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Assessment of operator's situation awareness for smart operation of mobile cranes

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ABSTRACT

Equipment operators play an integral role in the safe and efficient operation of heavy equipment. They observe the environment, understand the situation, and make decisions and actions accordingly. Compared with other types of equipment, operating a crane is more sophisticated and mentally demanding, and thus crane operators are more vulnerable to human errors. Therefore, special considerations to mitigate operator errors should be taken when designing an operator-assistance system for construction cranes. With the goal of improving the operators' situation awareness (SA) of safety risks, this research presents a novel framework and practical system architecture for an operator-assistance system by leveraging real-time motion sensing and 3D modeling of dynamic workspaces. An approach for evaluating operators' SA was proposed to validate the effectiveness of the assistance system in actual lifting operations. Results in a series of field tests indicated that the prototype system improved the operators' SA which resulted in an improved lift performance.

1. Introduction

Cranes play an integral role in construction projects, responsible for lifting various construction resources such as materials, equipment, and sometimes personnel [1]. Crane lifting operations are unique among other heavy equipment as they demand huge workspaces and have a significant impact on the safety and efficiency of the entire construction projects. As such, the consequences of crane accidents are catastrophic as they very often result in a significant cost overrun, schedule delay, and serious injuries and fatalities. Based on statistics from the U.S. Bureau of Labor Statistics (BLS) from 1997 to 2015, the number of fatalities in crane-related accidents totaled 1259 for all industry sectors [2] (Fig. 1). The U.S. construction industry was responsible for 586 fatalities (47%), in which 55% involved mobile cranes (e.g., truck-mounted, crawler cranes). Another source reported that 78% of crane-related accidents in the construction industry from 1992 to 2006 were associated with mobile cranes [3]. Following multiple highly publicized crane accidents in 2008, the number of fatalities decreased significantly and remained low with the introduction of more stringent crane regulations from Occupational Safety and Health Administration (OSHA) in 2010 [4]. Despite the improvement, crane operations in the construction sector remain a major safety concern. Unlike other types of construction accidents, the victims in crane-related accidents are not necessarily limited to construction workers but also pedestrians walking-by as observed in many crane-related accidents [5].

Behind the poor crane safety records, crane experts consider operator errors a prevailing source of risks in crane lifting operations [6]. It was found that 43% of the crane accidents from 2004 to 2010 were due to the operator failure in their responsibilities [7]. Mechanical failures aside, 75% of crane overturn accidents are due to operator error [5]. A recent investigation on risk factors in crane-related near-misses and accidents reveals that inattention is the most prevalent type of risk that accounts for 19% of the incidents, and errors by operators and signalpersons total 24% of the 212 investigated incidents [8]. These numbers are not surprising as operating a crane is inherently a sophisticated job that requires the operators have extensive training and experience. Repetitive lift tasks and extended work hours make them vulnerable to distraction and fatigue. In addition to the errors of crane operators, lifting safety can also be jeopardized by poor coordination and communication with personnel such as riggers, signal persons, and ironworkers.

Besides mechanical and environmental factors, human factor plays a critical role in mitigating hazards associated with construction activities [9]. With the development of information technology, researchers

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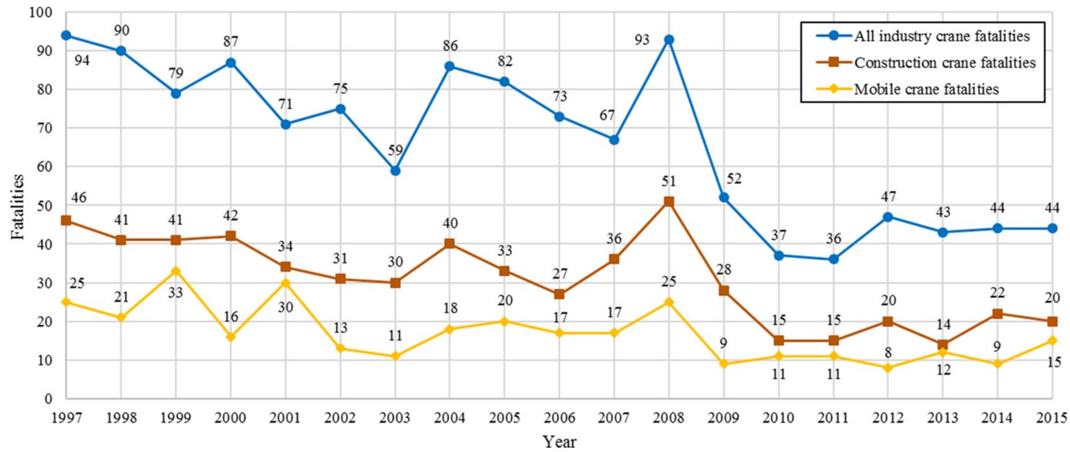

Fig. 1. Fatalities in mobile crane-related accidents from 1997 to 2015 [2].

realized that technology can provide another layer of protection in an attempt to improve safety performance [10]. Crane operations can benefit from technologies similar to the advanced driver assistance systems (ADASs) deployed on automobiles that provide real-time support to drivers based on surrounding situations [11]. With the goal of providing real-time assistance to crane operators, researchers in construction have explored the use of sensing, visualization, and simulation technologies. However, a holistic synthesis of existing technologies and a framework outlining further development is missing. In addition, previous efforts in evaluating a crane assistance system mainly focused on measuring accuracy, reliability, and ease of use of the introduced technologies [12] [13]. Very few emphasized on the system's effectiveness on helping the operators understand the situation and the safety risks [14]. This is partly because that the situation awareness (SA) of crane operators during lifting operations is difficult to define and measure in such complex and dynamic environment. This also leads to the fact that most of the techniques in previous research were only validated in a simulated environment instead of utilizing real lift tasks [15].

The rest of this paper is organized as follows. Section 2 presents a literature review on the state-of-the-art of operator assistance and the measurement of SA. Section 3 describes the proposed framework and system architecture, as well as an approach for SA assessment. Field tests and results are introduced in Section 4, followed by the discussion in Section 5 and conclusion in Section 6.

2. Literature review

2.1. Critical components in operator assistance for mobile cranes

The very first step in providing operator assistance is to accurately capture crane motions in real-time. The motions of a crane are essential to carry out a variety of spatial and temporal analyses for load capacity, crane stability, and collisions. Real-time location systems (RTLS) such as Radio-frequency Identification (RFID) have been utilized for tracking mobile assets (e.g., materials, equipment, workers) on construction sites [16]. For capturing crane motion, Ultra-wide Band (UWB), a more precise position tracking technology, were investigated and tested in controlled lab tests [12] and outdoor full-scale tests with real cranes [17]. Using computer vision techniques, the motions of a crane and other articulated equipment can be captured by tracking markers deployed on equipment parts [18] or mapping image to the 3D model of the crane [19]. Similarly, 3D geometry of a piece of equipment in the form of point cloud can be mapped to its 3D model to achieve equipment motion capture in 3D [20–23]. Similar to excavators [24], cranes can be considered as giant robots with multiple degrees of freedom in a rigid body or kinematic relationships. Therefore, the entire motion of a crane can be capture by measuring critical motions (e.g., swing, lifting, and extension of the boom, extend/retract hoist cable). These critical motions can be easily measured by inexpensive rotary encoders, laser distance finders [25], and inertia measurement units (IMUs) [26].

Given the spatial and temporal scale of crane lifting operations, crane workspace is subject to constant changes in its surrounding environment (e.g., presence of vehicles and workers, newly erected structures). Therefore, modeling the as-is condition and dynamics of crane workspace is of great importance to successful operator assistance. Building Information Models (BIM) can provide a general spatial context for the crane workspace [25], but fails to model the dynamics and changes in the surroundings. As-is conditions such as geometry and color of nearby objects can be capture by laser-scanned point cloud and updated by a hybrid visualization approach that takes advantages of the efficient data collection and computation from computer vision and comprehensive 3D geometric information contained in point cloud [27].

The interface presented to the operator by assistance system plays a pivotal role in operator assistance. A user interface provides visual feedback to augment the operator's understanding of lift tasks [25]. To this end, numerical feedback provided by traditional operator-assistance systems such as Load Limit Indicators (LMI) is limited. At the other end of the spectrum, vivid pictures from crane camera systems may lead to distraction and increased mental workload when the operator struggles with the depth perception and limited field of view [28]. The user interface (UI) needs to provide just-in-time alerts in multiple forms (e.g., visual, auditory, haptic) with the right amount of information that supports operator to make decisions to mitigate hazards [26].

Although an array of safety devices are available in the market, the effectiveness and utilization of these devices in the industry are unclear [14]. It is important to evaluate the effectiveness of these safety devices in actual lift tasks in order to identify potential challenges and suggest further improvement. Previous efforts predominantly focused on addressing technical limitations, while the impact of such systems on reducing the operator error and improving their SA remains unknown.

2.2. Operator error and situation awareness

From the perspective of cognitive psychology, a human error is considered a result of one or multiple failures in the human cognition process. This process can be described by the sequential stage model created by Furnham [29]. This model simulates the development of accidents as a sequential chain that consists of three cognition stages: hazard perception, hazard recognition, and decision/ability to avoid hazard (see Fig. 2). It is helpful to understand the causation of cognitive failures in the development of crane accidents by applying this model to