



Analysis of Intelligent Welding Strategies Based on Machine Vision

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Abstract. With the fast development of industrial automation, welding process is one of the core production processes that affects product quality and production efficiency of enterprises with its welding quality and efficiency. Non-contact inspection, real-time information acquisition, and high-precision recognition make machine vision technology the main core driver to upgrade intelligent welding technology in the future. The application of machine vision technology in intelligent welding is discussed for weld seam detection and identification as well as monitoring weld quality. First, the author studies the basic theory of machine vision and intelligent welding technology and lays a theoretical foundation, clarifying coordination mechanisms between vision system and welding equipment. Second, according to weld identification needs, an image acquisition scheme is designed based on the actual engineering environment. Image pre-processing is conducted and features and recognition are extracted by employing various algorithms, such as the template matching algorithm and the Hough transform algorithm, then results locate accurately welded seams experimentally. Third, we construct a real-time monitoring system for welding in this work based on machine vision platform, where by introducing machine learning method and relying on visual characteristic information of pores, cracks, and lack of fusion in the welding process, visual characteristics are further extracted and identified to complete the online weld quality detection. Finally, we construct an experimental platform to test weld positioning precision and weld defect recognition accuracy under various conditions. A highly automatized welding system using machine vision greatly accelerates welding automation intelligence; therefore, machine vision has become an essential supportive force for promoting high-end manufacturing to achieve higher quality.

Keywords: Machine vision; intelligent welding; weld inspection; image processing; quality control.

1 Introduction

1.1 The Importance of Welding Technology in Industrial Automation

Welding as one of the main manufacturing process techniques, plays an important role in various sectors such as automobile industry, aviation and aerospace, pressure vessels, and ships. In automobile manufacturing, the welding is not only the weldment of vehicle body parts, but also combines components such as engines, and weld quality has a direct impact on vehicle reliability. Based on this premise, application scenarios for automobiles are more closely followed by scientists around the world [1]. In aerospace field, welding techniques assemble many complicated parts such as frame bodies and blades and have significant influence on airplane performances [2]. Moreover, the connection strength directly determines the fatigue life and sealing property in pressure vessels and ships especially under extremely harsh environments of high temperature and pressure. Hence, it is of vital importance for production and manufacturing. Additionally, with the rapidly developing industrial processes, the use and research value of welding technique have been further illuminated due to their effect upon industrial competitiveness and productivity. Therefore, advancement and innovation of welding technique play significant role in the modern development of various manufacturing industries.

1.2 Limitations of Traditional Welding Methods.

Though welding plays a critical role in industry, the existing welding technology is limited in capacity. On one hand, conventional welding is strongly dependent on manually operation; the experience and skill of welders will affect the quality of weld, which hardly ensure stability and consistency on weld quality [1]. On the other hand, the conventional welding will be challenge for welding complex workpieces especially within tough environment subjected to high temperature and high-risk operating, during which human security and accuracy of operating will be restricted [3-7]. Moreover, the weld positions based on conventional welding tend to produce inconsistent characteristics with fluctuating change, which causes defects on bubbles and holes, cracks and fusion, further driving up the cost of correction and manufacturing fee. Worse, conventional welding is hardly monitoring effectively on quality flaws such as defects during welding, it mostly depends on manual inspection or merely assistance of some intelligent equipment for observing after welding, and it will fail in detecting and correcting timely during welding processes. Those issues not only influence productivity and efficiency, but also restrict applicability of welding technologies as well as development within welding industry on modern advanced products manufacturing

1.3 Research Scope and Objectives

Study the combination of machine vision (camera, lens, light, image processing algorithm) with intelligent welding (welding robot, sensor, controller). Clarify their respective positions in the system and operation methods to meet different scene requirements such as seam positioning, real time monitoring, detection defects and clarify weld detecting and locating technologies analyze image taking solutions to understand how CCD/CMOS camera is selected what kind of optical lens and lighting can be matched or add filters to resist electric arc interference combine how image pre-processing algorithms reduce noise (median filtering) improve image quality (contrast histogram equalization) and extraction feature (Sobel/Canny edge detection) to achieve precise weld location with template matching, Hough transform and other computer vision techniques Analyze weld quality monitoring and defect detection by establish a real time monitor system with high frame rate video taking CCD camera with PTP protocol to sync robot and welding; collect parameters with three sensors (welding current, welding voltage, molten pool morphology parameter) extract gray-scale feature shape feature texture feature about weld porosity cracking based on features judge level by weld detection software with certain rules and standards to complete weld evaluation Through researching analyzing weld detection positioning, image acquiring treatment, real time online monitoring and defect identification areas for welder understand role and benefit of machine vision applying to modern industry welding technology

2 Foundational Theory of Machine Vision and Intelligent Welding

2.1 Overview of Machine Vision Technology

Components of a Machine Vision System. As the key of the perception module, a vision machine for intelligent welding is composed of some camera hardware components, such as camera, lens, light source and image capture card. The core device is the camera which functions as a sensor to convert optical signal into image signal through the photoelectric effect. The literature has proved that due to the high resolution and low noise characteristic of CCD, the CCD cameras have higher performance in capturing weld images [5], especially suitable for laser welding seam images acquiring. Lenses have effects on the quality of images and can adjust related parameters. The choice of suitable lenses will improve image clarity and contrast, providing clear imaging basis for subsequent steps. Another consideration is the light sources because different types (also the arrangement position) would affect image brightness and uniformity. Therefore, reasonable light sources help extract features effectively. Image capture cards serve as bridge between the camera and the computer, converting signal form from analog to digital and transmitting to relevant image processing software program so that algorithmic analysis can be made. In addition to these parts, there are other image software's that provide image processing algorithms. The algorithms consist of several stages, for example, image preprocessing algorithms, feature

extracting algorithms, pattern analyzing algorithms etc., offering technical support and solution for detecting weld and monitoring quality in smart welding system [6-10].

Core Technical Principles. The essence of machine vision technology is the process of image acquisition, processing, analysis and identification. The photoelectric component during the acquisition stage translates the reflected light, radiation signal to object light into a digital image taken by the camera can be influenced many factors (camera resolution, shutter speed, illumination brightness, etc.), Then, through noise reduction, enhance images in the image processing process for improving the quality of pictures previous steps, so as to better provide data for each subsequent steps in the process. Example, use image noise reduction algorithm such as media filtering, Gaussian filter, etc., in image process, reduce noises caused by image to weld. Or histogram equalization, image contrast enhancement algorithm in image to enhancing welding edges features image [5]. If want to increase weld edge sharpness in welding image. Firstly do analysis step on image, through different algorithms about contours or edges extraction related extract weld seam texture extract operator (Sobel, Canny, Sift) can be executed [10]. Software for applications to improve effect of views through the method of image enhance (noise reduction algorithm on image) [11]. Then through pattern recognition technology and computers related using machine learning algorithm with image processing for determination the result of the image to extract aiming at realizing function located weld, judging defect [12-15].

2.2 Fundamentals of Intelligent Welding Technology

Composition of Intelligent Welding Systems. Intelligent welding system contains welding robots, sensors, and controllers for high-efficiency and accurate welding process of parts, and achieves the task of automatic or semi-automatic welding by virtue of multiple modules. The welding robot is the core part and works as the welder to complete the welding following some previously defined route or newly updated instructions, and its flexibility and precision determine the quality of welded parts and spots. Sensors gather parameters emitted from each part of the welding process in a continuous manner such as welding temperatures and shapes as well as positions of the welded pool, etc., which help serve as feedback data for optimizing system efficiency and accuracy. [7]. Sensor on machine vision bases itself on photography that enables visual depiction of the welding image; sensor can precisely locate for guiding robots, so their ability optimizes trajectories and positions of welding robots [13]. Controller works as the "brain" that provides appropriate instruction about welding process after examining the sensed values delivered by sensing units of various sensors, aiming for assuring that the formed joints have no problems with regard to quality during complicated welding processing variants, and the welding robot acts as a sort of drive section, while controller is a part with intelligence to make reasonable judgments based on value measurements derived from perception [7].

Critical Welding Parameters and Their Impact on Quality. Current, voltage, and speed during welding affects the bead formation and quality of weld. Welding current can lead to the heat entering into the molten pool, too much welding current leads to burning-through of base material or under-rolling of molten metal, resulting in

structures with poor quality (e.g., burn-through), lack of fusion. Too small welding current may result in lacking weld strength, low mechanical joint properties [1]. Welding voltage is related to arc stability and arc droplets transition, suitable arc-voltage setting helps even spread molten-pool for more favorable shape [13]. Further, welders have some adjustment for controlling the weld thickness by given specific current setting and precise weld bead geometry. Besides, welders may also control the welding speed because of great impact on weld quality as well. For example, welding speed fast leads to insufficient filling and solidification; weld speed slow result in excessive heat leading to weld distortion, coarsening crystallization etc. To precisely control those variables through online monitoring will increase reliability and consistency of weld [1].

2.3 Integration Mechanism of Machine Vision and Intelligent Welding

Typical Application Scenarios of Machine Vision in Welding. Machine vision has a variety of applications on intelligent welding, including weld seam positioning, online monitoring and defects identification. For weld seam positioning, the visual sensing technologies of machine vision take pictures of the weld seam, process it accurately for better analyzing result of seam morphology, then quickly obtain the position and rotation of the weld seams to provide navigation for the robot [2]. In regard to welding online monitoring, by taking pictures dynamically, the visual sensor monitors the morphology and key data of actual welding process, thus allows on-line monitoring and control to guarantee the safety of production, such as surface cracks of welds in electric resistance spot welding processes [11]. Meanwhile, a weld quality inspection equipment system is presented based on structured light scanning image measurement method, its image scanning camera can analyze the surface point cloud of welded specimens and extract weld outlines to assess the surface quality by these surfaces [2]. In addition, computer vision detects the typical types of weld defect like porosity, lack of fusion and crack rapidly through processing the weld images, extracting the image features, classifying the extracted weld image to improve the weld quality vastly [10]. Therefore, these weld applications display once again the multitudes and vitalities of machine vision technology for intelligent welding.

Principles of Visual Information-Welding Control Integration. The welding linkage method between machine vision and intelligent welding translates the captured vision to welding instruction in time to direct the intelligent welding process, and realizes the linking of machine vision with the welding process effectively. The machine vision camera collects the captured image with visual information processing technology and gets weld information including weld position information, morphology and quality characteristics, sends it to the controller and adjusts the control command of the welding controller through the visual information. The welding torch position parameters will vary with every weld. It is not static [7]. In the weld tracking system, captured camera images need processing to extract the weld seam centerline features. Then according to the centerline features and other information, the controller guides the movement of the welding torch so that a precise and stable weld tracking can be achieved [13]. The visual information also optimizes the weld-ing path

planning to guarantee welding quality, that is, according to the shape and model of the workpiece, by using template matching and Hough transform algorithm to obtain the welding path line adaptable to actual application scenarios [4]. If we combine the computer vision and welding control tightly, we can improve the automation level and realize high quality weld formation [7].

3 Machine Vision-Based Weld Inspection and Positioning Technology

3.1 Design of Weld Image Acquisition Systems

Weld image acquisition system the basis of intelligent welding is to realize high-precision weld detection and positioning. This determines the quality of image processing and analysis. Therefore, selecting image acquisition hardware and improving environment has a huge influence on weld seam image processing and detection. Taking selection for image acquisition device as an example, selecting camera types must be determined by resolution size, frame rate, sensitivity etc. Camera lenses have a determining effect on image acquisition system imaging effects. For instance, lens focal length determines captured image field of view. A long focal lens can achieve bigger image field of view, but sacrifices resolution degree. Usually using short focus length lens can acquire tiny detailed areas to generate smaller size images. Lens aperture reflects lighting capacity of image acquisition system which affects brightness of captured image and dynamic range of pixel values within each level. Moreover, selecting illumination device should also be considered because illumination light source also affects capturing effect. Traditional methods used bright and wavelength distributing range wide halogen lamps with the disadvantage of aging quickly. Nowadays choosing modern lights like LED because it's easy for lamp color to dimmer or become brighter and lamp lifetime is longer [5]. In addition to these, during welding spattering sparks, heavy smoke or strong arc light would affect the image acquisition system acquiring weld seam image and brightness. For instance, installing filters can avoid welding arc brightness and brightness reflected from the surrounding environment caused by spattering. Through designing light-shading filters, the light blocking function reduces the general reflectivity of lens materials which in turn significantly reduces the intensity of external ambient brightness [1]. Another typical approach is designing protective shields for welding vision devices or cameras and so forth avoiding welding electrode sparring brightness and physical damage (such as putting installable heat-resisting glass plates, heat-resistant metal plates or metal mesh front layer over lens), which protects internal cameras or lenses from scaring and keeps equipment lifespan [2]. In addition to protecting vision part, enhancing optical imaging performance. To illuminate weld edges well, need to ensure acquiring images through reasonable selection of positions and angles, installing lights or plates for reducing external surrounding brightness and increasing internal surrounding lights brightness so that image captured image could obtain a better visual effect, brightness and higher quality [1].

3.2 Weld Image Processing Methods

Weld image processing is the core step for achieving precise detection and localization, primarily comprising two stages: image preprocessing and feature extraction. During image preprocessing, denoising and enhancement are key techniques for improving image quality. Median filtering, as a nonlinear filtering method, effectively removes salt-and-pepper noise while preserving edge information, making it suitable for discrete noise points in welding images caused by spatter or sensor noise [5]. Gaussian filtering smooths images through convolution operations, reducing high-frequency noise interference, and is commonly used to process uniform noise distributions caused by arc light [10]. Additionally, histogram equalization and contrast enhancement techniques adjust the grayscale distribution of images, accentuating the contrast between the weld region and the background, thereby providing high-quality input data for subsequent feature extraction [10].

During the weld feature extraction phase, edge detection and contour recognition algorithms play a crucial role. The Sobel operator detects edges by calculating image gradients, offering simplicity and efficiency but exhibiting sensitivity to noise. The Canny operator combines multi-scale Gaussian filtering with non-maximum suppression, enabling accurate extraction of weld edge information in complex backgrounds and thus demonstrating excellent performance in weld feature marking [10]. Contour recognition algorithms extract geometric features of welds—such as width, height, and centerline position—by clustering pixels within closed regions. These characteristics are crucial for weld localization and quality assessment [4]. Experimental results demonstrate that integrating multiple feature extraction algorithms significantly enhances the accuracy and robustness of weld recognition [10].

3.3 Implementation of Weld Location Algorithms

Weld localization algorithm: It mainly includes the method of template matching and Hough transform as well as machine vision-based intelligent welding technology is the prerequisite to achieving smart detection. Template matching locates weld by comparing captured image with predefined weld image pixel by pixel, computing weld similarity degree, thus realizing weld location providing high-accuracy positioning for welds with simple geometric shapes [4]. Whereas, template matching is unfeasible for locating welds casted over curved surfaces or distorted welding components; thus, for such complex shape weld geometries, the Hough transformation can be adopted for weld location. It can be said the core of weld location lies in parameter space transformations of lines or curves from image space to weld parameter space to detect cumulative peaks of weld feature points thus calibrating weld positions precisely [10].

4 Machine Vision-Based Welding Quality Monitoring and Defect Detection

4.1 Real-Time Monitoring System Architecture for Welding Processes

Visual Monitoring and Welding Process Synchronization Mechanism. For intelligent welding, real-time vision synchronization is an essential part to ensure that data used in welding process monitoring should be accurate. Therefore, high frame rate industrial cameras must be used with a high precise synchronized data transmission technology such as IEEE 1588 (Precision Time Protocol, PTP), to synchronize and coordinate the data acquisition of visual data for the weld seam to the welding processes of the welding torch execution under the same speed [2]. Also coordinating control on the operation status of the whole welding system to the imaging acquisition operation of the vision system by hard trigger signals can also resolve problems such as observation errors caused by delay problems. For example, on arc-welding-seam-tracking systems, vision sensors real-time gathering images of weld seams and feedbacking to the welding robot controller processed position information extracted from the image so that adjustments to the welding torch posture and movement path during the welding progress can be done to guarantee accurate welding [7]. This loop ensures the highest quality for welding, and provides flexibility and adaption abilities against complex and variable weld conditions.

Real-Time Acquisition and Analysis Logic for Key Parameters. Real-time monitoring and recognizing of welding process key factors, such as welding current, welding voltage and molten pool morphology can better judge weld quality. For welding current and welding voltage parameters monitoring, high-precision sensors usually are employed to convert the signals to digital signals and sending them through data buses into data acquisition cards, then using analysis algorithms on the data acquisition cards to extract feature values. Such as spectrum analysis can monitor whether current is abnormal by waveforms of welding current, like the abnormal movement of the arc of welding or the current circuit interruption [1]. To monitor molten pool morphology in welding, image collection and processing technology of vision system is based. By the method of scanning with a structure laser or a laser ranging technology can get 3D topography information of molten pool. After that the geometric characters of molten pool including width, depth, symmetry are extracting by computerized vision algorithms [13]. Feature parameters reflect the dynamic process of welding process which also offer the clue for defect recognition later. Comprehensively analyzing these features can establish welding process quality evaluation model and achieve welding real time monitoring and optimization.

4.2 Types of Welding Defects and Visual Characteristics

Image Manifestations of Common Welding Defects. Porosity, cracks and lack of fusion defect can occur during the welding process, which have a great impact on weld quality. Porosity mainly presents as small round cavities on the weld surface or in the

weld, whose diameter and spacing can be calculated by image feature calculation [2]. Cracks appear in linear shapes in weld images, or irregular shapes with clear gray variations along their edges, which can be extracted by edge detection algorithm such as Canny operator [10]. Lack of fusion defect is presented as defects where the weld completely fuses with the base plate, which features locally brightness reduction and textures on weld image. Spatter and weld slag spatter defect occurring on welds can also negatively affect weld quality, whose morphological structure is able to be detected through the morphological processing algorithm [5]. The visual features from weld defects should assist us to conduct research and design in the defect recognition algorithm in accordance with defect patterns characteristics.

Defect Feature Extraction Methods. The Visual feature extraction for welding defects uses the methods of based on gray-scale, shape and texture features. Among the three, Visual features can be used to extract the following characteristics and distinguish the various defects. For the image in grayscale value, using image statistical properties such as the average gray level value, standard deviation and contrast of the defect image, it is determined that they can distinguish between various types of defects. For example, the low gray level value and uniform in the area of porosity region are different from those in the crack region where the gray level value are inconsistent [10]. Based on shape visual features to extract the area, perimeter, aspect ratio and other characteristics to judge whether they are pores or cracks. The algorithm of Texture Features, such as Gray-Level Co-occurrence Matrix (GLCM) and Local Binary Pattern (LBP), describe the roughness and direction characteristic in texture of defect area. It can effectively improve accuracy of recognition of defects [5]. In this article, we use the above method to combine all features extracted together as a character set of the defect, which can provide necessary basis for classification and identification.

4.3 Research on Defect Recognition Algorithms

Machine Learning-Based Defect Classification Models. Support vector machines SVM and neural networks method are widely used in weld defects identification because of its ability to identify defects. SVM can train a model that can effectively classify the sample space with a high-dimensional information, which is a powerful identification method in machine learning. For example, porosity and cracks can be classified using SVM by analyzing and learning feature information of some labeled samples on the boundary information between two types of porosity and cracks. It is easy for it to obtain good classification performance on test samples [5]. Neural network has good generalization ability to learn various kinds of information automatically and can deal with image data conveniently. The Convolutional neural networks can extract local rich defect information in the original images after several layers of convolution filtering or pooling operations. Or directly extract complex global structure through network construction. Thus, neural network provides a more convenient way for more powerful information expression, which significantly enhances weld defect recognition [10]. In addition, deep learning model has better performance. Based on transfer learning technique and network feature structure such as pre-trained model with CNN, it provides quick convergence and more precise recognition effect quickly. Deep

learning also improves identifying effect with the help of the solution for algorithm robust problems effectively. Application of machine learning methods facilitates identification technology of weld defects by an intelligent way.

Algorithm Performance Evaluation. It can test the effect of defect detection algorithm, such as accuracy, recall rate, F1 value and so on. Accurate meaning sample result identified or computed by the algorithm degree correct, Recall refers to the algorithm has found the true positives degree. In experiment about CNN recognitions weld defects: in observation from statistical results welding detection testing sets, one specific algorithm gains with 95.3% accuracy and with 92.7% recall, obtaining an excellent recognition performance [1]. While draw a curve that is receiving operation characteristic (ROC), gain by the amount accompanying with the area beneath the curve (AUC) calculating by using one algorithm, it also could reflect a comprehensive analysis to algorithm's performance situations when varying threshold at different occasions [7]. The experiments indicate that the welding surface's defects' detection algorithm based upon machine learning will do good under some situations concerning welds; and also see that they were needing better on some certain aspects, such as anti-interference ability, operate velocity, etc., fulfilling demands of practice.

5 Challenges and Outlook

5.1 Technical Advantages and Limitations

Compared with ordinary welding methods, machine vision-based intelligent welding technology has many advantages in improving the quality and efficiency of welding. First, non-contact detection of the machine vision system allows it to monitor the position of the weld in real time and overcome the shortcomings of arbitrary manual welding inspection and inefficient low-efficiency traditional methods [11]. Second, by using image processing algorithm and pattern recognition algorithm, it can help identify the weld features on complex workpieces quickly and accurately, generate welding path planning instructions, significantly improve the consistency and accuracy of the welding process [1]; Furthermore, by collecting and analyzing the welding parameters in real time, intelligent welding systems can dynamically adjust the welding parameters and optimize the formation quality of the weld beads and reduce the production of defects. Although there are so many advantages, this algorithm still has problems in actual applications. For example, arc light interference, spatter block, high temperature caused during welding may destroy the stability and accuracy of visual inspection system and reduce inspection accuracy [1]. In addition, existing visual inspection algorithms can still not solve the problems of variable welding conditions and complicated workpiece structures and need to be optimized to increase the robustness of visual inspection algorithm in dynamic welding environment [11]. How to enhance system anti-interference ability and adaptability becomes difficult point.

5.2 Future Research Directions

To further promote the intelligent welding technology using machine vision, we should also pay more attention to strengthening some key researches, such as (1) develop more efficient visual inspection algorithms for weld quality or improve visual inspecting techniques; (2) strengthen the adaptability and robustness in extraction of features of welds and identifying position and size of weld feature on-line during welding. For example, using deep learning algorithm methods for weld inspection through training neural network model with a lot of samples from database can extract weld feature accurately enough even in very complicated situation [11]. Or combine multiple kinds of technologies, such as integrating computer-based video image capturing detection technology with other technologies (like laser scanning technology, sonic test, etc.), by making multi-sensory perceptual systems that could be eliminating shortcomings alone or giving the combination information perception systems much higher capabilities [13]. Given that the high-temperature plasma radiation and arc light would influence the performance of camera lens during arc spot welding, some other new-type filters or protections devices can also be explored that removing disturbance caused by some complicated situations can guarantee an efficient working mode of visual inspection system; (3) promoting technical integration of computer-based technology with weld production process, especially the combination with the upcoming smart manufacturing technology and Industrial Internet. In order to achieve effective, advanced monitoring and management at higher grade, leveraging collected data from smart sensors and so on via putting data together into cloud platform that allows more effective, powerful and intelligent management of whole production manufacturing procedure will give more supports for realizing highly-developed automation and intelligence level via mining, storing, exchanging and analyzing [11]. As abovementioned study directions and contents, these future attempts can enable us overcoming limitations faced by existing problems and make more sophisticated progresses of intelligent welding technology.

6 Conclusion

This paper presents the modern mechanical welding by introducing and comparing welding technology of traditional welding technology with today's, machine vision takes for example the principles and visuals in processing machines to describe vision welding, analyze application of intelligent welding technology in weld seam detection and positioning, monitoring welding quality and weld defects identification. The study finds that in weld seam detection and positioning, through integrating intelligent welding system design and building an efficient image acquisition system, adding more efficient image processing algorithms, can detect and locate weld seams. For instance, adopt combinatorial template matching algorithm and Hough transform algorithm to effectively detect the weld features; Positioning experiments on weld seams are conducted, with accuracy of about one pixel. In application of welding process monitoring, it is required that establishes a real-time monitoring welding process system. Collect the related signal information as well as some real data from the video

camera sensors used in the visual imaging monitoring method by real-time welding process signals such as molten pool morphology, welding current and voltage to provide necessary support. In recognition of weld defects: use support vector machines, etc., in artificial intelligence classify typical defect characteristic extraction gas pores cracks and lack of fusion and realization of weld surface appearance defects aiming at detecting defect's goal by feature extraction and learning to classify weld defects, greatly enhance the accuracy and speed. The above welding research not only confirm the feasibility of applying machine vision in welding, but also give useful clues and guidance for practical applications. Progress machine vision technology in future progress to will weld huge value will be created.

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