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Robots for Aircraft Paint Stripping: An Assessment

Final Report

Uri Gat

MANAGED BY
MARTIN MARIETTA ENERGY SYSTEMS, INC.
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Project: Survey and Assessment of Robotics for Automatic Plastic Media Blasting (PMB) Paint Stripping of Navy Aircraft

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ROBOTS FOR AIRCRAFT PAINT STRIPPING: AN ASSESSMENT

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ABSTRACT

Requirements and desired characteristics of robots, manipulators, and other auxiliaries for the mechanization of paint stripping from military aircraft are identified and summarized. The impact of stripping methods on the robots is considered. Robots and manipulators that were available for review were considered in this review. It is concluded that complete autonomous robots for aircraft paint stripping are not yet (1991) commercially available. There are, however, robots with various degrees of automation being developed for this application.

1. INTRODUCTION

This work was initiated by the Naval Air Systems Command. The original request was to write specifications for the purchase of a robot to strip the paint from naval fighter-type aircraft. The fighter-type aircraft are relatively small (i.e., they readily fit in a hangar), expensive, sophisticated, and sensitive. The sophistication and sensitivity characteristics, for paint stripping purposes, are manifested as adjacent areas that vary widely in properties and which may not be easily distinguishable. For example, a simple skin plate surface may be thick in one part and thin in another. A composite material may be next to a metal skin, all covered by the same paint. Other sensitive materials include canopies and electronic and measuring devices, which often protrude from the surface. The paint stripping technology originally considered in this project, and dominating all others, was plastic media blasting (PMB).

The prime motivations to traditional chemical solvent stripping are pollution control, avoidance of hazardous materials, and environmental protection. The search for new and different stripping methods also brought about the desire to upgrade operations and use nonmanual methods such as robots. Since there are some hazards associated with the paint itself, consideration must be given to containment and operator protection. These considerations are secondary at this time because the requirements for protection and limits of exposure have not been well defined, and the hazards associated with the various types of paint have not been explored in detail.

The author of this report has also been involved in a task for the automation of paint stripping of Navy ships. Some of the reported work draws on that experience. For ship paint stripping, the emphasis was on containment and economy while utilizing water jets as the stripping mechanism. The author was also involved in the design and specification of equipment for a PMB facility for the Navy. Experience gained in that design is also brought to bear in this report. Insight acquired while dealing with the characterization and disposal of used plastic media is also reflected in this report. The related projects were under the auspices of various branches of the Navy, the Air Force, and the Army.

The search for robots revealed that no paint-stripping robots were available for purchase. At that time, no robot had been demonstrated actually stripping an aircraft. The task then changed to assessing robots that are offered for paint stripping of aircraft and to sorting out their characteristics.

Upon reviewing robots proposed for paint stripping, it became clear that the term "robot" is used freely for a wide variety of gadgets. These ranged from simple manually operated manipulators or servo-mechanisms to sophisticated robotic arms fully programmable and enhanced with sensors and safety devices. As the Navy has not defined the specific kind of robot it seeks or desires, no device was precluded because it did not seem to fit the terminology. In view of the above, this report has attempted to describe and rate attributes or properties associated with robots specifically for paint stripping of aircraft. This is, perhaps, the major accomplishment of this report. The proposed attributes are intended to serve as guidance and for general understanding of robotic properties of paint-stripping devices. These properties are not criteria for strict evaluation, but they may be used to define desired options and, perhaps in the future, provide the basis for evaluation criteria and specifications. Additional work is needed to assign weighting factors and relative importance to each of these attributes, which are unlikely to be universal. The weighting factors and importance ranking will be specific to aircraft types, operating facilities, time (at which time the assignment of the importance is made), and other inputs.

Initially, it seemed that PMB had become the chosen method for stripping aircraft paint; later on, this became less and less obvious. Therefore, other paint-stripping methods were also considered. This was an important consideration because some methods, such as laser stripping, could be enhanced or even made possible in conjunction with robots. If so, this will require that emphasis be placed on different specific properties and required accuracy. While, for the example of laser stripping, the precision needed, the repetition and repeatability, and the small area stripped per pass may be impractical for manual operation, it could be indifferent for automatic operation. In other methods, such as blasting with frozen pellets, the forces required to hold the nozzles steady make some degree of auxiliary manipulation necessary. Health and safety protection equipment for operators may make manual operation of some methods so cumbersome that great advantage and needed economy would be derived by altogether removing the operator from the stripping area.

This report is comprised primarily of portions of previously published progress reports and special reports.

No specific additional research or development was done. The scope was restricted to assessing the available equipment and information. Some recommendations for needed work are made.

2. PURPOSE, SCOPE, AND BACKGROUND

2.1 OBJECTIVE AND SCOPE

The objective and scope of this review were to survey and assess availability and practicality of available robotic technology for the removal of protective coatings from aircraft.

2.2 BACKGROUND

The Navy is in the process of phasing out chemical paint stripping from aircraft and phasing in methods that are more economical, efficient, nondamaging, and enivornmentally acceptable. Two prime candidates for the new methods are laser stripping and media blasting stripping. Among the media being considered for blasting stripping are plastic media, bicarbonates, and frozen carbon dioxide pellets.

To achieve better quality, uniformity, efficiency, and economy and to minimize any possible environmental hazards, the use of robots and automatic methods for aircraft paint stripping is a desirable option.

It is desirable that robots selected for stripping paint be as flexible and versatile as possible. Flexibility and versatility refer to the ability to (1) recognize and adjust to variations within an aircraft type; (2) handle different types of aircraft, including segments of aircraft; and (3) accommodate different stripping methods, primarily laser stripping and PMB. However, such flexibility or versatility may not be readily available. Furthermore, practical robots or even a partial degree of automation may not be presently available.

2.3 AIRCRAFT PROTECTIVE COATING REMOVAL

Coatings are removed from aircraft to check the underlying substrate material for corrosion, structural integrity, or damage. Specifically, any cracks in the outer skin are of great concern. The coatings are also removed and replaced to renew protective properties since aged paint loses its ability to prevent corrosion that can induce and/or enhance cracking.

2.3.1 Motivation -- Robots for Aircraft Protective Coating Removal

The Navy is seeking coating removal robots for the following five major reasons.

1. **Economy.** Reduction of the labor-intensive manual stripping should provide better economy.
2. **Damage Avoidance.** Inadequate coating removal can cause damage to the substrate materials. It may even cause fatigue, fatigue cracking, or other damage. Manual operations are not very precise in all application parameters, such as distance away from the surface, amount of material applied, momentum of medium, angle of incidence, and dwell time. It is believed that a precise application, as is possible with a robot, of all parameters will avoid or minimize damage. Damage avoidance is achieved through precision and control of application parameters.
3. **Hazardous Waste Reduction.** Greater precision, optimization of application, and complete containment are some features that will help reduce hazardous waste. Complete containment is all but impossible when human operators are present.
4. **Reduction or Elimination of Worker Exposure.** A robot that is completely autonomous and requires only remote supervision can eliminate worker exposure.
5. **Inspection.** Currently, inspection is done by visual observation. An efficient robotic inspection of the substrate will fulfill the purpose of stripping more effectively and economically.

As an additional goal, the reapplication of protective coatings could be done as an integral part of the process, further achieving greater economy.

2.4 CONSIDERATIONS AFFECTING CHOICE OF ROBOTS

The five motivators listed above for seeking robots for aircraft paint stripping have many more aspects, some of which are listed here by the same categories as the motivators. Because robots in general and their application for paint stripping of aircraft are very new, much of the information needed for their complete specification is not yet available. The following considerations are proposed as areas needing attention. Additional aspects will be unveiled as the issues are better understood and with actual experience emerging.

1. **Economy.** No one dominating measure for economy is commonly available, and there is no thorough cost analysis, or definition, for comparison. There are partial, incomplete, and varying measures such as stripping rates -- area per unit time, area per worker (nozzle), time, and waste disposal cost. None of these measures is either sufficiently well known or provides an adequate basis for comparison. Some of the most important, and most likely overriding, driving forces do not even have an attempted cost quantification. These include worker exposure, present and anticipated future cost of waste handling, quality and reproducibility of work, and cost of the effects of stripping on the substrate and on the aircraft in general (such as damage and reduced life expectancy).

2. **Damage Avoidance.** Damage avoidance is generally considered a very important factor; nevertheless, there is neither a consensus for what damage occurs nor a comparative measure for this. Various studies have checked some of the stripping parameter effects on such material properties as cracking, crack propagation, fatigue, peening, warping, and others. A common measurement performed uses almen strips, but the results are interpreted only with relation to one another in the same set of experiments, or by intuition. No unambiguous measure of damage is available or used.

3. **Hazardous Waste Reduction.** The goal, and often the driving force, for robotics is to reduce hazardous waste and its handling. The usual basis for evaluation is by comparison to presently used methods. Often just avoiding chemical stripping is considered a major and worthwhile accomplishment. No criteria or goals are identified. There is great concern about even stricter regulations, laws and requirements, and the associated increasing cost of handling and disposing of waste. A major advantage anticipated for robots is immediate containment and "closed loop" operation to reduce waste generation. Though not related to automation per se but

more coincident in time, improved separation and classification of medium and waste are anticipated. There are no established criteria or measures for separation or classification. There is a military specification for the cleanliness of virgin medium that is used as a guideline.

4. **Reduction or Elimination of Worker Exposure.** There is no defined goal in this area; however, there is a trend toward as low an exposure as reasonably (and economically?) achievable. There is no measure or comparison basis for worker exposure, though some measurements have been made on several occasions.

5. **Inspection.** There are no established measures or criteria for the inspection of the stripped aircraft. Many measurements and studies have been done, but there are no firm and accepted conclusions or guidelines.

3. ROBOTS FOR REMOVAL OF COATINGS FROM AIRCRAFT

The term robot is used for a wide range of devices with varying capabilities, self-containment, autonomy, and facility to change. While the name given a particular device may not be very important, it is important to clearly understand the capabilities of the device. This understanding is of instrumental importance when comparing "robots."

A spectrum of devices that could at times be called robots may include:

1. **Auxiliaries.** Devices such as wheels that fix the distance parameter and sensors to measure or detect parameters and their status, such as distance sensors.

2. **Programmable Manipulators.** Manipulators that can perform repetitious functions and be preprogrammed.

3. **Autonomous Manipulators.** Programmable manipulators that have a limited self-adjustment capability and can correct minor mistakes; these may require only limited operator supervision.

4. **Learning Manipulators.** Manipulators that are programmed by doing a sample operation, which the robot then repeats on demand.

5. **Intelligent Robots.** Robots that have sensing and recognition capability and can adjust their operations accordingly by applying artificial reasoning.

3.1 DESIRED FEATURES FOR COATING-REMOVAL ROBOTS

To achieve the goals for advanced coating-removal robots, the robot should possess the following several advanced features:

Repetition. The robot must be able to repeat its functions with great precision.

Programmable. The robot must be able to adjust to different aircraft and know which substrates are at what location and adjust parameters accordingly.

Precision. To avoid damage, the robot must work at all times within a very narrow range of parameters. The parameters vary with respect to the area of the aircraft being stripped.

Self-adjustment. The robot must be able to recognize any deviations of location or shape of the aircraft and adjust the parameters accordingly.

Quality. High-quality performance is required for all robotic functions. Quality assurance and quality control must be included in the overall quality parameter.

Sensing. To optimize (minimize) application, the robot must be able to sense any differences in aircraft location or topography, local or overall, and adjust parameters accordingly. The sensing applies specifically to the recognition of adequate and complete paint stripping.

Reliability. Because airplanes are a significant economic asset, the robot must be very reliable and not damage the aircraft.

Inspection. The robot should be able to perform the exposed substrate inspection reliably, quickly, and effectively. A more advanced robot should be capable of inspecting the substrate and coating in a nondestructive manner and limiting the stripping only to the required areas.

Flexibility. The robot should be able to remove paint from the entire aircraft, including intricate corners and other difficult areas.

Versatility. The robot should be able to adjust to changing requirements, different aircraft, and new functions, such as recoating or perhaps some minor repairs (for composites).

Mechanical. The robot must have adequate reach and weight-carrying capacity.

3.2 RANGES OF ROBOTS' DESIRED FEATURES

To specify and assess a robot for paint stripping, it is necessary to determine the desired features. At this time (1991), a determination of these features is not possible because there is insufficient information available and very little experience with some of the basic processes. To reach a starting position, and as a general guideline, an estimate is made of an acceptable range of the desired features. The ranges and values given here are estimates based on assumptions and information gathered by "word of mouth" from various sources. The information is derived from some experience with PMB and some theoretical considerations of laser stripping. There was insufficient information directly related to carbon dioxide pellet stripping; therefore, it was assumed that these pellets are analogous to plastic medium. At present there are some indications that carbon dioxide pellets need to be treated very differently from plastic medium.

Repetition. Aircraft are precisely engineered and constructed contrivances. It is estimated that repetition to within ± 20 mm will suffice in most cases. However, in transition areas such as substrate thickness, material change (canopy), strong curvatures, or external gadgets (small electronic devices), a repetition capability of ± 5 mm or better may be desired or necessary. Better repeatability will enable the reduction of masking, when done for surface protection (not to avoid penetration). Repetition is closely related to several other features particularly self-adjustment, sensing, and precision.

Programmable. Programmability is needed for different types of aircraft. Within one type of aircraft it must be possible to program the detailed map of that type and variations within that type, such as specific deviations resulting from modifications, maintenance, or repairs. The teaching of programmability must be possible; this means operator-guided override of the program that can be stored for future use. This information would accompany each individual aircraft with its own detailed design and manufacturing details, starting at the design and manufacture stages at the factory (through CAD/CAM) and remain there its entire life, with changes, modifications, and maintenance added to its computer-readable history.

Precision. All operations of the robot must be precise. Some of the required parameter ranges are distance of nozzle to surface within ± 30 mm (there are claims that much better distance precision is desirable or even necessary to prevent damage); angle of incidence $\pm 20°$ (here again there are claims that better precision is needed); mass flow rate $\pm 10\%$; and particle velocity $\pm 10\%$. (This parameter is often referred to as the air pressure. However, there are methods, for example, turbines, in which the air pressure is only of secondary importance. Air pressure is poorly correlated to the particles' momentum, which is considered the important parameter. Furthermore, this parameter may be very sensitive to other changes, such as distance and angle, so that much better precision may be necessary for compensation. Claims have been made for the need for 1% or better precision for particle velocity and 10% or better for dwell time or moving velocity.) It is preferable that only selected predetermined layers of a multilayer coating be removed. Laser stripping or CO_2 pellets require much better precision by as much as one order of magnitude or more over the values stated here for PMB.

Self-Adjustment. This feature requires the robot to be a self-learner; that is, it should recognize and either adjust or stop operation when there is a deviation of the aircraft from the program (or a wrong program). Also the robot must recognize and adjust to any deviations that have occurred, for example, in the robot itself.

Quality. The robot must perform in conformance with its specifications and within the range allocated for any parameter, individually and in concert, at all times. Quality assurance and quality control must also be covered. Any deviations that occur must be recognized and recorded.

Sensing. The robot must have sensors for all relevant parameters, such as location, distance, flow rates, coating removal, etc., that facilitate operation within the required range of the parameters.

Reliability. The robot operation must be reliable within the range of operation parameters. If a deviation occurs, it must be recognized and registered. A minor deviation, one that causes, or can cause, minor damage (possibly <$5000) to an aircraft, should occur <1%; major damage (>$5000) should be restricted to <1 permille.

Inspection. The robot should inspect the substrate, with respect to criteria to be established with no significant additional time for stripping. Thirty minutes or less should be needed to inspect each aircraft. The inspection must comply with the criteria, which will also specify the reliability.

Flexibility. The robot should strip at least 60% of the aircraft surface without a need for "touch-up"; 100% coverage is desirable. This feature is economically important. If less than complete coverage is achieved, several of the base reasons for seeking a robot are compromised, such as worker exposure, hazardous-waste-handling reduction, and inspection. Also the requirements imposed on the entire facility are not removed.

Versatility. The same robot should be able to handle new future aircraft and new, yet undetermined, future requirements, including, nondestructive inspection, that is, without coating removal; recoating; handling (minor) repairs; adjusting to different coatings, such as new materials, and coating thickness.

Mechanical. An engineering design requirement is that the robot perform all tasks equally well in all configurations. Of particular concern is the ability to retain precision and reliability at extreme reaches. It should be able to handle vertical, inclined, and horizontal – facing upward or downward – surfaces and be of a mass and configuration that can be readily deployed and utilized in facilities similar to existing ones, as well as outside of enclosed facilities for large aircraft.

3.3 THE INTELLIGENT ROBOT

The ultimate robot is the intelligent robot. The intelligent robot would have an advanced degree of all features mentioned and also have a learning capability. The robot will be able, with no external intervention, to recognize, analyze, and provide a solution to situations that are neither programmed nor previously experienced. There is, of course, an infinite number of such situations; some examples could be that the wrong aircraft is in place, the aircraft was put in backward, the aircraft has wrong parts on it, or the aircraft has not been adequately prepared (not masked).

A completely intelligent system does not exist, and even some degrees of intelligence may be prohibitively expensive and not justified economically.

Safety, not damaging the aircraft, and collision avoidance are probably the areas that justify some consideration of advanced applications. Related areas where advanced methods may be usable are recognition and adjustment to variations in the aircraft, such as dimensional and position variations; paint specifics, such as type, age, and condition; cracks; position of controls; specific equipment; etc. The intelligence of the system should be sufficient to compensate for the interaction between different operating parameters.

A highly desirable intelligent feature for the robot is the ability to recognize and adjust to the presence of paint. Preferably, the robot should be able to recognize paint and paint removal by layers, because often only one or two top layers are removed, leaving the primer or other layers intact.

The intelligent robot would be sufficiently autonomous to operate without human supervision.

4. ROBOT EVALUATION

More than ten robots were reviewed in association with this report. They varied from auxiliaries to fully programmable robots with attempted degrees of intelligence. Some of these robots were being developed specifically for PMB for military-type aircraft; others were actually in use for removing coatings from specific objects. The robots reviewed used PMBs, water jets, lasers, and CO_2 pellets and claimed the ability to use other methods.

None of the robotics was developed to the state of being ready to demonstrate paint stripping from an actual aircraft, nor were any of the robots ready for routine operation with aircraft.

The science of robotics has advanced to the degree that their theoretical construction and programming is readily possible. This capability was demonstrated on various occasions. Sample panels were stripped by several of the reviewed robots. This demonstrates the technology is available in principle.

Because the technology is available in principle, actual assessment of robots for paint stripping must be done with respect to their ability to perform in the field under actual conditions and in routine operations. Because none of the robots could be observed in actual operation, an evaluation of their capabilities was impossible. The reasons for their unavailability for demonstration varied from incomplete development to delay in funding of the demonstration.

Another important factor hindering the evaluation of the robots is the lack of performance criteria. Even the basic stripping process has no generally accepted performance criteria. One common concern in coating removal is the stripping rate. The stripping rate is of less concern, however, when automated stripping is used. Another common concern is damage to the substrate material. This is a valid concern, and several studies have been performed to determine the effect of stripping on the substrate. No agreed-upon criteria or measures are available for application.

5. NEEDED INFORMATION

To evaluate and specify robots for paint stripping of aircraft, much more information is needed. Perhaps the most important types of information needed are an established agreed-upon current or state-of-the-art status of paint stripping. This agreement would provide the basis with which a specification and an evaluation could be made. Next in importance are the needs for information on the goals for paint stripping and some criteria. Though some goals are mentioned in this report, they are not recognized as the accepted goals. Once the goals are established, some measure of importance must be assigned to them so a trade-off study can be done.

Specific information is needed and should be accurately formulated in several areas. The purpose of paint stripping from aircraft should be precisely defined, as well as the desired quality of stripping. These definitions are to include stripping by lasers, when and how these are desired, and to what quality is a layer to be removed with the underlying layer remaining unscathed. The cleanliness of the remaining surface needs to be defined along with such items as the remaining paint spots or streaks and amount of dust that is acceptable. All these definitions should be specific by substrate material.

Lists of items to be done and those to avoid in the stripping operation need to be compiled. These lists may be different and specific to what stripping methods are applied. At times, different methods may have different purposes. For example, laser stripping may be applied after the bulk of the stripping is complete to remove remaining paint patches, in lieu of "touch up," to remove paint from areas difficult to reach otherwise, or around rivets, etc. A water stripping may be applied as a wash-off method in combination with a touch-up by recognizing remaining paint patches and momentarily increasing the water pressure or including some grit in the stream. The lists should be specific by substrate material.

The required areas of agreement are the definition, characterization, and means of recognition and quantification of the meaning of "damage" to the aircraft. Several studies have been made and various characteristics used to define damage, such as cracks and their size, surface stress, fiber damage for composites, almen strip results, and others. The studies, however, have not been summarized and combined into a recognized and accepted study that includes measurable parameters that can be evaluated with respect to established criteria. The "damage" needs to be further characterized with respect to expected (this probably would be better called changes rather than damage), tolerated, and unacceptable since these characteristics are likely to be method specific. There is also a need to provide quantitative measure and economic value to facilitate trade-off studies and enable evaluations and selection decisions. The characteristics need to be distinct with respect to age of the aircraft, substrate age, paint type and age, number of previous strippings, and probably additional parameters. Manufacturer's recommendations must also be considered, to the extent available.

Detailed information is needed about the treatment and disposition of the removed coatings and the other material used in the process. This information must include present restrictions, limitations, regulations, laws, and future anticipations. The regulations differ by location (locality, county, state, federal, foreign countries) and are subject to change. The information is needed for the operation time, such as local (in hangar, air, water), permissible concentration, operator exposure, and disposal roles and cost.

6. CONCLUSIONS

Specific robots for paint stripping of military-type aircraft could not be assessed or evaluated because none was ready for actual demonstration, neither was any of the robots characterized or specified in sufficient detail. The basic technology for sophisticated robotics is available. The specific application and operational details and technology are yet to be demonstrated. The economics of applying robotics has not been resolved.

The term robots is used for a variety of devices. The terminology is not important, but the trade-off studies and technical and economic viability of any proposed system must be evaluated.

There is need for agreed-upon goals and accepted quality of paint stripping from aircraft. The quality is to include characterization of the desired outcome (paint stripping) and quantitatively accepted results and consequences.

Paint stripping could be expanded and integrated with other maintenance functions. Some possibilities are inspection with no stripping or selective stripping, performance of repairs or other maintenance, and cleaning and repainting. Stripping methods need to be fully characterized.

7. RECOMMENDATIONS

The following recommendations are made to enhance the Navy's aircraft maintenance program and make relevant information more readily available. These will facilitate the most satisfactory decision about robots for aircraft coating removal and the associated methods for paint stripping.

1. Commission a systematic study of the effects of the various stripping methods on the different substrates. The study should include all the information already generated. Part

of the study shall be the definition of the effects ("damage") of the stripping methods and their importance, and the anticipated impact on aircraft. The study shall also establish criteria and measures for these effects. The results of the study should be carefully reviewed and approved by the Navy as the basis for future evaluations.

2. Continue to support an evaluation focal point for using robots for paint stripping. The enormous variety and possibilities available in robots need to be evaluated from an overall point of view and, a cross comparison should be made.

3. Support a consulting task that will be "all inclusive" and "outside the main stream." This consulting center should integrate all aspects of the aircraft maintenance with respect to its skin. This consultant will gather and evaluate (1) all information about the protective coatings, their purpose, function, and effectiveness; (2) all knowledge about stripping methods, their effectiveness, efficiency, and impact; and (3) the information about waste handling, treating, requirements, and regulations. Proposed alternatives for these, their outlook, and expectations shall also be included. All this information shall be available in an evaluated, weighted, and summarized fashion to anyone in the Navy who has need for it. To start this effort, a doctoral-level thesis on these maintenance methods and treatment should be supported. While this effort need not be on a very high level, except initially, it is extremely important that it be continuous and all encompassing. Annual reviews of the state of the art should be part of this effort.

A study needs to be done to look at protective coatings from design to completion. The study will examine all aspects of protective coatings: their function, treatment, manufacturability, enhancement, and alternatives. The study will integrate the considerations of the design, manufacturer, operator, and maintenance of the aircraft from its inception to decommissioning, including the disposition of material.

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The literature cited here is of general nature and can help in providing some initial input when the recommendations are implemented.

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