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Real-time simulation of construction workers using combined human body and hand tracking for robotic construction worker system

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ABSTRACT

Construction is an inherently less safe sector than other sectors because it exposes workers to harsh and dangerous working environments. The nature of the construction industry results in a comparatively high incidence of serious injuries and death caused by falls from a height, musculoskeletal disorders and being struck by objects. This paper presents a new concept that can tackle this problem in the future. The central hypothesis of this study is that it is possible to eliminate injuries if we move the human construction worker off-site and remotely link his/her motions to a Robotic Construction Worker (RCW) on-site. As a first steppingstone towards this ultimate goal, two systems essential for the RCW were developed in this study. First, a novel system that combines 3D body and hand position tracking was developed to capture the movements of human construction worker. This combination of tracking enables the capture of changes in the orientations and articulations of the entire human body. Second, a real-time simulation system that connects a human construction worker off-site to a virtual RCW was developed to demonstrate the proposed concept in a variety of construction scenarios. The simulation results demonstrate the future viability of the RCW concept and indicate the promise of this system for eliminating the health and safety risks faced by human construction workers.

1. Introduction

The construction industry is one of the largest industries in both developed and developing countries. Employing two million people in the UK, it is the country's biggest employing industry. Unfortunately, it is also well known that construction is an inherently less safe sector than other sectors because it exposes workers to harsh and dangerous working environments. This nature of the construction industry results in a comparatively high incidence of serious injuries and death. This safety handicap is also one of key reasons behind the lack of construction workforce. According to the Health and Safety Executive (HSE) UK [1], deaths and serious injuries amongst construction workers are unacceptably high and more frequent than in any other sectors of the UK economy. In 2014–15 [2], 35 construction workers were fatally injured and a further 65,000 suffered a major injury at work in the UK, and the fatal injury and work-related illnesses rates are over 3.5 times and 20% than the average rate across all industries. One immediate impact of this high rate of work place injury and illness is cost to business. The total economic cost of workplace injury and ill health in the construction sector in 2013–14 was reported as £0.9 billion [2]. In a similar manner to the UK construction industry, more than 26,000 U.S. construction workers have died at work over the past two decades [3]. As these statistics indicate, safety in construction remains a major problem which needs to be fundamentally resolved.

The causes of the safety problems of construction workers arising from construction activities are varied. For non-fatal injuries occurred in the UK in 2015 [2], about 80% were due to falls from a height, trip falls, lifting/handling or being struck by an object. For fatal injury cases, falls from a height accounted for nearly 50% of cases. Considering workplace illnesses, about 65% of cases were due to musculoskeletal disorders (MSDs). To act on this issue, the Health and Safety at Work etc. Act 1974 [4] imposed a duty on employers to ensure the safety of workers. The HSE in the UK also has strict safety criteria and use the deterrent effect of prosecution to enforce the criteria, primarily focusing on aiding all sectors to improve compliance with the law through inspections and investigating accidents and complaints. In addition, activities such as awareness days, issuing guidance, and providing advice ensure that the regulatory measure encourages the industry to focus on long-term health and safety. However, this action by law leads to a significant expense (the HSE spent $111 million in 2002–03) and the effectiveness of this approach is unclear due to a difficulty in assessing the improvement.

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Alongside the regulative efforts, there are other approaches aiming to increase the safety of construction workers. Technological advances in areas such as personal protective equipment (PPE), Building Information Modeling (BIM) and safety training have improved worker safety. For example, the protective gear worn by construction workers including helmets, steel-toed boots etc., helps reduce the impact of falls, trips and being struck by objects on the body [5] even though the PPE increases worker discomfort and is ineffective against MSDs. Some recent studies show the potential that BIM can enable the automatic identification of construction safety issues [6–8]. In addition, as a means of safety training, involvement of the workers in the decision-making processes of evaluating workplace risks also helps identify and manage risks effectively since the workforce has direct experience of site conditions and they are most aware of potential hazards [9]. For this approach, the awareness and willingness of the workers and the managers should be required to address the risks in construction site.

Although the aforementioned regulative and technological efforts have positive impact on construction workers's safety, it is reported that the improvement rate has plateaued in recent years according to [10], indicating the pressing need to tackle the problem. This paper presents a robotics-based novel approach to not only minimize the health and safety hazards of human construction workers at construction but also increase the productivity in construction. The concept of 'Robotic Construction Worker' (RCW) which moves the human construction worker off-site and remotely links their motions to a RCW on-site is proposed. This approach aims to not only minimize the risk of MSDs and the risks associated with humans being present in a hazardous environment but also increase productivity. Two essential systems for the RCW were developed in this study as a first steppingstone towards this ultimate goal, which are (1) combined body and hand tracking system for the efficient and natural control of the humanoid robot and (2) simulation environment system to test and demonstrate the RCW system. First, a novel framework of combining vision-based hand tracking with body tracking was developed. This framework is integral for the RCW system in order to control both the hand and body of the robot naturally and simultaneously in a real-time and to implement detailed construction tasks which often require hand-based elaborate skill and cannot be achieved without accurate hand tracking of a construction worker. In this study, this framework was realised with coordinate mapping and development of a software pipeline to enable the tracking systems to run independently and simultaneously. Second, a simulation game engine was used to develop virtual construction sites and test the proposed RCW system. It is assumed in this study that a realistic and real-time simulation is vital to enable training, testing, planning and model-based control of the robotics. The rationale and details of the two systems are described in Sections 3 and 4.

The paper is organized as follows. In Section 2, a review of the state of research aiming to address the current problem of construction workers safety is presented. Section 3 describes the long-term solution of the RCW and the framework proposed in this study, followed by the research methodology and the derived results in Section 4. Finally, Section 5 summarizes this study with future research directions.

2. Related work

Research efforts in improving construction worker safety have mainly lied in three areas: (1) wearable sensing techniques, (2) computer vision techniques and (3) robotic techniques.

2.1. Wearable sensing techniques

The use of on-body wearable sensors is widespread in several academic and industrial domains. Accelerometers and IMUs are one of the most popularly used sensors used to track the motions of construction workers. Such sensors can measure velocity, acceleration, orientation, and gravitational forces, and the acceleration data can be used to monitor the physiological condition of a human body [11]. Fang and Dzeng [12] developed an accelerometer-based fall portent detection system that used a hierarchical threshold-based algorithm. Bakhshi et al. [13] proposed an approach for measuring and monitoring human body joint angles using inertial measurement unit (IMU) sensors. Jebelli et al. [14] proposed to use IMU sensors attached to the ankle to characterise the fall risk of workers. Valero et al. [15] also presented a wearable system that can measure the postures and body motions of workers using scalable IMUs with a low level of intrusiveness and real-time processing. Cheng et al. [16] proposed an approach for monitoring safe and unsafe behaviour of construction workers using data fusion of Ultra wideband and electrocardiography sensors. In addition, researchers have also successfully employed motion sensors to evaluate heart rate, respiratory rate and energy expenditure [17–18]. However, there is a limitation in the wearable sensing techniques that attaching accelerometers and IMUs to the human operator can affect negatively the accuracy of measuring the targeted signals since sensing accuracy is heavily dependent on whether the sensors are attached correctly in the correct positions.

2.2. Computer vision techniques

Recently, computer vision has gain attention because it can be used for automated and continuous monitoring of construction workers at construction sites. Seo et al. [19] identified that continuous monitoring of conditions and actions at the construction site is essential to eliminate potential hazards in a timely manner. Computer vision techniques enable an automated means of monitoring the site to overcome the current limitations of slow and unreliable manual inspection by safety managers. These techniques involving object recognition and object tracking can reduce the risks of being struck by an object or vehicle and of falling from heights. However, there are very challenging issues to this approach, including occlusion and the identification of good camera positions, due to continuously changing environments and diverse machinery and objects on-site. Furthermore continuous monitoring may also impact privacy negatively and reduce the motivation of construction workers.

Monitoring the individual construction worker's actions might prevent unsafe actions that lead to work place accidents. Han et al. [20] investigated the use of Microsoft Kinect to collect prior models of unsafe actions and then identify similar actions in site videos. They address safety at heights by extracting 3D skeletal models using the Kinect from videos of workers climbing ladders and evaluating their behaviour. The main drawback of this approach is that it is very difficult to form representative priors of unsafe actions due to the large motion ranges of human movement and the varied nature of construction site activities.

Ray et al. [21] focused on real-time construction worker posture analysis to improve ergonomics. Such techniques employ training and monitoring to reduce the risk of MSDs. They utilized the Microsoft Kinect to extract the worker's pose (body joint angles and spatial locations). Then, using a set of rules formulated using body posture information, the worker's activities were classified into two classes; ergonomic or non-ergonomic. The automated method can reduce the risk of MSDs and address other key issues such as risks involved in lifting/moving objects. The shortcomings of this approach are that they do not account for the factors of time, repetition, and forceful exertion. A particular pose can be safe for short periods of time, or with minimal force whereas the same pose can be unsafe with larger forces or with repetition.

Another limitation in existing computer vision techniques for tracking the motion of a construction worker is that accurate tracking of the worker's hands has not been settled yet. According to [22], factors such as the high dimensionality of the hand pose and the chromatically uniform appearance of the hand and self-occlusions during hand movements make tracking the hand a challenge. Specifically, tracking of the human hand using RGB-D data is a difficult problem due to the