Predictive Assessment and Proactive Monitoring of Struck-By Safety Hazards in Construction Sites: An Information Space Approach

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ABSTRACT

Struck-by accidents are one of the major causes of fatalities in construction projects. The dynamic and complex nature of construction sites leads to layouts and motions that increase the vulnerability of workers and equipment to struck-by accidents. In this paper, we present our initial efforts towards a methodology based on *information spaces* for predictive assessment and proactive monitoring of struck-by safety hazards in construction sites. Our working hypothesis is that struck-by accidents occur due to undesirable *states* and *trajectories* in the *physical state space* that can be partially *predicted* and *monitored* in real time through efficient and robust algorithms. Our methodology includes multiple steps related to defining the physical state space and information spaces to compute filters for detecting hazardous states. In order to illustrate our methodology, we present three case studies of construction safety monitoring tasks related to: (1) worker-equipment collision avoidance, (2) falling/swinging load collision avoidance, and (3) distribution of workers in hazardous regions.

INTRODUCTION

Struck-by accidents are one of the four most deadly hazards found on construction jobsites. Approximately 75% of struck-by fatalities involve heavy equipment such as trucks or cranes (OSHA 2013). The complex, dynamic, and continuously changing nature of construction jobsites is one of the main drivers of struck-by hazards. Different research studies (e.g. Hinze et al. 2005) have evaluated the nature of struck-by accidents in construction jobsites and have proposed solution concepts (e.g. radio frequency proximity warning system proposed by Teizer et al. 2010) to prevent accidents. However, a crucial missing element is a methodology that enables: (1) predictive assessment of struck-by hazards based on an integrated evaluation of the construction site layout, dynamic behaviors of workers and equipment, and the sequence of construction activities, and (2) proactive monitoring of the dynamics of construction sites to identify hazardous configurations and take corrective actions to eliminate them. The objective of this paper is to propose a vision for such methodology. Our working hypothesis in creating the methodology is that struck-by accidents occur due to undesirable states and trajectories in the physical state space that can be partially predicted and monitored in real time through efficient and robust algorithms. According to this hypothesis, the undesirable states and trajectories in the physical state space can be modeled based on the information related to the construction site layout, dynamic behaviors of workers and equipment, and the sequence of construction activities and used in the planning phase to reduce the likelihood of hazards. In addition, the dynamics of the physical state space can be monitored using an information space, $\mathcal{I}$, for which filters can be computed to detect undesirable states.

BACKGROUND

Different studies have investigated struck-by safety accidents in construction jobsites. Hinze et al. (2005) investigated the root causes of struck-by safety accidents and suggested creation of methods that facilitate consideration of major equipment and materials involved in struck-by accidents. Two coupled phenomena affect the level of safety hazards related to struck-by accidents on construction jobsites: (1) sequence of activities and jobsite layout, and (2) movement patterns of workers and equipment. Two streams of research evaluate these phenomena for the analysis of safety accidents. In one stream of research, different studies (e.g., Ning and Lam 2013) have developed optimization-based methodologies for safety assessment of construction site layouts. These studies have two main limitations: (1) lack of consideration of the impact of the layout of construction jobsites on the spatio-temporal motion trajectories related to the workers and equipment, and (2) lack of consideration related to the dynamic changes in the layout of construction sites at different stages of project schedule. Another stream of research (e.g., Wu et al. (2013) and Pradhanaga and Teizer (2013)) has focused on automated monitoring of movement patterns of workers and equipment to identify hazardous situations and develop preventive strategies. The major limitation of these studies is the lack of understanding pertaining to the minimum information that needs to be sensed to solve the problem related to construction safety monitoring task.

In this paper, we propose a vision for a methodology based on *Information Spaces* (LaValle 2006 and LaValle 2009) to solve the problem related to safety analysis of struck-by accidents. We adopt a minimalist philosophy to understand information requirements to solve tasks involving moving bodies in the construction site. An example of this philosophy can be found in a system that tracks and counts moving bodies in the workspace (Bobadilla et al. 2011). Instead of attempting to estimate the full physical state of the system, a smaller information space is defined where the task can be solved (LaValle 2009). This methodology has led to the development of systems that implement exact algorithms and whose sensing, computation, and communication requirements are reduced. Our contributions are the following: 1) we create a mathematical model of the elements of a construction project that include a characterization of the workspace, bodies, and obstacles in a physical state space, 2) we present initial ideas to calculate unsafe states, configurations that can lead to accidents, and 3) we propose filtering algorithms that are able to detect unsafe configurations using inexpensive sensing, communication, and computation components. The illustration of the proposed methodology is shown in three case studies of construction safety monitoring tasks related to: (1) worker-equipment collision avoidance, (2) falling/swinging load collision avoidance, and (3) distribution of workers in hazardous regions. To the best of our knowledge, this is one of the first attempts to formalize the construction safety problems and present inexpensive solutions for real time monitoring of hazardous situations.

PROBLEM FORMULATION

Our formulation follows closely traditional *Motion Planning* (LaValle 2006 and Choset et al. 2006) definitions and recent work on *Information Spaces* (LaValle 2009).

1. Physical Configuration Space

Let $\mathcal{W}$ be the *world* or *workspace* which represents the space where the construction project takes place. The workspace can be either $\mathcal{W} \subset \mathbb{R}^2$ or $W \subset \mathbb{R}^3$. We will concentrate initially on the case of $\mathcal{W} \subset \mathbb{R}^2$. The workspace is populated by a set of *bodies* and *obstacles*. Let O represent a set of *obstacles* that are inaccessible regions. Let $\mathcal{B}$ represent the set of n moving entities in the construction site, this includes machinery, materials, and workers. Each body $B^i \in \mathcal{B}$ will have a configuration, $\mathcal{C}^i$, that includes, for example, position and orientation, $q_i = (x_i, y_i, \theta_i)$, where $(x_i, y_i) \in \mathcal{W}$ and $\theta \in [0,2\pi)$. Since all rotations defined by $\theta \pm 2\pi$ are equivalent, we denote S^1 the set of possible rotations in a circle. More complicated examples can be found in machinery such as cranes, excavators, and dozers.

We call X the physical state space of the construction system. The physical state space of the construction system includes the configurations of all the bodies but can also include other physical quantities such as velocities. Let $X = \mathcal{C}_1 \times \mathcal{C}_2 \times \ldots \times \mathcal{C}_n$ be the cartesian product of the individual configurations of each body. Each element, $x \in X$, represents a particular configuration of the set of bodies and can be denoted as $x = (q_1, q_2, \ldots, q_n)$. Let $T = [0, t_{final}]$ be a time interval and $\sigma: T \to X$ be a trajectory in the physical state space; this trajectory is a continuous sequence of configurations parameterized by time. Each construction activity represents a trajectory σ_i in the workspace. Let $D \subset X$ be a set of *undesirable* or accident prone configurations. Examples of these configurations include when equipment is close to a worker, when two pieces of equipment are close to each other, or when a worker or equipment is in the zone directly below a crane.

2. Three Construction Safety Problems

Based on the research hypothesis and the formulation in the previous section, we define the following problems:

1. *Safety evaluation of jobsite layout:* Given a set of construction trajectories, $\Sigma = \{\sigma_1, \sigma_2, \ldots, \sigma_m\}$, make sure that they do not visit D such that $\sigma_i(t) \cap D = \emptyset$ for all i and $t \in T$
2. *Identification of safest layout and construction plan*: Given a high-level construction plan, find the set of construction trajectories, Σ, that minimize the probability of visiting D.
3. *Real time monitoring of execution*: During the execution of a construction project trajectory, σ, ensure that D is not visited.

In this paper, we will propose a solution to problem 3, and will discuss problem 1 and 2 in the final section. One way to solve problem 3 is to precisely determine at each instant of time the physical configuration state of the construction site, $x \in X$. However, this will require huge modeling, computational, sensing, and communication burdens. A possible physical deployment would involve installing a 3D real-time positioning system that will report and alert whenever $x \in D$. This may prove costly, since the construction site is usually composed of dozens of bodies and the cost on implementation can be prohibitive for most of the construction projects. Instead of relying on an estimation of the physical state space, we use an information space approach to, starting from a safety monitoring task, to understand the information requirements necessary to effectively monitor the regions of D and to design *virtual sensors* that detect when $x \in D$ and allow a robust implementation.

3. Information Spaces

In this section, we present some definitions necessary to understand the methodology and case studies. We closely follow definitions and notations from (LaValle 2006 and LaValle 2009). The information about the status of the construction site will be collected through sensors and will lead to the development of a *safety plan*. More formally, let Y be the *observation space* of a sensor that represents the possible sensing outputs. Let U be the *action space* of the system, or space of possible actions of the system. Let $\mathcal{I}$ be the information space. As opposed to the *physical space*, X, the information space is a reduced representation of X that can be effectively monitored. Each element, $\eta \in \mathcal{I}$, is called an information state. Let ϕ be a *combinatorial filter* (LaValle 2009) expressed as $\phi: \mathcal{I} \times Y \to \mathcal{I}$ that updates the information state of the system based on the most recent observations, $y \in Y$. Let $\pi: \mathcal{I} \to U$ be a plan that specifies which actions to follow in each information state.

METHODOLOGY

Given a construction safety monitoring task related to the research hypothesis, our methodology consists of the following steps:

1. Define the workspace, $\mathcal{W}$, and the physical state space, X.
2. Define the dangerous configurations, $D \subset X$.
3. Find an observation space, Y, and a virtual sensor, $h: X \to Y$, to detect the dangerous configurations.
4. Define an information space, $\mathcal{I}$, that can be efficiently computed and that will capture the information requirements for the tasks.
5. Find a filter, ϕ, to update the information state based on the sensed information.
6. Define action spaces, U, that encapsulate the action components.
7. Create a plan, $\pi: \mathcal{I} \to U$, that will help prevent accidents.

We argue that the above procedure will lead to inexpensive, robust, and reliable implementation for predictive assessment and proactive monitoring of construction safety. We will illustrate this methodology with 3 cases and will present a proof of concept physical deployment for each of the cases.

STUDY CASES

In this section, we show how our methodology can be used to solve different safety tasks.

1. Collision avoidance between equipment and workers

For this case study, we have equipment that is moving in the construction site among obstacles as illustrated in Figure 1a. The construction site is also populated by workers. The workspace is $W \subset \mathbb{R}^2$ and there is a set of obstacles, O, that represent inaccesible regions for both workers and equipment. Let $E = W \setminus O$ be the free-space where workers and machinery can transit. The configuration space for a single piece of equipment is $\mathcal{C}_{equipment} = E \times S^1$ where E is its position and S^1 is its orientation. There are n workers moving in the site, where the configuration space for the i^{th} worker is $\mathcal{C}_{worker_i} = E$, which means that the worker can be in any part of the workspace that is not blocked. The physical state space for this particular monitoring task is $X = \mathcal{C}_{equipment} \times \mathcal{C}_{worker_1} \times \ldots \times \mathcal{C}_{worker_n}$. A particular configuration $x \in X$ describes the configuration of the construction site, where $x = (q_{equipment}, q_{worker_1}, \ldots, q_{worker_n})$. In this construction safety task, we would like to avoid a collision between a piece of moving equipment and workers. Let D define the configurations that are collision prone. For this purpose, we require that the workers stay at a safe distance r from the equipment. We can express this condition as $D = \{x \in X: d(q_{equipment}, q_{worker}) < r\}$ where $d(q, q')$ is the Euclidean distance (only $\mathbb{R}^2$ coordinates) between the equipment's position and the worker. In order to detect dangerous configurations, we use a *moving binary sensor* with a circular detection area, $V(q_{equipment})$, in the equipment which can detect the presence of a worker within a radius, r, as illustrated in the Figure 1a. For this virtual sensor, the observation space is $Y = \{0,1\}$ and the sensor mapping is given by:

$$h(q_{worker}) = \begin{cases} 1 & \text{if } q_{worker} \in V(q_{equipment}) \\ 0 & \text{otherwise} \end{cases}$$

For a safety plan, we choose $\mathcal{I} = Y$ and action space, $U = \{stop, continue\}$. Suppose that the equipment senses the presence of a worker inside its sensing region, $V(q_{equipment})$, this will require the equipment to halt to avoid an accident. We can express this plan, $\pi: \mathcal{I} \rightarrow U$, as follows:

I-state	Action
0	continue
1	stop

2. Distribution of workers in hazardous regions

In this example, we will try to monitor the counts of workers in hazardous regions on the construction site. This idea followed the concept presented in (Bobadilla et al. 2011). Similar to the previous case, we represent the workspace of the construction site as $W \subset \mathbb{R}^2$ with obstacles, O. $E = W \setminus O$ is the free space where workers can transit. The physical state space is $X = \mathcal{C}_{equipment} \times \mathcal{C}_{worker_1} \times \ldots \times \mathcal{C}_{worker_n}$. In the construction site we will place a set of *directional beams*, $\mathcal{B}$. These beams are line segments with both endpoints on the boundary of E. For example, in Figure 1b the beams are labeled $\mathcal{B} = \{a, b, c, d, e, f, g, h\}$.The set of obstacles and beams decomposed the environment, E, into a set of *regions*, R. These regions are places of interest in the construction site that correspond, for example, to areas close to excavated zones. As an illustration, the beams in Figure 1b divide E into five two-dimensional regions. Let $R = \{r_1, r_2, \ldots, r_5\}$. The n *workers* move along paths $\tilde{x}_i: [0, T] \rightarrow E$ where $[0, T]$ represents a time interval. The workers will cross the directional beams that will inform the direction of crossing. The sensor mapping is $h: X \rightarrow Y$ in which $Y = \mathcal{B} \times \{1, -1\}$ where each element in Y is the beam that is crossed and its direction of crossing. A simple graph, G, can be defined as follows: every vertex in G corresponds to a region in R and a directed edge is made from $r_1 \in R$ to $r_2 \in R$ if and only if an agent can cross a single beam to go from r_1 to r_2. The corresponding beam label, B, is placed on the edge. We also create an edge from $r_2 \in R$ to $r_1 \in R$ with the beam label, B^{-1}, for the opposite direction. Our information space in this case will be the count of workers in regions. Let $\mathcal{I}_{count}$ denote the set of possible arrangement of n agents in p regions and each $\eta \in \mathcal{I}_{count}$ can be expressed as a vector of counts $\eta = (c_1, .., c_p)$. A filter, ϕ, to update the information state is defined as follows: when observation, y, is obtained, we can obtain the source, r_s, and the destination region, r_t, the crossing. The worker count from the region of origin $c_s = c_s - 1$ is reduced by one and the count of the destination region is increased such that $c_t = c_t + 1$. This filter will keep the number of agent in regions based on received crossings. Different safety plans can be proposed based on this filter. For example, suppose that we want to alert a manager of the presence of more than 10 agents in an excavation region, r_e. Let $U = \{normal, alert\}$ and define $\pi: \mathcal{I}_{count} \to U$ as follows:

I-state	Action
$c_{r_e} > 10$	alert
otherwise	normal

3. Falling/swinging object collision avoidance

Falling objects from cranes are another source of struck-by accidents. Let E denote the free-space as defined in the previous two examples. We model the configuration of a static crane as follows: the position $(x_c, y_c) \in E$ is fixed, and θ_0 is the angle of rotation of the jib, θ_1 is the angle of elevation and d_{hook} is the distance from the tower of the crane to the tip of the hook, as illustrated in Figure 1c. The configuration space of the crane is given by $\mathcal{C}_{crane} = \mathbb{R} \times \mathbb{R} \times S^1 \times S^1 \times \mathbb{R}$. In this example, there is also n workers moving in the construction space and the physical state space is $X = \mathcal{C}_{crane} \times \mathcal{C}_{worker_1} \times \ldots \times \mathcal{C}_{worker_n}$.

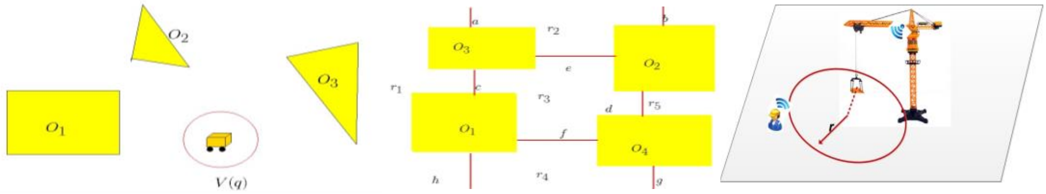
The dangerous configurations are when there are workers in the workspace right below the crane. We call $V(q_{crane}) \in E$ a circle of radius r that is located in the workspace and represents zones where the objects lifted by the crane can fall, this is illustrated in Figure 1c. The dangerous configurations in the physical space can be expressed as follows $D = \{x \in X: q_{worker_i} \in V(q_{crane}) \text{ for any } i\}$. The only issue to solve is how to obtain $C(q_{crane})$, this can be easily calculated by keeping track of the 5 variables of the configuration space of the crane, $q_{crane} = (x_c, y_c, \theta_0, \theta_1, d_{hook})$ and doing a simple geometric calculation. First (x_c, y_c) determine the center of coordinates and θ_0 provides the orientation of the arm of the crane, that ranges from $[0,2\pi)$ and θ_1 represents the angle of inclination of the arm that ranges from $[0, \frac{\pi}{2}]$. The projection of the center of the hook of the crane in the workspace can be simply calculated as $((x_c + d_{hook}) \cdot \cos\theta_0 \sin\theta_1, (y_c + d_{hook}) \cdot \sin\theta_0 \sin\theta_1) \in E$ and $V(q_{crane})$ is the circle with radius r centered at that point. Using the previous calculations, we can create a virtual sensor to detect the dangerous zone below the jib of the crane. Let $Y = \{0,1\}$ be the observation space where 0 represents a normal configuration and 1 represents the dangerous zone. The sensor mapping is defined as follows:

$$h(q_{worker}) = \begin{cases} 1 & \text{if } q_{worker} \in V(q_{crane}) \\ 0 & \text{otherwise} \end{cases}$$

The information space for this example is $\mathcal{I}_{crane} = Y$. We can define an action space to alert workers entering the dangerous area, let $U = \{normal, dangerous\}$, and let the plan $\pi\colon \mathcal{I}_{crane} \to U$ be defined as:

I-state	Action
0	continue
1	stop

This plan can be used to alert workers of their proximity to a dangerous zone.



(a) (b) (c)

Figure 1. Illustration of case related to monitoring of (a) dangerous zone surrounding moving equipment, (b) the distribution of workers in dangerous regions, and (c) dangerous zone under a swinging crane load

EXPERIMENTAL RESULTS

We created scaled prototypes of the three-study cases. For the first study case, we added an inexpensive Arduino 8-bit micro-controller (under US $25) to a scale excavator. For computational processing, we added an ultrasound distance sensor mounted on a continuous servo motor (under US $35) and a Zigbee chip for communication (under US $25). The motor rotating the distance sensor simulates the sensor described in the first study case and detected the presence of humans or equipment entering its proximity. This information was sent through the communication chip. This experiment is illustrated in Figure 2.

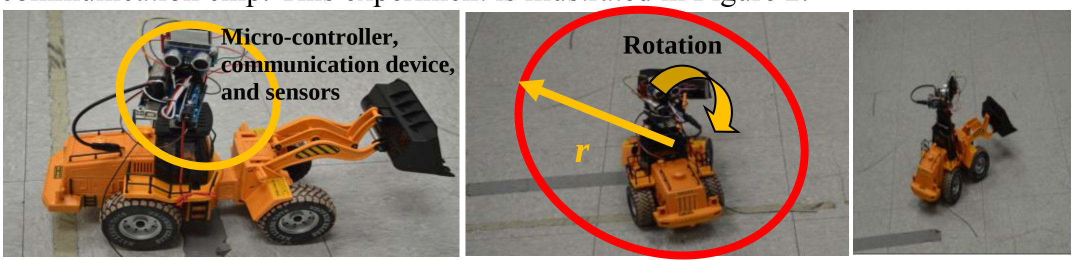


Figure 2. Snapshots of the experiment for dangerous zone detection

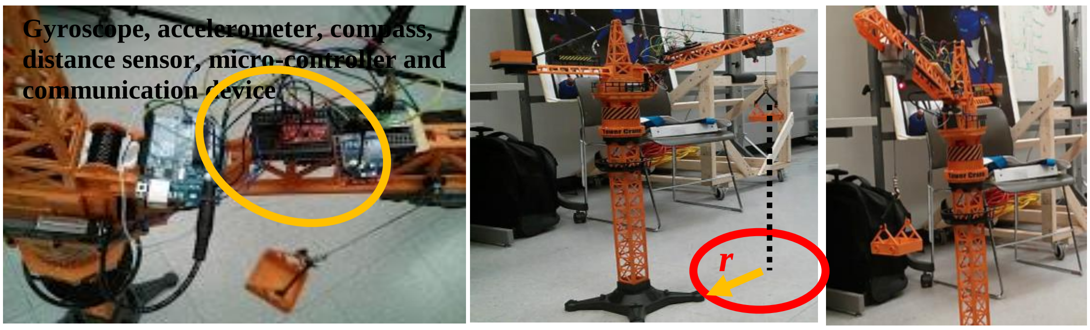


Figure 3. Dangerous zone under the load of swinging crane

In order to test the second study case, we made the following additions to a scale crane model: 1) An inexpensive Arduino micro-controller for computation, 2) a Zigbee communication chip for sending information wirelessly, 3) a compass (less than US $20) to measure the orientation of the crane's arm, 4) an accelerometer/gyroscope pair to obtain information about the inclination of the crane's arm (less than US $20), and 5) a distance sensor to obtain information about the position of the hook of the crane (less than US $15). This setup is illustrated in Figure 3. This information will allow us to calculate the dangerous zone below the crane and report it to managers and workers in real time. Figure 3 presents snapshots of the execution of an experiment. We implemented the directional beam described in the third study case as shown in Figure 5. Two directional sensors (under $15 US each) were connected to an Arduino micro-controller and a Zigbee communication chip. When an agent crosses a single distance sensor, the distance is reduced for a brief period of time. The direction of crossing of can be inferred from the order in which the distance sensors are crossed.

CONCLUSIONS AND FUTURE WORK

In this paper, we presented a methodology to model and pro-actively monitor accidents in construction sites based on studying physical states and information spaces. We presented a mathematical formulation, three case studies, and an initial implementation in scale models. The most immediate research direction is translating our prototype implementation and testing it in a construction site. Most of the hardware and software components of our deployments will not need major modifications: micro-controllers, communication devices, accelerometers, gyroscopes and compasses since they will all work in a construction site. Only the distance sensors (for equipment collision and worker distribution) need to be replaced to ensure a larger sensing range and outdoor capabilities. We define two additional problems in construction safety based on our formulation: evaluation of the *safety* of a jobsite layout and *identification* of the safest layout and construction plan. We are currently pursuing these directions by studying how to automatically translate the set of construction plans to trajectories in the physical state space. This will allow us to assess the risks of a construction project before its execution.

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