{m} - X^{s} \quad (15).$$

Combining Eq.(13) and (14) yields the error equation:

$$\left(K_{p}^{s} + K_{p}^{m}\right)e + \left(K_{d}^{s} + K_{d}^{m}\right)\dot{e} = 0 \quad (16).$$

Hence, e converges asymptotically to zero with appropriate gains, and then from Eq.(13) or (14), Eq. (8) is also satisfied. This means that the ideal response is realized. In practical control, the position, velocity and acceleration of the other side were used as the input of the impedance function as shown in Eq.(17) and (18) to improve the speed of response.

$$F_{dr}^{s} = K_{P}^{s}(X^{m} - X^{s}) + K_{d}^{s}(\dot{X}^{m} - \dot{X}^{s}) + Z^{S}(X^{m},\dot{X}^{m},\ddot{X}^{m}) + F_{op} \quad (17)$$

$$F_{dr}^{m} = K_{P}^{m}(X^{s} - X^{m}) + K_{d}^{m}(\dot{X}^{s} - \dot{X}^{m}) + Z^{m}(X^{s},\dot{X}^{s},\ddot{X}^{s}) - F_{en} \quad (18).$$

Here $Z^{s}(X^{m},\dot{X}^{m},\ddot{X}^{m})$ and $Z^{m}(X^{s},\dot{X}^{s},\ddot{X}^{s})$ behave as a feedforward controller having inverse dynamics. The controller symmetrically sends the values of displacement and external force to one another. This symmetrical system is able to change the roles of master and that of the slave side.

Acquisition of inverse dynamics using a neural network

To implement Eq.(17) and (18), it turns out that the impedance function and the external force must be given in addition to the position. Here, it should be noticed that the driving force of pneumatic cylinder can be obtained from the differential pressure as shown in Eq.(1). Therefore, if the values of the impedance are given, the external force F_{ext} is given by

$$F_{ext} = F_{dr} - Z\left(X,\dot{X},\ddot{X}\right) \quad (19)$$

where F_{ext} denotes the vector of external force to the cylinder, which is F_{en} at the slave side and $-F_{op}$ at the master side. We can estimate the external force from Eq.(19) using a disturbance observer. Therefore, it is significant to obtain the impedance of the manipulator which is equivalent to the inverse dynamics problem. Thus, acquisition of the inverse dynamics enables both estimation of the external force and feedforward control.

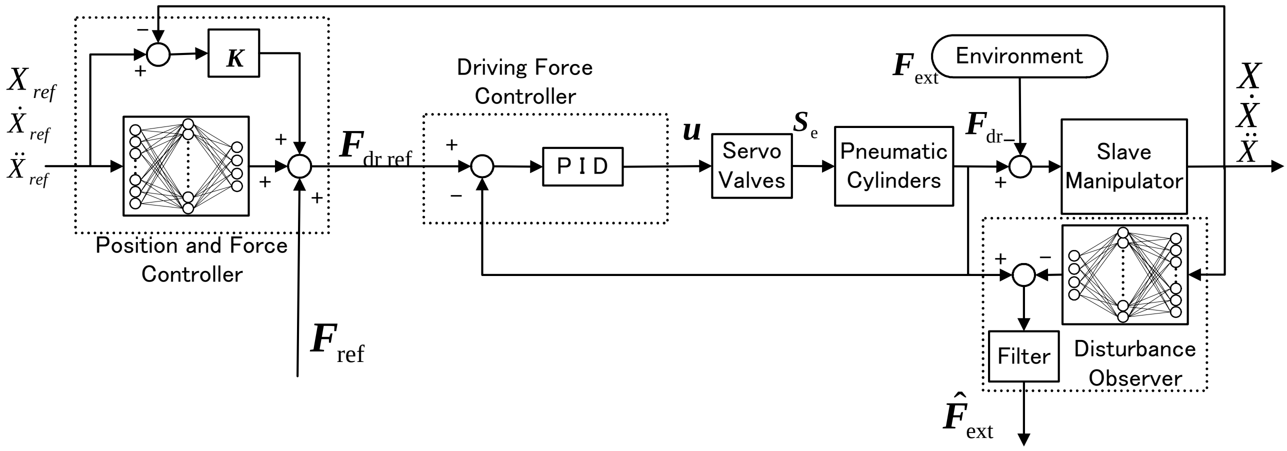

Fig.6 Block diagram of the designed bilateral control

Generally, the dynamics of a multi-DOF manipulator depends on its attitude, mainly because of the influences of inertia and gravity varies with the position. The tip of the forceps manipulator is small and light so that their effects are negligible. In the prototype manipulator, there is, however, the dependence of dynamics due to the position. This is because of the variation in friction caused by the wire rope. This friction characteristic seems to have strong nonlinearity and is very difficult to model mathematically. Although friction model in a single pneumatic cylinder has been reported [8], the model is unable to represent the dependence on the position.

For the reason mentioned above, a neural network is used to obtain the inverse dynamics of the manipulator. We used a three-layered neural network in which there are twenty-one inputs (displacements, velocities and acceleration of each joint) and seven outputs of impedance. The network is trained offline with back-propagation using the data collected through a closed-loop experiment in which the manipulator is assigned random position trajectries and no external load. In no-load motion, the driving force corresponds to the impedance from Eq.(19). After the training is finished, the network can be used as a feedforward controller and disturbance observer. The detail of the master or slave controller is represented as Fig. 6. The controllers are the same at the master and slave side. The controller has a major loop for position and a minor loop for differential pressure which realize the desired driving force. The neural network is incorporated as feedforward and disturbance observer. The measured position and estimated external force are provided to the other side as an input.

EXPERIMENTAL RESULTS

Examination of Force Estimation

Some experiments were undertaken to verify the precision of the force estimation by the disturbance observer. We placed a single axis load cell that is a force sensor as an object on the slave side. To compare the external forces estimated by Eq.(19) with the output of the force sensor, we transformed them into Cartesian coordinate system at the tip of the manipulator using a Jacobian matrix.

Fig.7 shows the experimental results. It is clear from the results that the estimated force is slightly larger than the output of the load cell especially at the maximum value. This is because the force at the tip of the manipulator was not entirely transmitted to the cylinders due to mechanical flexure and the friction caused by the load. This could be improved by modifying the structure of the manipulator. However, the estimated value corresponded well with the output of the load cell on the whole.

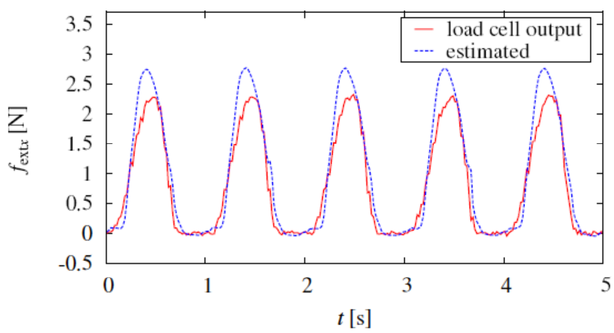

Fig.7 Experimental results of force sensing

Bilateral Control Experiment

The performance of the master-slave system was examined with the proposed bilateral control by use of the estimated inverse dynamics and external force. The neural networks in the master and slave side were previously trained with the data in the no-load motion. The slave manipulator was brought into contact with an object by the operator handling the master manipulator.

The experimental results at joint J_1 and J_{3L} at the tip are shown in Fig.8 and Fig.9.

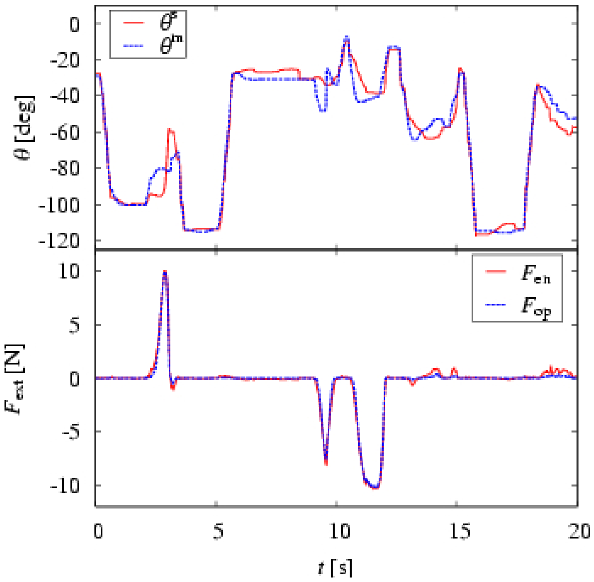

Fig.8 Experimental results of bilateral control at J_1

The upper graphs indicate the position of the cylinder.

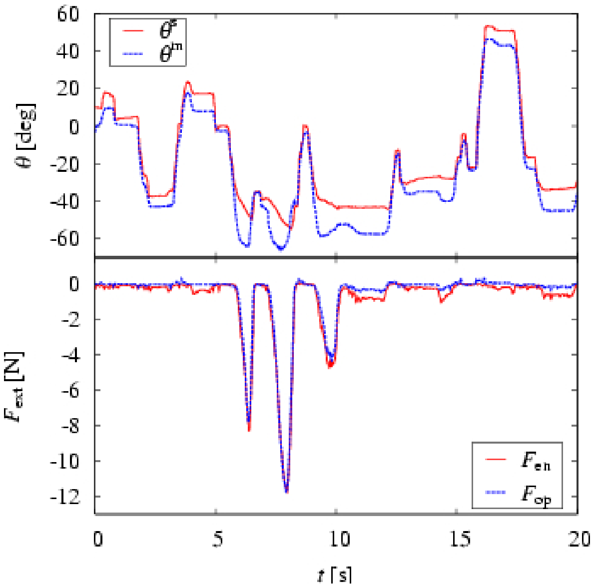

Fig.9 Experimental results of bilateral control at J_{3L}

The lower graphs show the external forces at the master and slave side. While there are some disagreement in the position, which is caused by the mechanical flexure and friction under load and also by the convergence speed of the controller, it can be seen that the force exerted by the operator on the master side and the force applied on the environment correspond well. The effectiveness of the proposed bilateral control method was therefore demonstrated.

CONCLUSIONS

In this paper, a manipulator has been developed which has 7-DOFs actuated by pneumatic cylinders. A master-slave system has been established with the manipulator for laparoscopic surgery. Neural networks were applied to the controller for acquisition of the inverse dynamics and the external force without using force sensors. The experimental results indicated that the operator felt the force at the slave side to a satisfactory extent.

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