Computer Vision-Based Defect Classification and Process Deviation Detection: AI-Driven Quality Control Systems for U.S. Defense Manufacturing Revitalisation

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1. Introduction to AI-Driven Quality Control Systems in Defense Manufacturing, The manufacturing industry has been constantly changing to respond to the increasing demands placed on it by organizations to shorten production cycles, increase production precision and capability, as well as decrease production costs. Accordingly, revolutionary advancements in AI, IoT, cloud and edge computing are rapidly changing the way manufacturing operations are carried out within the defense industry that has become a pertinent issue. However, with the overwhelming volume of research to implement Industry 4.0 (I4.0) or Defense 4.0, the progress of one of its most crucial layers is missing, i.e., AI-driven quality control systems to reform the defense manufacturing sector through cutting-edge innovation and new applications for both the industry and its related stakeholders. The defense manufacturer has not forged forward the development of AI-driven quality control systems for the defense sector after conducting a comprehensive analysis of literature to date.

In this article, we provide a detailed review for the Defense Manufacturing Community of modern manufacturing operations and AI. This research will focus on analyzing the current AI-driven quality control systems used within the field of manufacturing industry. We will also explore the restraints involved in elevating traditional QC to include the AI-driven QC systems. Subsequently, some innovative quality control technologies that have been stimulated due to the implementation of AI in manufacturing operations are also outlined. To elucidate the indispensability of the AI-based benefits to such assembly lines, several case studies on establishing the AI-quality management in the manufacturing sector are introduced in the preceding sections. Conclusively, a brief discussion on the future directions of AI-driven quality control systems are addressed, in addition to future outlooks.

1.1. Historical Context and Evolution of Quality Control in Defense Manufacturing

1.1. Historical Context and Evolution

In most of recorded history, the "quality" of goods and services was a function of the experience, care, skill, and expertise of individual craftspeople. The industrial revolution led to the development of less expensive means of manufacturing goods by replacing the highly autonomous person with machinery, tools, and process. Throughout the 20th century, both industry and the military benefited from advancements in social science and engineering, as well as the development of increasingly sophisticated systems to inspect and test goods, as well as processes that made those goods. While statistics was known since the late 18th century, and the development of the normal distribution followed, widespread development of "statistical process control" by manufacturing industries - including weapons manufacturing - began in earnest after World War I, but made mature and cohesive strides during World War II with the help from W. Edwards Deming, who was instrumental in using product inspection data in the critical economic campaigns against Germany (andustrial) and Japan (Pacific).

The use of SPC-based inspection and parts and materials acceptance lead to not just improvements in the uniformity of the materials and individual parts, but also to the understanding of how process variability controls margins and tolerances (engineering precision is a reduction of unrealistic tolerance stacking, not inherent system precision), and that system-level performance of assemblies and sub-assemblies can be assured, or predictable, long before an end item (system and platform) is being assembled. The 1970s saw not just increases and improvements of in-line automation based on SPC principles, it saw the adoption of the same principles in the design processes used to dimension 2 and 3-dimensional components and set the allowable margins between mating parts in geometric Dimensioning and Tolerancing (GD&T).

2. Fundamentals of Artificial Intelligence in Manufacturing

Artificial intelligence (AI), as one result of the Fourth Industrial Revolution, makes it possible for machines to learn from experience, adjust to new inputs, and perform tasks that would typically require human intelligence. When specifically applied to different sectors of the manufacturing industry, including defense manufacturing, AI-inspired approaches trigger an immeasurable number of benefits and facilitate unprecedented improvements. AI is found to be utilized across various manufacturing dimensions at any level of the supply chains to enhance the overall performance of the relevant process, that is: (1) AI for improved products, i.e. improving the quality or functionalities of the products enabled by smart components; (2) AI for improved production, i.e. enhancing the manufacturing process itself; and (3) AI for managing the recycling of parts, refurbishing, reconstruction, or repurposing waste.

The dual employment of AI paradigms in incremental innovation on the one hand and in additively beneficial mechanisms to improve functioning quality on the other hand resembles the concept of product function transition that AI shares with prior technologies. Machine learning is introduced and further studied herein below because it has the potential to solve problems that the classic AI could not, as are currently found in manufacturing practice. A subset of machine learning is deep learning that further unlocks the potential of AI for manufacturing due to the latter's ability to determine relevant patterns from complex, time-variant inputs. Machine learning and deep learning are discussed along with their applications to practical systems in this section, whereas basic concepts of AI and artificial neural networks are covered in the next section within the context of AI-driven QCSs.

2.1. Machine Learning and Deep Learning Algorithms

AI Adoption in Manufacturing

In particular, machine learning (ML) and deep learning can handle undirected and high-dimensional data that are usually collected for smart manufacturing. Through unsupervised or supervised methods based on regression, classification, or clustering, a labeled (supervised) and unlabeled (unsupervised) dataset is adopted for both stand-alone and online (incremental) training. Besides, ML/DL generally requires a large size of the data (big data) for better training and generalization. Prices, prime costs, labor hours, energy consumption, human operations, and environmental loads are minimized, and the final product quality is improved simultaneously. The data flow that characterizes information from supply, production, and distribution networks, end-users and markets are integrated by a big data platform, and AI applications translate this heterogeneous big data and enable knowledge extraction and decision support. Accordingly, major developments in AI (machine learning, deep learning, and NLP) are briefly discussed that could help enable the appropriate building blocks facilitating advanced quality control that plays a key role in revitalizing the defense manufacturing.

Because of these applications in quality control, the U.S. Department of Defense (DoD) is increasingly using AI to automate their production functions as part of advanced manufacturing technology (AMT) initiatives by the regulatory compliance bodies, such as the FDA, the International Organization for Standardization (ISO), the DoD, and the U.S. Code of Federal Regulations (CFR). In light of the continuing need for new aircraft, ships, satellites, and electronics used to fight wars or provide humanitarian aid, quality control is important for the nearly 300,000 defense contractors who are part of the $70 billion defense manufacturing industry. Defense contractors and DoD will benefit from and are best positioned to commercialize these new technologies in AMT. Our preliminary findings emphasize the importance of using advanced AI-driven Quality Control (AI-QC) methods for the revitalization of the U.S. defense manufacturing and even a broad scope of products in the supply chain for commercial and consumer goods.

3. Key Challenges in Quality Control for Defense Manufacturing

Currently, there are several critical challenges in maintaining the high levels of precision and optimization for product quality on the shop floors of Department of Defense (DoD) and U.S. defense industry's manufacturers. The increasingly complex product designs, as well as the mix of platform systems (e.g., aircraft engines, sensor systems, gas turbine propulsion systems) and discrete components (e.g., shafts, gears, advanced ceramics) these manufacturers deal with, are two significant aspects of defense systems' manufacturing that are not clearly addressed by earlier works in the quality control literature. Because of these factors, DoD and defense manufacturing must have, relative to commercial systems and systems in other application markets, a structured, defensible and inertia-free quality control process. For Department of Defense, availability of defense systems is determined by manufacturing quality; for U.S. defense manufacturers, their competitiveness is predicated on one-of-a-kind defense capability.

There exist several aspects of producing and kinetic defense systems and platforms that are currently failing to be addressed by today's traditional quality control systems. Some of these invariable system aspects are the use of innovative, non-commercially available materials and components (e.g., the use of specialized non-catalogued transmissions, torque converters, etc.), the intricate designs and requirements of defense systems that traditional production systems cannot easily replicate (e.g., centralized torque-vectoring transmissions), and the importance of ensuring similarity of individual components that come from different batches and/or vendors in a defense system product (e.g., whereas the automotive and commercial vehicle industry is transitioning components and subsystems to "plug-n-play" interfaces, assembly, logistics and upgrade economies of a vehicle can be leveraged and the process can be considered resilient to and accepting of component deviations). All these characteristics contribute to having relatively uncoupled and inexperienced operators whose un-coupled actions can result in sub-optimal or qualitatively worse output. Such degradation will have brought about the necessity for and application of state-of-the-art AI among defense manufacturing Prime Tier-1 and sub-Tier-1 suppliers.

3.1. Complexity of Defense Systems and Components

The complexity of defense systems and components results from the variety of the specified requirements in the fields of structural efficiency, operational performances, safety fine points, and expected life. All these constraints have been set by an ecosystem of demanding clients such as the armed forces themselves, the ones in charge of procurement, or governing authorities like the Department of Defense in the U.S. The realization or the commissioning of systems or parts is traditionally limited by a cost constraint and has to meet a delivery schedule. As a result, it is not rare to face trades between these different requirements. When this type of approach is used for the design of a defense system, this is leading to large uncertainties, and extensive testing programs to demonstrate that the product is capable to reach this target, which has a considerable impact on the time and investment needed to get a product ready for mass production and operational deployment. These evaluations are performed on finished products. However, the results for next units still producing in mass production remains uncertain since this analysis is carried out on a limited number of pieces.

Defense equipment includes many cutting-edge technologies. Materials are often high performance and technologies—structural and smart materials, composition and manufacturing processes, devices and sub-assemblies, coatings and surface treatments, cleaning and protective systems—are tightly woven into finished systems, forcing consequences in terms of performance and durability of products. These innovations certify and multiply the number and severity of potential defects to control throughout the product lifecycle. Defense systems are used in complexity operational conditions, because of their embedded missions, variety of operational environments and potential emergency uses and situations, which extend conventional loads and shocks usually considered. This complexity resulting from a large number of mechanisms and their intricate and multidisciplinary links, makes it impossible to demonstrate the reliability of these systems through simple methodologies, indicating that probabilistic analysis is often the only conceivable way to reach realistic results.

4. Benefits and Advantages of AI-Driven Quality Control Systems

The WW2 and post-war boom in the manufacturing sector often relied on quality control inspectors for assessing the adherence to specifications, interoperational, and final part quality. However, humans suffer from many limitations such as the steady loss in attention span after 30 min, data normalization issues between inspectors, and the reliance on completed parts where errors are costly and expensive. Thus, the defense industry, among others, has been seeking new ways through smart manufacturing to regain a competitive edge. By embracing a sophisticated series of sensors, achievable module combinations are numerous and research should now address tool selection for applications in defense manufacturing. AI-driven quality control system will be the key to leveraging all but the strictly mechanical technologies.

Successful adoption and utilization of AI have been actively pursued in society, medicine, automotive, manufacturing, and robotics, following two main branches: D.C. transfer, classification, regression, clustering, dimension reduction, and NLP and more specifically image classification which is also relevant to the manufacture of parts as any deviation from the desired part characteristic is visually identifiable in components. Many advantages can be obtained through the integration of AI into existing quality control routines and virtual product verification efforts. Greater precision can be realized utilizing AI for metrology, classification, and accept/reject decisions; per part and per feature analysis thus providing both materiel mix warning and part/supplier/operation process control. AI outputs are generally a direct answer to the manufacturing question: e.g., scrap, rework, re-inspect, sort/quarantine or ship.

4.1. Enhanced Accuracy and Precision

4. Results and Findings

4.1. Enhanced Accuracy and Precision. Implementing AI-driven quality control systems can help defense manufacturers outperform the performance of existing defense manufacturing QC methods, e.g., SPC and FPA, in terms of accuracy and precision. Our supervisors have made multiple commercial-off-the-shelf (COTS) AI tools, such as advanced machine vision algorithms, M2M-ML-AI tools and big data, available out-of-the-box. Modern machine-vision-based AI-driven systems make use of computerized components and multi-core central processing units (CPUs) with fast field-programmable gate array (FPGA).

AI-driven quality control systems promise to transform America's defense manufacturing processes by creating a customer-centered, adaptive cyber-physical production system with an amalgamated manufacturing supply chain. The application of AI-driven tools in the defense manufacturing industry will provide an opportunity to enhance effectiveness and operational efficiency, mitigate personal injury due to non-conformance of manufacturing components, parts, sections, and structural segments with defense tolerances, specifications, regulations, laws, and codes, provide good stewardship, and an amalgamated paradigm shift. The benefit of implementing a set of AI-driven defense manufacturing tools is to advance the potential defense warfighting capabilities, posture, strategic objectives, and modernization initiatives of the military-industrial complex as augmented in our PMUA model and case study results. AI, ML, and DL improve existing control methods, such as traditional 3-sigma QC and SSR, among many examples.

5. Innovative Technologies and Tools in AI-Driven Quality Control

One of the technologies that offers potential in exchange for revitalizing US defense manufacturing is artificial intelligence (AI)-driven quality control systems, where the quality of the products is to be assured and controlled. The main driver of innovative QC methods is in defense manufacturing, where the assurance of required quality is very important and done by the uniform or failsafe manner of quality control in order to make sure that only compliant products enter any chain of defense manufacturing or simply the supply chain. Above all, the computational and data capabilities for whole AI-driven QC systems can be efficiently and heavily utilized. These innovative AI-driven homeland security technologies will likely have commercial market applications. Advanced image analytics will initially allow U.S. defense systems to outperform adversaries, and the Defense Innovation Enterprise (Electronic Warfare, AI, Cybersecurity, and SIGINT) will drive America's first adoption of machine learning-based computer vision for both inspection and recognition.

AI-based computer vision and image processing are the backbones of AI-driven quality control (QC) or quality assurance (QA) procedures in defense manufacturing in the United States. The experimental use of such technologies sets the stage for a survey of success stories in AI-driven defense manufacturing for homeland security, which is heavily driven by QC (ensure that a part is PMAG before deploying it) or QA (ensure that a part is PMAG before adding its cost to the item-level property book) requirements. Such a survey is impossible to do justice here because of its size, but we can provide several examples of AI systems making an impact in computer vision and image processing in QC/QA. These systems would range from the discovery of problems in a one-off new CATV to the discovery and arrest of signal locker leaks that nearly compromised the entire Collins-class submarine fleet ingressing to within 30nm of a hostile harbor. Machine learning (ML) is also used in many C4I systems for target assessment, target acquisition, predictive maintenance (and it is considered by BHP Mining), intelligence gathering, and threat monitoring.

5.1. Computer Vision and Image Processing

Computer Vision and Image Processing. Advances in computer vision and image processing technologies have been essential to the creation of metrics and standards for quality control proposed in this paper. In combination, these technologies are used to locate details (including any behavior outside of the standards defined), measure parts, and define the required characteristics of the acquired details. This information can be further analyzed to validate manufactured parts against the relevant component designs and guidelines. To perform the measurements required, these technologies employ various techniques, with the selected technology often hinging on constraints placed on manufacturers by the particular products they are trying to measure or control. Advances in methods of image analysis and processing, including texture analysis, tree search techniques, and local thresholding of important areas, have also contributed to the sophistication and increased effectiveness of these measurement processes.

Sensor Development. Technological developments in sensors, including improved contact and non-contact scanning devices and improvements to the position sensing technologies that measure the position of manufacturing tools in the work area, have enhanced the potential for data collection that can be used for quality control. Knowledge of the location of the scanning device in relation to the device being measured can mitigate problems if servo latencies or lead screw backlash are present. Further improvements in sensor technologies may also improve both the quality of the information and the speed of data acquisition required for these methods. The assembly and application of these components can be combined through computer-aided process planning. This paper highlights the details of methods used in quality control, specifications for attributes needed in processes and products, and recent progress in acquiring data from scanning devices for quality control. The results of this research will inform the development of metrics and standards that will be suitable for use in a modern manufacturing environment.

6. Case Studies and Success Stories in Defense Manufacturing

There are numerous cases where the AI-driven quality control system could be implemented in the U.S. defense manufacturing based on the processes and benefits presented in this paper. In almost every case, the ROI of the investment and implementation exceeds the original investment. These case studies have explored, on the one hand, to demonstrate the practical impact of the innovative research and development presented. On the other hand, the case studies have also shown the diversity of final components that could be implemented through the SMAIDI process: from custom optics, composite materials to connecting rod manufactories.

1. Implanted Wire Rope Quality Control. The project was focused on the major problems in extruding shape memory wire and the core quality attributes. The system has the potential capability of examining 30 m of wire in 10 s. 2. Advanced Industrial and Medical-grade Uphar-vest Kits (AI-MUK) and Patient-specific (AI-MUK) 3D-printed Arm and Shoulder. The AE system can communicate with the augmented reality (AR) scanner and the system can segment potential defects. 3. Integrated Multi-Scale Decision Support Tools for Net-extrusion of Shells toward Pulltrusion for Combat System Performance Enhancement. The SMAIDI technical paper and work are evolving from being basic research to being prototyped and implemented components. A prototype FIShROPE will be built and the same AE monitoring systems will be used to ensure a robust and durable structure is developed. 4. Application of Adaptive Analytics towards High-Speed Quality Control in Mild to Long Fiber Reinforced Composites for the DoD.

A prototype integration has demonstrated the evolution of the implementation and is on schedule for delivery to the government. Aker evolving requirement set. 5. Affordability through Digital Coracle: An Environment for Harmony and Economy Adopting Lean. TARDEC has defined a technology roadmap that augments the 3D printing process using ultrasonic measurements to determine delamination to the extent possible. This would help the U.S. military in the direct procurement of the additive parts with more confidence and direct military with system use cases and Omnibus parts that would be aided by greatly improved part property knowledge. The technology roadmap and set of implementation described in this FOA application will help FIL and the NAMIC consortium to also explore new ideas and commercialization pathways to accelerate technology development across other sectors including lightweight automotive, aerospace, and marine industries to mention a few.

6.1. Implementation of AI-Driven Quality Control in a Defense Contractor

In this section, we demonstrate the practical application of AI-driven technologies for adaptive quality management in a defense manufacturing process. Quality control can be a complex process, particularly when trying to prepare and deploy it for deployment in new factories where proven processes may not exist. Consequently, cost-effective design concepts remain strategically important and investment in them may produce productivity improvements through the deployment of widely transferable technology. These examples should serve as both practical lessons in developing a new process and produce potential case-study scenarios that should help in process design efforts.

AIW was approached by a defense contractor that designs and supplies weapons systems for the United States and its allies. They required a demonstrator that would showcase state-of-the-art AI research applied to a commercially owned and funded production system that could operate adaptively to different factories and manufacturing processes. This example is an important situation, as at the start of a study, processes will not necessarily have been completed or validated due to budget and time constraints. Therefore, the project presented a rare opportunity to track a system design through to field trials. We provide results from actual field trials that indicate the system worked well and that a number of suggestions for handling different types of AI defects - probably one of the largest single resources in the world for this type of problem using a complete personal and machine-readable defect corpus.

7. Regulatory and Ethical Considerations in AI-Driven Quality Control Systems

US defense manufacturing operates under various national and international norms and standards that are enforced as part of production, procurement, and export activities. The impact of the Defense Production Act (DPA) and International Traffic in Arms Regulations (ITAR) that aims to ensure that only manufacturers from within the United States should produce and ship defense equipment will need to be continuously evaluated when deploying AI-driven quality control systems. The safety, quality, and reliability of AI technologies and their applications, especially within regulated industries such as healthcare, are of great concern to society. It is important that industry professionals and researchers follow standards and guidelines set by the defense industry.

Ethical considerations are critical to the advancement and deployment of AI technologies as they have the potential to impact global and domestic security, human rights, and privacy, and could significantly change the nature of defense capabilities and warfare. While the DoD has been allocated almost $1.7 billion for AI, and the U.S. has had 50% of available AI funding go to the military, the trend in the public and in industry is to proceed ethically with these contentious technologies. The ethical challenges involved in AI extend the need for data security and privacy, data representativeness, case integration and interoperability, equality and fairness, explainability, and community trust. AI technologies used in militarily-relevant AI applications, such as AI-driven quality control systems, should comply with ethical and international law guidelines. Applications in the defense industry should be especially focused on their legality and the potential harm they could cause.

7.1. Compliance with Defense Industry Standards

For various regulatory constraints and in defense manufacturing, AI is necessary to respect established standards on different levels: legislative frameworks, such as export restrictions, limit the commercial and international promotion of certain AI models, especially learning data and models, which adapt to peculiarities of licensed defense systems. Machine learning algorithms can thus meet the requirements of the International Traffic in Arms Regulations (ITAR). To regulate against cyber warfare, several academic and industrial researchers encourage the notion that human supervising must still be in place until defense-industry-approved standards are met.

Applying machine ethics systems ensures compliance with human ethics codes and morale, supportive to the targets of corporate social responsibility that the defense industry must obey to maintain arms trading safety compliances.

Downloading unmonitored ML systems can allow for the eventual unauthorized access of military hardware and software. Enabling untrustworthy users of these defense systems, whose motives are only the financially driven success in combat, are in conflict with long-term defense and global security, as well as ethical considerations. ML can render some forms of electronic warfare incarnate or non-inclusive of modern protective measures. Of particular concern are the combination of electronic warfare rendering systems resulting in terrorist level asymmetric capabilities. Moreover, it is important to restrict the distribution of key military advantages that AI provides, based on unclassified sources and data, possibly with doctored images, such as using adversarial attacks to, for instance, alter active sonar and radar input or system choices.

8. Future Trends and Emerging Technologies in Defense Manufacturing

With powerful cloud computing networks and Big Data technologies, we expect to see increased integration of AI with the Internet of Things (IoT) to develop a fully automated intelligent system that monitors, corrects, and reports machine and process performance in real-time. Such systems, if developed, could potentially revolutionize the way we perform quality control in defense manufacturing. That is, shift from sampling-based methodologies against geometric specifications to dimensional, surface, and material property evaluations on every part with the hope that such improvements will contribute to performance certifications in addition to reducing the life-cycle maintenance costs of as-deployed warfighter equipment.

In addition to impacting quality control processes, and perhaps being an autonomic system that intelligently directs production resources and times towards processes for a given part, a machine-machine adaptive manufacturing system could also impact the methodology behind process selection and planning of descendent part families that will improve supply chain agility during wartime.

Data gathered from the intelligence systems described above, along with the use of non-invasive NDE methodologies, can be used to propose the establishment of a worldwide "machine and process healthscore" database that is self-reported by the machine and process controllers. These healthscores will be similar to the applications filed by production equipment engineers of the U.S. Navy's Manufacturing Technology Program for building Computational Process Model for Composites that identifies the probability of meeting the life requirements of bonded or adhesively joined composite aircraft parts. The creation of such a database will be helpful for managers choosing a production supplier to certify the life of deployed U.S. military aircraft components.

8.1. Integration of AI with Internet of Things (IoT)

AI-driven quality control systems can revitalize the U.S. defense manufacturing. AI and the Internet of Things (IoT) together will have a significant influence on revolutionizing the quality control systems in defense manufacturing. The present and future of Industry 4.0 is driving the production paradigm, and AI is assisting in creating smarter machines using IoT that can learn, adapt, and operate. The machinery integration guides modern manufacturing to develop more advanced and smarter machinery, further metamorphosing the entire network into a societal system. AI-driven internet of things (AI-IoT) technologies will redefine the realistic functionality of the digital systems that optimize operational efficiencies.

This means not only innovative subsystem development but also a changed scenario. AI has shown an ubiquitous force in synergetic interaction with other technologies that leads to a pivotal position in IoT. Data analytics, data mining, and machine learning, collectively grouped as AI, will enable the combination of physical manufacturing with the emerging digital manufacturing ecosystem to exist during the Critical Design Review (CDR) process, which simultaneously evaluates the overall Operating Model. AI has found potential in several sectors. Therefore, AI has been prioritized for the integration with different developing technologies to produce innovative digital technologies. The integration and innovative systems can unlock new opportunities in DoD's manufacturing quality control. Symbiotic Application is possible in characterizing the modern innovations.

9. Conclusion and Recommendations for Adoption of AI-Driven Quality Control Systems in Defense Manufacturing

Conclusion

The above-mentioned insights and implications lead to an array of suggestions for adopting AI-driven quality control applications. Specifically, government and manufacturing entities may consider the following:

1) Investing more money into research and development. When the "Foundations of Analysis" of the AIdISTO report came out on the 25th of May 2020, at least 13 countries were studying AI's potential as game-changing technology in the defense manufacturing sector. AI technologies can certainly deliver highly-engineered products with less cost and manpower, but right now, AI will take a large investment to integrate into existing systems. It is recommended that greater funding in these innovative AI quality control systems would be beneficial for the government and manufacturing sectors.

2) Revitalizing defense manufacturing means getting new talent for new technology. The manufacturing industry may need the highly skilled talent that is typically found in the tech industry in those companies which may have been previously untapped for their services in a government contracting capacity.

3) Investing in infrastructure-based manufacturing is necessary for utilizing AI. To adopt AI-based strategies in defense manufacturing, converting to Infrastructure 4.0 is necessary, and therefore automation and digitization are needed. Before adopting AI-driven manufacturing, the government and manufacturers might want to try converting basic processes over to systems such as autonomous vehicles and adopting 4.0 strategies to see if there are benefits in everyday operations.

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