Cyber Agent to Support Workers' Decision Making for Mechanized Earthwork

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Abstract -

We have been and are doing development and research on construction AI system based on Actor-Critic framework. This paper discusses cyber agents who are computerized agents of mobile entities, which are composed of construction machines, vehicles and workers. Each of the cyber agents would carry with simple function to work together in the Actor-Critic cyberspace. The cyber agents will passively or actively walk through the cyberspace to help for workers to explore and capture critical factors latent in a large amount of information that might go into making decisions. The contents described in this paper might be almost a sublimation of the papers we have submitted to the ISARC for the past decade. This paper is organized as follows. First, this paper describes Actor-Critic framework for construction AI system. Secondly, this paper reports role of cyber agent. Thirdly, this paper explains inference mechanism of abduction reasoning and briefly shows example of inference. Finally, this paper presents further development and research on functions that the cyber agent should carry with in future.

Keywords -

Cyber agent; Humanware; Actor-Critic; Abductive reasoning; SRK model; Subsumption

1 Introduction

We have been and are doing development and research on construction AI system based on Actor-Critic framework (hereinafter called "construction AI") to support workers' decision making for earthworks. Cyber agents are computerized agents of mobile entities, which are composed of construction machines, vehicles and workers (i.e., operators, drivers, foreman, resident engineers, line-manager, and others). Each of the cyber agents would carry with simple function that work together in the actor-critic cyberspace. This cyberspace has three layers structure that consists of knowledge, rule and skill levels (SRK model), and the higher level subsumes lower level with downward commitment and the lower level provokes the higher level with upward activation. The Actor has policy structure to select and take actions, and further the state- or action-value functions to fire signal, sign and symbol. The Critic has functions of edit, calculation and analysis of readings captured by the PoC as explained later.

The cyber-agent will inhabit and passively or actively walk through the cyberspace to help for workers to explore and capture critical factors latent in a large amount of information that might go into making decisions.

The contents described in this paper might be almost a sublimation of the papers we have submitted to the ISARC for the past decade. This paper is organized as follows. First, this paper describes framework of the construction AI system. Secondly, this paper reports role of cyber agent. Thirdly, this paper explains inference mechanism of abduction reasoning and shows example of inference in brief. Finally, this paper reports further development and research on functions that the cyber agent should carry with in future.

2 Framework of Construction AI

Figure 1 shows schematic view of the construction AI system.

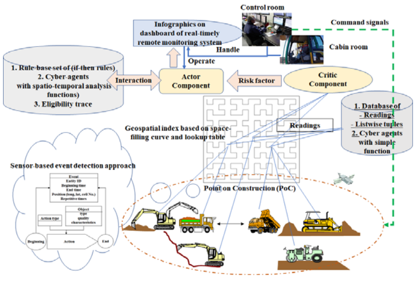

Figure 1. Schematic view of construction AI system

The construction AI system consists of the components as described below.

2.1 Points on Construction (PoC)

The PoC takes sensor-based event detection approach to track fleet of construction machines, vehicles and workers which are working together on site. The PoC automatically and real-timely gather a set of readings related to events occurred by the fleet activities [1],[2]. In other words, the PoC looks like a feeler of the cyber agents.

2.2 Geospatial Index based on Space-filling Curve

We use the Hilbert curve that folds one dimensional axis into a 2D space. The Hilbert curve here covers fully minimum bounding box covering working area. A serial number [1, max (number of vertices)] is assigned to each of vertices of the Hilbert curve. The position of the vertices of the Hilbert curve coordinates cell centres of the ground grid, for examples, the position index (i, j) of the corresponding vertex in a 2D array indicates the "i" th vertex in x and the "j" th one in y direction. The serial number might be almost equivalent to zip code in our daily life.

2.3 Database of Readings and Lookup Table of Tuples

Readings are captured by the PoC and then knowledge would be represented by lookup table of tuples. Each of the tuples is composed of code_id, cyber agent name, file name of the readings, proposition, condition, consequent, threshold, effects, belief, w_{ij} and action. The proposition is a parent of conditions and these are organised as a parent - child relationship on a semantic network. In many cases, the condition is expressed as potential cause of failure mode, and the consequent is expressed as potential failure mode in a production rule, which is presented as a disjunction literal and might be a hypothesis.

The threshold is a value above which the condition is true or might take place and below which it is not or might not.

The effect indicates potential effects of failure that forks into two categories "High" and "Hazardous." The former means "Will affect product performance, and some product will have to be scrapped, and rework possible," and the latter means "Will affect workers' safety."

The belief means a posterior probability that is an element of Bayesian Belief Network of the condition and the consequent.

The w_{ij} indicates weight in element [i-th row, j-th column] of Hebbian weight matrix, which represents strength of relationship among the conditions and the consequents or the consequents. The Hebbian weight is defined by the equation (1) [11].

$$w_{ij} = \log \frac{p(y_j, x_i)}{p(y_j) * p(x_i)} \tag{1}$$

In many situations, the consequents might be trouble phenomena happened on site, and otherwise potential failure modes from an action that the cyber agents at the actor component should take as described later.

2.4 Critic Component

Figure 2 shows relationship between the actor component and the critic component. Each of the cyber agents inhabit the critic component, and carries with simple function that could edit, calculate and analyse a set of the readings captured by the PoC. They could set threshold values at the 5% and 95%, or the 1st and the 2nd quantiles of empirical distribution function, and then do quantile processing to convert from the continuous variables to dichotomous ones.

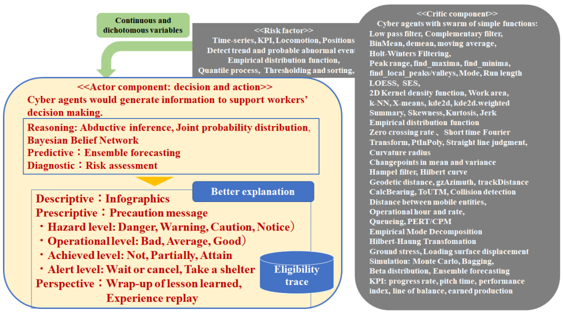

Figure 2. Relationship between actor and critic components

They would hand over their results of calculation and analysis to the cyber agents inhabit the actor component.

2.5 Actor Component

As is shown in Figure 2.4.1, the actor component functions decision and action based on the results received from the critic component. More loosely speaking, the actor component has three mechanisms as follows:

2.5.1 Production rule

Production rule associates a condition or a proposition (if) with the consequent, i.e., a phenomenon or an action (then). Besides, the rule states what cause is most likely to trigger what failure when the consequent might be true.

Strength of production rule indicates firing priority. The production rule is chosen based on the order of priority predefined by expert experience, or indicated by the calculated Hebbian weight “w_{ij}.”

Dichotomous variables received from the critic component would trigger that the cyber agents here would interact with rule-base, that is, listwise production rules and take predetermined action. Besides, each of the cyber agents would carry spatio-temporal analysis model, and functions to generate infographics. The spatio-temporal analysis model would be used to analyse dataset with spatial and temporal property and to visualize a region or points of interest.

2.5.2 Better explanation

The current situation is descriptively depicted by infographics with precaution message might prescriptively be informed as follows:

- Hazard level: Danger, Warning, Caution, Notice,
- Operational level: Bad, Average, Good,
- Achieved level: Not, Partially, Attain, and
- Alert level: Wait or cancel, Take a shelter.

2.5.3 Eligibility trace

The actor produces list-wise infographics with early precautionary messages, and forwards them to the dashboard. Moreover, the visiting of a state or the taking of an action, Hebbian weights are temporary recorded as an eligibility trace. The eligibility trace marks the token (i.e., signal, sign, symbol) associated with the event as eligible for undergoing learning changes. And then, wrap-up of lesson learned would be informed from different person perspectives.

Eligibility trace has two levels: which experiences to store, and which experiences to replay (and how to do so). Here, prioritized experience replay is used to remember and learn from more frequently past experiences [3].

2.6 Dashboard of Remotely Real-time Monitoring System

Figure 3 shows structure of remotely real-time monitoring system.

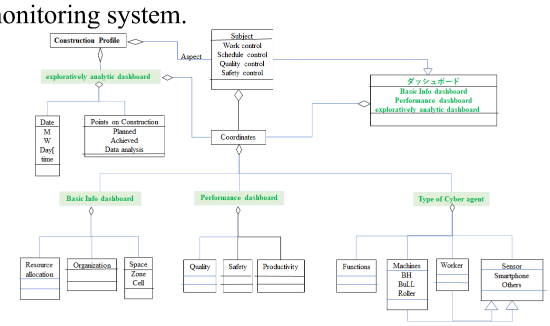

Figure 3. Structure of remotely real-time monitoring system

The dashboard is a visual display on screen of smart phone, PC or other device that are installed at the control or cabin room, and otherwise the operators carry. Information displayed on the dashboard is consolidated and arranged on a single screen so that infographics can be monitored at a glance [2].

2.7 Workers

The workers mean people who are actually working together on site, for examples, operators in cabin room or remote-control room, drivers, foreman, resident engineers, line manager, and others.

3 Role of Cyber Agent

Main role of cyber agents is to pick a set of building block of information at the right level of abstraction and at the right time, and then provide workers with infographics on real time basis. Each of cyber agents with simple functions forms a swarm of them, and interacts with each other. Figure 4 shows schematic view of the cyber agent.

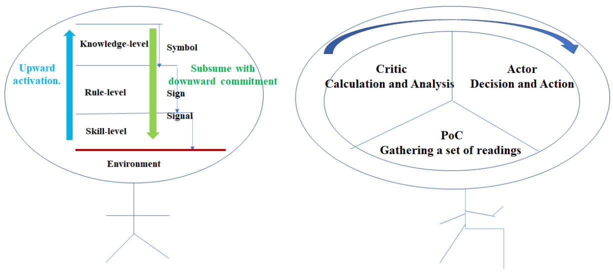

Figure 4. Schematic view of the cyber agent

The actor-critic space, that is, brain of the cyber agent, consists of hierarchy of skill-level. rule-level and knowledge-level （SRK model), and the higher level subsumes lower level with downward commitment and the lower level provokes the higher level with upward activation as shown left in Figure 3.1[4],[5]. At the skill level, signal might distribute from the 1st person point of view. The signal is directly grounded the perception-action coupling with environment. At the rule-level, sign might flow from the 2nd person point of view. The sign is grounded based on social convention, for example, crossing sign "red" means "stop." At the knowledge-level, symbol might propagate from the 3rd person point of view. The symbol has meanings that live in their mind, not in the item itself, for example, flags are symbols for nations. Each of the cyber agents would proceed along cycle of the PoC - the critic - the actor as shown right in Figure 3.1.

Supports for workers’ decision making from the 1st, 2nd and 3rd-person point of views are described below.

3.1 The 1st Person Point of View

In general, the 1st person point of view (POV) is used the term that depicts a method to control a radio-controlled machine or vehicle from the operator's or driver's view point. Discussions in this study shall narrow down the eye-hand coordination task regarding to operate construction machine and to drive vehicle from the operator's or driver's view point.

Handling joysticks to operate construction machines or steering wheel in vehicle, either remotely or directly, is an inherently eye-hand coordination task. The eye-hand coordination means to control eye movements with hand movements, and as processing visual representation of the situational views to handle joysticks or to steer control along with the use of proprioception of the hands, or vice versa. In either manned or unmanned operation, the operators' or drivers' performances limited by humanware in their behavioural frameworks, and continuous or intermittent mental workload burden on them. The humanware is defined a function composed of leadership, followership and the reciprocal interaction between the two [6],[7],[8].

Besides, a mechanized earthwork process is separated into several works that are sometime independently and at other time interactively performed by different workers. For examples, road construction includes a series of discretely repetitive operations such as excavating, loading, hauling, dumping, grading, compacting, etc., which are performed by different operators, drivers and other workers, who are belonging to different subcontractors. Consequently, it becomes difficult to gather field data concerning each operation, to grasp their own operations in progress on real time basis, and to understand the "Do's" and "Don'ts" in the whole earthwork process. Here, since workers might reduce their vigilance, they might take physical reactions to startling or unexpected events in the monitors or in front of vehicle, and might not secure the safe, reliable and effective earthwork process.

The cyber agents here would compensate for operator's realistic sensations to enhance spatial awareness by providing workers with physical cues as shown in Figure 5.

It would be significant to provide them with physical cues which would enhance their diagnostic and prognostic capabilities to reflect on their own unsafe behaviour. The information modelling here means a process involving acquisition of field data and feedback of relevant digital representations of physical and functional characteristics of works in progress.

The role of the information modelling is largely grouped in to the followings:

(1) To find signals of overturn, slither, or skid of mobile entity (i.e., machine or vehicle), and then issue alert message. Concretely, the x-, y-, and z-axis acceleration responses are captured and analysed to

- Find signals as to overturn and slither of the mobile entity, and
- Visualize phenomena of rolling, pitching, and vacillation of the mobile entity in order to prognosticate dangerous sections or spots in emergency, and
- Suggest work zone with the driving path to be repaired,

(2) To provide workers with infographics that play role in the following matters:

- Feedback of physical cues related to behaviour of mobile entity, and
- Spatio-temporal visualization of hazards latent in in-situ earthwork process.

(3) To provide oneself with the opportunities to reflect on their own bearings as facing their own works at hand,

(4) To take timely and quickly correct actions based on detailed visibility of appearances and motions of mobile entities in an earthwork process, and accordingly,

(5) To reduce likely mental stress burden on operator and driver in the remote-control or cabin room.

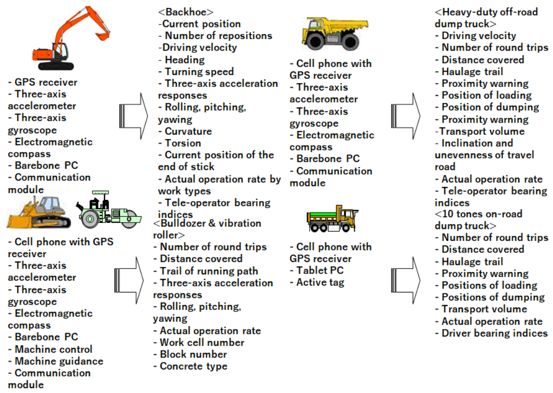

Figure 5. Enhancement of spatial awareness by providing workers with physical cues

3.2 The 2nd Person Point of View

Cyber agents might use push notification service for early precautionary or forced messages to the worker being targeted at, where the use of pronouns: you, your, yours, yourself, yourselves.

The early precautionary messages would hold, referring to ANSI Z535,5 definitions, the levels of early precaution are set as danger, warning, caution, and notice.

The forced message might include changes or stoppage in work order, or evacuation. The forced message could force you to take action in order to prevent undesirable behaviour or events.

3.3 The 3rd Person Point of View

Cyber agents here would pick a set of building block of information at the right level of abstraction, and produce construction profile at the right time. The construction profile is defined as a set of data to vision characteristics of phenomena being generated along with earthwork in progress and indexes to show their patterns [9],[10]. Figure 6 shows image of cross section and longitudinal analyses. It is expected here to take situational awareness into account in changes and to find any hotspot in spatiotemporal situations.

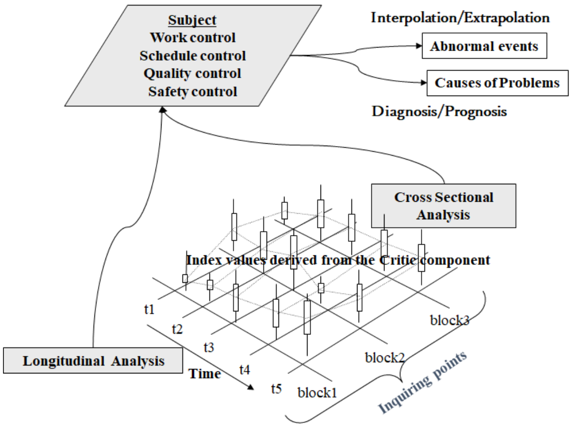

Figure 6. Image of cross section and longitudinal analyses

Based on the above information, the 3rd party people (i.e., resident engineers, line manager and others) would be able to find changes in the situation of work zone or points of interest and to evaluate force account work performed at cross section and toward longitudinal in earthwork progress from the following viewpoints:
- Viewpoint 1: Watch line balance. For example, search unbalance of productive capacity among construction resources;
- Viewpoint 2: Search abnormality in earth work progress. For example, find construction resources that have extra-high production capacity and one in the opposite side;
- Viewpoint 3: Watch state- or action-value of control. For example, find change in mean and variance or shift change in time series, and look at trend of increment or decrement;
- Viewpoint 4: Watch productivity. For example, look at planned versus actual productivity of a work package, and make a comparison between the two. The work package is a group of related tasks within an earthwork process; and
- Viewpoint 5: Look at construction speed based on the following step: first, set base line of earthwork progress; secondly, calculate progress rate in situ, and finally make a comparison between the two.

Infographics could be very helpful for the 3rd people to consider current situation of earthwork in progress from the above viewpoints. The infographics would be displayed on the dashboard of the remotely real-time monitoring system [2].

4 Abduction Reasoning

4.1 Inference Mechanism

The cyber-agent here is a virtual worker who inhabits the cyberspace composed of the actor component and the critic one. The cyber-agent will passively or actively walk through the cyberspace to help workers explore and capture critical factors latent in a large amount of information that might go into making decisions. The cyber agents would utilize abductive reasoning to form threshold value generated by quantile processing of experience probability function, Bayesian Belief Network, Hebbian weight, etc. presented in the tuple, and then inference backwards from consequent to antecedent. The inference is to affirm consequent and then conclude that the condition or the proposition is supposed to be true. In other words, this is inference from the observations to the best explanation, that is, the simplest and most likely conclusion. This inference, however, does not positively verify it.

Figure 7 shows abductive reasoning composition.

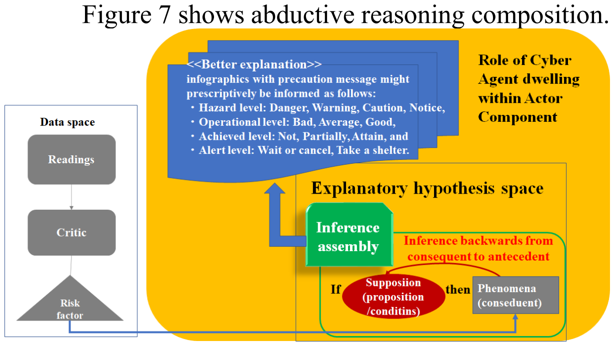

Figure 7. Abductive reasoning composition

4.2 Examples of Abductive Inference

This section shows examples of abductive inference related to dozer operation on highway construction site. First, this section presents a class of the cyber agent. Secondly, composition of tuple is explained. Thirdly, infographics are reported. Finally, Example of abductive inference is briefly shown.

4.2.1 Class of Cyber Agent

The cyber agent is set as a class (ex. R5 in R language). Example of class of dozer is shown below.

```
Bll <- setRefClass(
Class = “dozer ", #character string name for the class.
fields=list(#either a character vector of field names or
a named list of the fields.
maker_name = "character",
model_number = ”integer”,
operating_weight_kg = "numeric",
engine_power _rpm = "numeric",
speed_km/hr = "numeric",
overall_length_mm = "numeric",
```

```
overall_width_mm = "numeric",
overall_height_mm = "numeric",
shoe_width_mm = "numeric",
track_on_ground_mm = "numeric",
ground_contact_area_m2 = "numeric",
ground_pressure_kPa = "numeric",
ground_clearance_mm = "numeric",
),
#named list of function definitions that can be
invoked on objects from this class.
methods =list(
Initialize=function()
  )
)
```

Similarly, each of the required functions is set as a class. A part of the class of the required functions is listed below:

- gg.gauge #progress gauge,
- inflect #Finding local maxima and minima,
- geodetic.distance #distance on the surface of the earth between two points,
- trackDistance #Distance travelled,
- kde2d.weighted #kernel 2D density with weight,
- HampelFilter #median absolute deviation,
- loess (locally weighted scatter plot smooth),
- ses (single exponential smoothing),
- movingAverage,
- LongLatToUTM #Converting lat, long points to UTM meter unit,
- zcr (zero crossing rate),
- PtInPoly #extract points within polygon,
- Hilbert #HilbertCurve,
- force #3-axis acceleration composition value,
- real operational rate of machine by each work-in day,
- body attitude, and
- calculation of polygon area, and so forth.

4.2.2 Composition of Tuple in Lookup Table

As mentioned before, the tuple consists of i code_id, cyber agent name, file name of the readings, proposition, condition, consequent, threshold, effects, belief, w_{ij} and action. This section reports a part of proposition and production rules below.

(1) As for productivity and safety, a part of propositions is listed below.

1. Productivity:
- Reference of productivity per one hour,
- Driving forward or back distance of dozing operation,
- Real operational rate per a day,
- Dumping volume of material per a truck,
- Dozing area performed,
- Performance index (a ratio of the precedent rate to the successive one in each of work cells), Pitch time (time lapsed/production volumne),
- Abnormal observation, and so on.

3. Safety:
- Vehicle uphill/ downhill on a steep slope,
- Jump start; Sudden brake; Sharp turn; Excessive speed,
- Skidding, Overturn,
- Hazards latent in haulage road,
- Proximity Awareness, and so on.

(2) A part of production rules is listed below.

1. Impact and free-fall

Threshold values depends on quantile processing of empirical probability distribution.

If (95% <= the 3-axis acceleration composition value) then it is presumed that strong impact occurred at the longitude and the latitude, and

If (the 3-axis acceleration composition value < 5%) then it is presumed that free-fall occurred at the longitude and the latitude.

2. Dangerous proximity during operating machine when entering into the proximate area of 100 m range from other machine or dangerous spots like those.

3. Dangerous operation:

a) Sudden acceleration or rapid deceleration, when the jerk value of travelling speed gets larger than the predefined threshold value;

b) Turnover risk when finding trend for machine body to lean to crosswise or longitudinal direction and value of rolling or pitching more than 15 degrees; and

c) Defect productivity warning when finding

- Run length of key performance indicator changes in time series more than the threshold "7";

4. Other thresholds are set at the points 5% and 95%, or the 1st and the 3rd quantiles of experience distribution function;

4.2.3 Infographics

Readings in this example are captured by on-board smartphone for dozer. The sampling frequency was one HZ. The array element of the readings consists of [time, longitude, latitude, 3-axis acceleration, 3-axis angular velocity, direction, speed, FB]. The FB is a code that indicates forward, backward, or stopping

Figure 4.2.3.1 shows spatiotemporal trajectory of dozing and compacting In Figure 8, slate blue dashed line means "running trajectory on plane"; Brown dot indicates "spatio-temporal trajectory of running along with the axis of time." It is from Figure 8, we will be able to explore existential changes in spatial and thematic properties of travelling, dozing, and compacting, and also the time lapsed. This trajectory is plotted along with the vertical time axis and with locations on two-dimensional plane of longitude and latitude coordinates. Stopped and/or idling states of machine are dotted vertically along with the time axis. It can be seen from Figure 8 that the stopped and/or idling time is short during dozing and compacting operations. Total distance travelled here was 6030.622 m.

Besides, this infographic can be utilized for a fleet management of several machines, such as backhoes, crawler carriers, dozers, and vibration rollers, and so on. If dotted marks should be plotted at the same time and at the same position, the machine works related to the dotted marks are liable to be interfered with each other.

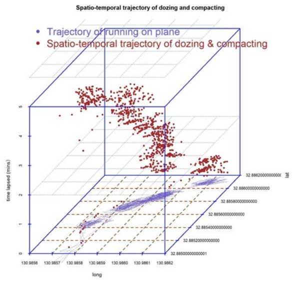

Figure 8. Spatiotemporal trajectory of dozing and compacting

Figure 9 shows index-based Hilbert curve to portray terrain of dozer operation. The Hilbert curve is drawn as following step:
Step 1: Set level=4, then the partition_number=2^leve-1=15; and
Ste 2: Convert longitude and latitude to UTM meter unit; Normalize to range [0,1].

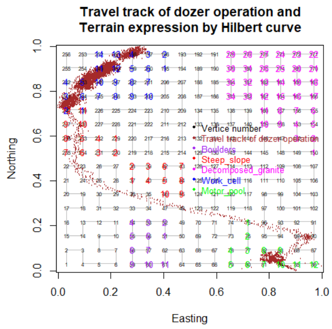

Figure 9. Index-based Hilbert curve

The index-based the Hilbert curve enables us to map multi-dimensional data to one-dimensional sequence values that could be inherently clustered, and then to allow for fast retrieval and storage. As mentioned above, the serial number assigned to the vertices might be equivalent to zip code in our daily life.

4.2.4 Example of abductive inference

The cyber agents could handle many kinds of physical cues to enhance workers' spatial awareness as shown in Figure 5. Due to limitations of space, examples of abduction inference regarding only one part of them are shown below.

Figure 10 and Figure 11 show occurrence spots of sudden acceleration and rapid deceleration while running; and existing of impacts and free-falls on site, respectively.

Some cyber agent might be interested in whether or not impact depends on speed. Here, inference would be proceeded along with the following steps:
Step 1: Set thresholds at the 5% and 95% points of experience distribution function,
Step 2: Generate cross table, that is, contingency table,
Step 3: Do chi-square test,
Step 4: Calculate joint probability and the Hebbian weight.

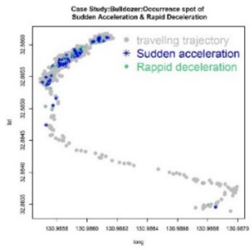

Figure 10. Occurrence spots of sudden acceleration and rapid deceleration while running

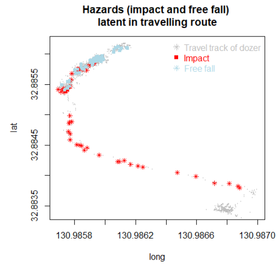

Figure 11. Existing of impacts and free-falls on site.

Figure 12 shows a part of semantic and propagation network related to the issue here.

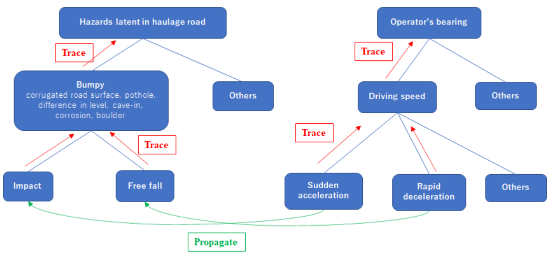

Figure 12. A part of semantic and propagation network

If the Hebbian weigh might be significant, then the cyber agent would trace upward to the parent node, that is, the hazards latent in haulage road in this case. Otherwise, the cyber agent forgets it. The forget here means “take no-action” but “remember it, in other word, record it.”

The occurrence spots of sudden acceleration and rapid deceleration, and the impact and free-fall are significant, considering the thresholds, respectively, and then the cyber agent would inform workers of that facts, that is, the parent node of them with precaution on the dashboard of the construction AI. The phenomena of sudden acceleration and rapid deceleration is supposed to be triggered by the dozer operation of "Pushing material" or "Releasing, spreading and compacting material." As for impact and free fall, the workers would investigate the haulage road in situ or review the recorded images of on-board camera for dozer to explore any hazard, for examples, corrugated road surface, pothole, difference in level, cave-in, corrosion, boulder, and so forth, latent in the haulage road.

As for the propagation from sudden acceleration and rapid deceleration to the impact and free-fall, the chi-square test does not show the significance. Moreover, The Hebbian weight values are minus. Consequently, the cyber agent would forget the relationship among the them, that is, "Take no action" but "Remember it."

5 Further Development and Research

The contents described in this paper might be almost a sublimation of the papers we have submitted to the ISARC for the past decade.

Implementation of the cyber agents is yet insufficient and still going on the road. We are required to gain experience of applying the way of thinking about the cyber agents to construction control on site.

For the present, we are scheduled to do further development and research on the following themes:

- Fulfilment of contents built in the tuple, especially, propositions, production rules, belief, Hebbian weights;
- Equipment of existing functions and objects fully with a reference class "setRefClass" in the R language;
- Objectification of abductive inference and to pile up the examples; and
- Experience replay with belief and Hebbian weights propagation.

In closing, we would like to say that any help and suggestions on this study would be heartedly appreciated. We are looking forward to meeting and discussion on the cyber agents with you all at the conference of the ISARC 2021 that will be held in UAE.

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