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Computer vision aided inspection on falling prevention measures for steeplejacks in an aerial environment

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ABSTRACT

Falling from height accidents are a major cause of fatalities on construction sites. Despite a lot of research conducted on the enhancement of safety training and removal of hazardous areas, falling accidents remain a major threat for steeplejacks. According to NOISH FACE reports, 75.1% of the fall from height decedents didn't use the Personal Fall Arrest Systems (PFAS), which shows insufficient supervision of the use of Personal Protective Equipment (PPE) by steeplejacks. Few scholars consider PFAS an important measure to prevent falls and the existing studies on PPE inspections showed that they were unsuitable for the scenarios faced by steeplejacks. This paper proposes an automated inspection method to check PPEs' usage by steeplejacks who are ready for aerial work beside exterior walls. An aerial operation scenario understanding method is proposed, which makes the inspection a preventative control measure and highly robust to noise. A deep-learning based occlusion mitigation method for PPE checking is introduced. We tested the performance of our method under various conditions and the experimental results demonstrate the reliability and robustness of our method to inspect falling prevention measures for steeplejacks and can help facilitate safety supervision.

1. Introduction

Falls from height is one of the main causes of fatalities in the construction industry [1]. According to the data provided by the Bureau of Labor Statistics, out of 937 fatal construction accidents in the United States in 2015, 350 of them were caused by falls [2]. According to the HSE's (Health and Safety Executive) summary, in Great Britain, falls from height also remained the biggest cause of injury in the construction industry during 2016 [3,4]. Similarly, the National Institute for Occupational Safety and Health suggest that fall accidents account for around 40% of fatal accidents and 30% of accidents resulting in injuries in Japan, and 40% of fatal accidents and 17% of non-fatal injuries in Korea [5]. In addition, fall protection remains at the top of the safety violations lists of OSHA's (Occupational Safety and Health Administration) reports since 2016 [6], where inadequate fall protection is one of the major causes.

Most fatal falling from height accidents are in fact preventable [1]. Plenty of standards and regulations about prevention measures have been implemented in various countries and regions to ensure the safety of steeplejacks. The *Practical Guide to Working At Height*, published by the Hong Kong Housing Authority [7], points out that appropriate implementation of barriers, fences, guard-rails and working platforms, as well as Personal Fall Arrest Systems (PFAS), are necessary measures to prevent falls. The *Duty to Have Fall Protection* [8] and *Fall Protection Systems Criteria and Practices* [9] standards of the United States specify how to construct safe platforms under various working environments at height, as well as a detailed description of how to use personal protective equipment (PPE) for the work. In Great Britain, *The Work at Height Regulations* stipulate that 'every employer is required to carefully inspect the fall protection measures of the whole aerial workplace and steeplejacks shall select suitable PPE according to their trades' [10]. In summary, necessary inspections and appropriate use of PPE assists in the development of a safe working environment at height.

In view of the high frequency and severe consequence of falling from height accidents, a lot of research has focused on searching for every possible way to avoid such accidents from happening, e.g. by removal of hazardous areas, use of guardrail or safety net systems, administrative controls or fall portents detection. However, due to various unexpected situations, steeplejacks are inevitably faced with the risk of falling so the use of the PFAS is the protection measure most likely to save their lives. OSHA pointed out that PFAS are only required to be used in the working environment at height of 6 ft or more [11]. In fact, in NIOSH FACE reports [12], it was found that at the time of the fall, 54.2% of the fall decedents did not have access to PFAS; 23.1% of

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the PFAS status is present but not in use; and only 2.2% of the decedents fall from height of < 6 ft. In other words, a total of 75.1% of the fall decedents are required to use PFAS but fail to do so.

Meanwhile, in certain specific situations, especially when decorating exterior walls, workers are occasionally exposed to dangerous working platforms (e.g. edges without barriers, fences, guard-rails etc.). Therefore, a new automatic inspection method is urgently needed to protect steeplejacks by enhancing the supervision of PFAS use at height. However, two aspects challenge the application of the automatic inspection of a PFAS by computer vision methods. First, the usage of PFAS is conditional and is only used when workers are at a height of 6 ft or more [11]. The automatic supervision method is required to determine whether a worker is engaged in works at height before inspecting their usage of PPE. On the other hand, the supervision of the PFAS is not limited to harness wearing but also rope anchor checking and wearing hardhats [11,13].

The aim of this paper is to promote the use of the PFAS in working environments at height beside exterior walls, since falling accidents remain the leading cause for work fatalities in the construction industry in many countries, including the U.K. (44%) and the U.S. (35%) [14–16]. Supervision enhancement of the use of the PFAS in aerial work is one of the most effective ways to ensure the safety of steeplejacks. Few studies considered taking approaches to strengthen the inspection of the PPE use by steeplejacks and the existing studies on PPE monitoring are not yet applied to PFASs. Accordingly, this paper proposes a novel method, based on computer vision, to automatically inspect the appropriate usage of PFASs among steeplejacks before they enter an aerial working environment. The core of this paper lies in two parts as follows: First, considering the scope of usage of PPE, this paper proposes a method of scenario recognition for aerial working environments, which is used as the basis for judging whether PFASs are needed. Second, we have a trained deep learning model to identify multiple PPEs. And the inspection of PPEs includes not only harness checking but also webbing, anchoring and wearing hardhats. Our method can identify and distinguish multiple combinations of unsafe behavior.

2. Literature review

This study focuses on preventing accidents caused by falls from heights for steeplejacks through inspecting the appropriate use of PPEs. Thus, firstly, we reviewed solutions provided by related literature for the falls from height prevention in Section 2.1. Then, related research on PPEs' inspection is discussed in Section 2.2. In fact, few scholars considered the PFAS as an important measure to prevent fall accidents and the existing studies on PPEs' inspection did not meet the requirement of specific scenarios for steeplejacks. Therefore, an introduction to the development of computer vision based object detection methods, which were used in our solution, is followed in Section 2.3.

2.1. Related research of fall prevention

According to the provisions of OSHA [17] and the summary of Esmaeil, Hallowell, et al. [18], removal of hazardous areas, use of guardrails or safety net systems, administrative controls and PFAS, constitute the primary protection for steeplejacks.

Scholars have done a lot of research on how to prevent construction workers from falling at height. On the one hand, removal of hazardous areas by design optimization is a feasible solution. Qi, Issa, et al. [19] expand on the IFC hierarchy to conduct compliance checking and optimize building designs for safety, which provides an opportunity to prevent workers from falling. Zhang, Sulankivi, et al. [20] developed a BIM based prototype with safety rule checking algorithms which can identify and eliminate potential fall hazards in the planning phase. Wang, Pradhananga, et al. [21] proposed a laser scanning method to identify fall risks by analyzing geometrical properties during the construction phase. On the other hand, some of the scholars have committed to the appropriate use of guardrail or safety net systems to protect workers. Navon and Kolton attached sensors to guardrails to inspect their installation, and warnings will be issued whenever guardrails are missing or different from the planned ones [22,23]. Zuluaga and Albert [24] use virtual prototyping methods to check bridge guardrails' usage. Cheung and Chan [25] directly invented a Rapid Demountable Platform (RDP) device, which can be flexibly applied to prevent external workers from falling from height. Furthermore, administrative controls are another method to help reduce falling accidents by improving workers' safety awareness. Kaskutas, Dale, et al. [26] found that groups trained by a foreman and apprentice in fall prevention, greatly improved the safety awareness and working environment of workers. Lin, Migliaccio, et al. [27] used a 3D training platform to promote the knowledge of canonical working procedures of falling protection. Evanoff, Dale, et al. [28] focus on improving the workers' participation in training, such as hands-on practice, simulations and reality-based training. These improved training methods aimed at enhancing the safety behavior of workers when working at height. In addition, many researchers recognized workers' postures and movement patterns by making them wear devices and then analyzing the fall portents, thus reducing fall accidents [29–33].

Despite PFAS being one of the most important measures in preventing fall accidents, few scholars work on the appropriate usage checking of PFAS for the steeplejacks.

2.2. Related research on PPEs inspection

Despite few scholars focusing on the inspection of PFAS usage for steeplejacks, a lot of research proceeds in other PPEs' inspection for workers on construction sites. Here, PPEs refer to garments or equipment designed to protect the workers from being injured, mainly including fall arrest systems, protective clothing, helmets, goggles and so on [34]. The state-of-the-art studies for PPEs' inspections are introduced below.

Sensor based methods are widely used in PPEs' inspections due to their portability and flexibility. Barro-Torres, Fernández-Caramés, et al. [35] attached RFID tags to all PPEs and a RFID reader was given to every worker at the same time. This way, the readers attached to the workers could detect the presence of PPE that was worn by the workers. Kelm, Laußat, et al. [36] used automated identification (ID) and information technologies (IT) to design a RFID portal that was positioned at the entrance of the construction site to check PPE compliance of personnel. If a RFID portal is placed beside the window, we can check the presence of PFAS when a steeplejack is going out through the window. However, whether the harness is worn by the steeplejack and the hook has been anchored or not, can hardly be distinguished. Podgórski, Majchrzycka, et al. [37] use the Internet of Things (IoT) technologies to create smart working environments in which not only PPEs' information, but also hazardous and strenuous factors, such as noise, exposure to toxic chemical substances, optical radiation and high or low temperatures are monitored. Dong, He, et al. [38] combine pressure sensing and Bluetooth to assess how the hardhats are worn. The sensor-based methods listed above are limited by their intrusive nature, which is highly dependent on workers' active cooperation. Moreover, it's hard to confirm the proper use of PPEs.

Besides sensor-based methods, the application of computer vision techniques in PPE monitoring is becoming more and more popular. Some scholars use vision based methods to determine whether workers are wearing hardhats or not. Du, Shehata, et al. [39] determine whether the PPEs have been worn by comparing the color features of the target area on workers with the predefined template of the PPEs. Shrestha, Shrestha, et al. [40] improved the above method by adding more feature information besides color to improve the recognition accuracy of PPEs. These handcrafted features defined by researchers are based on an assumption that the template features are the same as the practical objects, which is often unrealistic. Park, Elsafty, et al. [41] proposed a