Infographics on Unmanned Dozer Operation

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Abstract –
As for unmanned dozer operation, this study aims development on infographics to reduce likely mental stress burden to operators in the remote-control room. First of all, this paper introduces problems in unmanned construction and the purpose of this study. Secondly, actor-critic based construction control system is described, which generates infographics. Thirdly, point on construction system is presented, which gathers readings from onboard smartphone for dozer in real-time manner. Fourthly, lesson learned from examples of infographics are reported; Finally, concluding remarks and future works are mentioned.

Keywords –
Unmanned construction; Infographics; Actor-Critic; Loading surface displacement; Underground stress

1 Problems and Purpose

Basically, operators can feel their realistic sensation of their own machine's behaviour based on the seat of the pants under their operations, e.g., distance and clearance perception using front views, possible motion space, and speed, acceleration, jerk, jolting, rattling, rolling, pitching, and yawing of the machine body, and so on. Handling joysticks to operate a machine, either directly or remotely, is an inherently eye-hand coordination task. The eye-hand coordination means to control eye movements with hand movements, and to handle joysticks along with the use of proprioception of the hands, or vice versa, as processing visual representation of the situational views.

Considering unmanned operation, however, the operators handle the joystick controllers to operate construction machines remotely in narrow field of views produced by camera-monitor system at the control room. Here, the operator receives a visual representation of the situational views from the camera monitor, process it, and select an action by handling the joysticks. Although, the operators have to make a decision instantaneously on do's and don'ts in their operations, it is sometimes difficult to ensure line-of-sight for or visuospatial perspective taking to location and movement direction of their machines or positions of their targets. Then they have to mentally translation, rotation and scaling between different frames of references to [1]:
(1) Orient the different sets of information into the same of reference, and
(2) Understand the relationships between the sets of information.

Therefore, the unmanned construction asks the operators to acquire extensive trainings and broad experiences on problem-solving skills. The skilled operators of these kinds are imperative for the unmanned construction. In Japan, however, there are very few skilled operators, and most of them are aged people.

Overcoming these sort of problems, it is significant and requisite to compensate their realistic sensation in order to enhance spatial awareness, in other words, conscious awareness of actions. To do so, we have been and are doing research and development on infographics pertaining to construction state, and trying to build actor-critic based construction control system, which could provide the operators with the infographics in a timely manner. The infographics are a visual representation of construction profile with graphics, numerical tables, quantitative evaluation indexes, and early precautionary messages, which are inferred from outputs of spatiotemporal analysis models built in the critic component as explained later. The construction profile is defined as a set of data to vision characteristics of phenomena being generated along with construction in progress and indexes to show the patterns [2]. The infographic makes it possible for the operators to quickly grasp the essential insights on construction situation at a glance.

As is well known, an unmanned construction process is separated into several operations such as excavation, loading, hauling, unloading, filling, dozing, compacting, slope shaping, etc., which are sometime independently and at other time interactively performed by different operators. Focusing on dozer operation, included in the unmanned construction process, this paper reports research and development on infographics to compensate operator's realistic sensation. Dozer operation presented here is remotely dozing and compacting to build retaining embankment as countermeasures to additional landslide.

First, this paper describes overview of actor-critic based construction control system, which handles readings and derive relevant infographics from a data set of readings. Secondly, lessons learned from examples of infographics are reported. Finally concluding remarks and future works are presented.

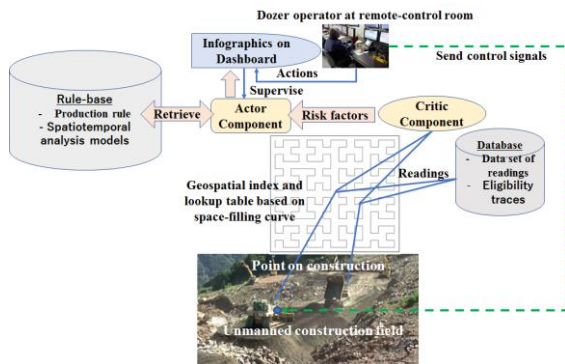## 2 Overview of Actor-Critic Based Construction Control System

Figure 1. Schematic view of actor-critic based construction control System

The actor-critic based construction control system is largely classified into construction machine, points on construction (hereafter called POC), operator at the remote-control room, rule-base, database, actor-critic architecture, and dashboard as shown in Figure 1.

2.1 Points on Construction (POC)

POC takes sensor-based event detection approach to track construction machines and to automatically and real-timely gather a data set of readings related to events occurred by unmanned construction operations as shown in Figure 2 [3].
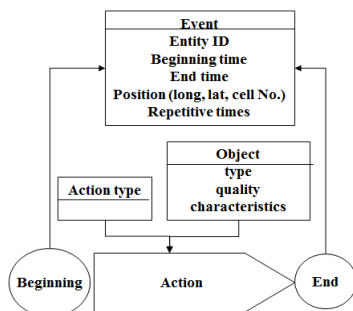

Figure 2. Image of sensor-based event detection approach

In this approach, the beginning and end of action could be automatically detected by sensors built in

smart phone (e.g., 3-axial accelerometer, 3-axial angular velocity meter, GPS receiver, and communication module), and otherwise recognized by a button pressed event, that is, pushing predetermined function key on the smart phone by operator. Unmanned construction machine has on-board smart phone whenever it is being operated. And then, the smart phone automatically sends the data set of readings via the Internet to store them into the database. Readings gained from the POC consist of time, longitude, latitude, direction, speed, 3-axis acceleration, 3-axis angular velocity, and son.

2.2 Operator

Operator here includes not only machine operator but also resident engineers and experts in unmanned construction. The operator can supervise the actor by inputting previous setting into the dashboard. The previous setting consists of sampling frequency, various elements of machines, thresholds for discriminations, local coordinates and bounded box of construction area, positions of landmarks (i.e. spots of digging, loading and unloading, waypoints on haulage route), and numerical targets of construction works such as digging, hauling, dozing, the order of priority to select the if-then rule inside the actor, and so on.

Construction site area is expanded by quadrangular work cells with geospatial indexes, which are labelled by the unique number that defines cell's position in order of cell vertices in sequence of space-filling curve, that is, Hilbert curve. This is conversion between positions on the Hilbert curve and local coordinates in geometric range of construction area. The labelled work cells build an index structure that enables us to retrieve information effectively and efficiently.

The operator can choose spots containing the point of interest from the work cells to be controlled, e.g., loading spot, haulage route, dumping spot, embanking spot, compartments of concrete placement, hazards latent in construction area, dangerous phenomena, and so forth.

2.3 Critic Component

The critic fetches the readings sent from on-board sensors built in smart phone, calculates risk factors and propagates them towards the actor. The risk factors consist of:
(1) Descriptive statistics as to running speed, 3-axis acceleration, 3-axis angular velocity;
(2) Composition value of 3-axis acceleration gained by

$$force = \sqrt{ax^2 + ay^2 + az^2} \qquad (1)$$

where force: composition value, ax: lateral acceleration, ay: longitudinal acceleration, and az: vertical

acceleration;

(3) Values of jerks: The jerk is the first-order difference of consecutive data elements in time series;

(4) Change-points in mean and variance of the values of jerks;

(5) Run length: The run length in this study is defined as a continuous sequence of repeated upward or downward values in many consecutive data elements;

(6) Distance: distance travelled, distance to other machines and landmarks;

(7) Attitude of machine gained by applying complementary filter to 3-axis acceleration and 3-axis angular velocity;

(8) Dozing area and density; and

(9) Progress rate.

2.4   Actor Component

Largely speaking, actor component includes two mechanisms as follows:

(1) Production rule (If-then rule <state, action, strength>)

This rule associates a condition (if) with an action (then); The rule states what action to perform when a condition is true; The strength indicates firing priority (i.e. rank, utility, severity, probability, cost, etc); The production rule is chosen based on the order of priority predefined by the operator; and

(2) Eligibility trace

Eligibility trace is a temporary record of the occurrence of an event, such as the visiting of a state or the taking of an action, and so on; The eligibility trace marks the memory parameters associated with the event as eligible for undergoing learning changes.

The actor component incorporates spatiotemporal analysis models to analyse the risk factors. These models are applied to:

(1) Visualize travelling trajectory of construction machines, and to show interference among work lines,

(2) Calculate jerks of running speed and to detect occurrence spots of sudden acceleration and rapid deceleration

(3) Calculate composition values of 3-axis acceleration and the jerks, and to calculate frequency of impacts and free-falls and then to show rugged sections or damaged spots on haulage road,

(4) Calculate distances to other machines and any landmark,

(5) Apply complementary filter to 3-axis acceleration and 3-axis angular velocity and then gain attitude of machine, and to show probable turnover and sliding,

(6) Grasp dozing trajectory and to calculate the constructed area, and more to show the progress gauge of the operation,

(7) Grasp compacting trajectory and the compacted density,

(8) Calculate loading surface displacement after dozing and show the time-series changes,

(9) Calculate underground stress below dozing and show the time-series changes, and

(10) As for acceleration and angular velocity in time series, detect change-points in the mean and the variance and to find the trend by counting the run length.

The actor produces list-wise infographics with early precautionary messages, and forwards them to the dashboard. The early precautionary messages inform operator of the phenomena prognosticated from the risk factor. The early precautionary messages are composed of:

(1) Objective: description of the infographic's objective;

(2) Hazard clarified: dangerous behaviour or phenomena identified by the built-in spatiotemporal analysis models, for examples,

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

2) 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 (hereafter called KPI) changes in time series more than the threshold "7";

- Any shift in the mean and the variance of KPI; and

- Actual progress behind the planned baseline.

(3) Early precaution

Referring to ANSI Z535,5 definitions, the levels of precaution are set as follows:

1) Danger: indicate an extreme hazardous situation which, if not avoided, will result in death or serious injury,

2) Warning: indicate a hazardous situation which, if not avoided, is liable to result in death or serious injury, to decrease one's productivity, or to end degradation of construction quality,

3) Caution: indicate a hazardous situation which, if not avoided, is likely to result in minor or moderate injury, to decrease productivity, or to end degradation of construction quality, and

4) Notice: address current practices that are not related to the above hazards.

2.5   Dashboard

A dashboard is a visual display on screen of smart phone, PC or other device that are installed at the

control room or the operators hold. Information displayed on the dashboard is consolidated and arranged on a single screen so that infographics can be monitored at a glance.

2.6 Database and Rule-based Database

Database and rule-based are web-based cloud systems. The database stores a data set of readings. Infographics and early precautionary messages generated by the actor component are displayed the dashboard, and stored in the database. Also, the eligibility trace data is stored in the database. The rule-base stores if-then rule and spatiotemporal analysis models that the actor component uses.

3 Lesson Learned from Examples of Infographics

This chapter reports examples of the infographics that show images of the exploratory spatiotemporal visualizations with wrap-up of lesson learned. The wrap-up of lesson learned is composed of objectives, hazard clarified, dangerous operation identified, early precautionary message, and reflective description on lesson learned.

3.1 Data Set Used to Generate Examples of Infographics

In order to generate examples of infographics, we utilized a data set of readings with respect to remote-controlled dozing and compacting operations applied to build retaining embankments as countermeasures to further large-scale landslide. The data set of readings was obtained from sensors, such as 3-axis accelerometer, 3-axis angular velocity meter, digital compass, GPS receiver, which were built in the on-board smartphone for the dozer. The data set utilized here is structured of meta data and variables as follows:
(1) Machine id
(2) Number of original obs.: 12013
(3) Sampling frequency: 4 HZ
(4) Measurement start time: "2017-03-09 08:24:00 JST"
(5) Measurement end time: "2017-03-09 16:25:00 JST"
(6) Analysis object: 3000 obs. of 11 variables (dd: num Time: POSIXct, long: num, lat: num, speed: num, ax: num, ay: num, az: num, gx: num, gy: num, gz: num)
The observations of analysis object here were chosen from the original observations at random sampling with replacement.

3.2 Travelling Trajectory

Spatiotemporal trajectory of dozing and compacting is shown in Figure 3.

Wrap-up of lesson learned from Figure 5 is listed below.
(1) Objectives: Visualization of travelling, dozing, compacting, and time lapsed
(2) Hazard clarified: None
(3) Dangerous operation identified: None
(4) Early precautionary message: Notice
(5) Reflective description on lesson learned:

By Figure 5, 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 5 that the stopped and/or idling time is short during dozing and compacting operations. Total distance travelled here was 6030.622 m.

Furthermore, 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. As far as possible, it is desirable for these dotted marks to be plotted at the different start time and then in parallel with each other.
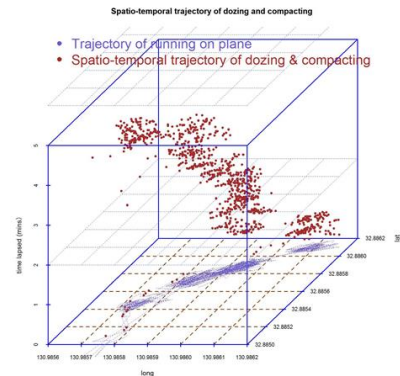

Figure 3. Spatiotemporal trajectory of dozing and compacting (Slate blue dashed line: "running trajectory on plane"; Brown dot "spatiotemporal trajectory of running along with the axis of time")

3.3 Safety Control

It is significant and required to compensate operator's realistic sensation, when remotely operating machine at dangerous spots, for example, at the steep slope, at the ridge of steep cliff, etc. In addition, spatial awareness is very important for operators to infer and understand the present and future surroundings of their own machines and to watch oneself in the work space.

In order to compensate operators' realistic sensation

and evoke their spatial awareness, it would be significant to provide them with physical cues related to appearance and posture of machine body, which would enhance their diagnostic and prognostic capabilities to reflect on their own unsafe behaviour

Examples containing to spatiotemporal visualization of unsafe behaviour and potential hazards are presented below.

3.3.1 Occurrence Spots of Sudden Acceleration and Rapid Deceleration

Upper 95% and lower 5% points in the jerk distribution of running speed are used as the threshold to detect occurrence spot of sudden acceleration and rapid deceleration, and then the if-then rules are shown below:

If (the jerk of speed >= the upper 95%-point value), then it is presumed that sudden acceleration occurred at the longitude and latitude; and
If (the jerk of speed < the lower 5%-point value) then it is presumed that rapid deceleration occurred at the longitude and latitude.
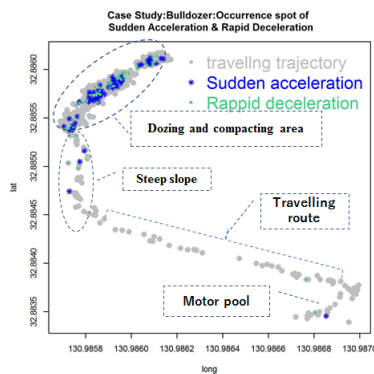

Figure 4. Occurrence spots of sudden acceleration and rapid deceleration while running

Wrap-up of lesson learned from Figure 4 is listed below.
(1) Objectives: Detection of occurrence spots of sudden acceleration and rapid deceleration while running.
(2) Hazard clarified: Many sudden accelerations and rapid decelerations were found.
(3) Dangerous operation identified: It is liable to evoke traffic accident, and degradation of quality as to surface and subsurface soil.
(4) Message: Warning
(5) Reflective description on lesson learned:
Many sudden accelerations and rapid deceleration were found at the dozing and compacting area. It is presumed that the dozing and compacting might be rough or harsh operations, which are liable to trigger disturbing and stirring the ground surface. It might involve risk of quality degradation of the surface and subsurface ground. Many sudden accelerations were found when

climbing at steep slope,. Conversely, some rapid decelerations were found when descending.

3.3.2 Detection of Rugged Sections or Damaged Spots on Site

It is more likely to find phenomena of impacts and free-falls at rugged sections or damaged spots. Nevertheless, operators could not easily envisage any hazard latent in a narrow field of view from camera-monitor system at the control room without any background information on unmanned earthwork process.

The if-then rules to identify levels of impact and free-fall are shown as follows:

If (2G<=the 3-axis acceleration composition value) then it is presumed that strong impact occurred at the longitude and the latitude;
If (1.4G =< the 3-axis acceleration composition value & the composition value<2G) then it is presumed that somewhat strong impact occurred at the longitude and the latitude;
If (1.2G=< the 3-axis acceleration composition value & the composition value<1.4G) then it is presumed that impact occurred at the longitude and the latitude; and
If (the 3-axis acceleration composition value<0.7G) then it is presumed that free-fall occurred at the longitude and the latitude.
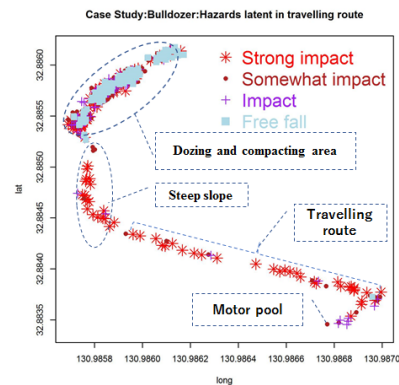

Figure 5. Existing of impacts and free-falls on site

It would be helpful and significant for operators at the control room to see severe dangerous spots with coloured marks, and to watch the early precautionary messages on the screen of their smart phone or PC, when approaching to the severe dangerous spots.

Wrap-up of lesson learned from Figure 5 is listed below.
(1) Objectives: Detection of rugged sections or damaged spots on site.
(2) Hazard clarified: Many strong impacts, and impacts were found everywhere. Furthermore, There were many

occurrences of free-falls in dozing and compacting area.
(3) Dangerous operation identified: Remote operation of dozer might be poorly handled and harsh. There would be otherwise many rugged sections or damaged spots latent in the whole area of the construction.
(4) Message: Alert
(5) Reflective description on lesson learned:
It can be confirmed in Figure 5 that there are many impacts and free-falls within dozing and compact area, and many strong impacts were found everywhere on the travelling route. The former phenomena indicate that dozing and compacting is rough or harsh operations, which are likely to trigger disturbing and stirring the ground surface. It is likely to result in traffic accident, degradation of quality as to surface and subsurface soil. The latter phenomena indicate the travelling route might be severe uneven.

3.3.3 Detection of Probable Turnover and Sliding

It aims to prevent a dozer from accidents of rollover, slide and falling. The method here largely forks the two:
(1) Find signals of turnover, slither, or skid of the machine body, and then issue early precautionary messages, and
(2) Visualize phenomena of rolling, pitching, and vacillation of the machine body in order to prognosticate likely dangerous sections and spots latent in the travelling route to the work zone.

More concretely, both the 3-axis acceleration and 3-axis angular velocities are captured by sensors built in the onboard smart phone, calculated by a complementary filter, and then rolling and pitching of machine body are visualized in time series. Moreover, if and when finding both of run-length more than "7" in the time series of rolling and pitching and the values more than 15 degrees, and then the occurrence places denote dangerous sections and spots latent in the travelling route to the work zone. Figure 6 shows dozer attitude in time series.

Wrap-up of lesson learned from Figure 6 is listed below.
(1) Objectives: Finding dangerous sections and spots latent in the access road to the work zone.
(2) Hazard clarified: None
(3) Dangerous operation identified: None
(4) Early precautionary message: None
(5) Reflective description on lesson learned:
It can be shown from Figure 6 that there are not dangerous sections and spots latent in the access road to the work zone, no matter whether rough or harsh operations
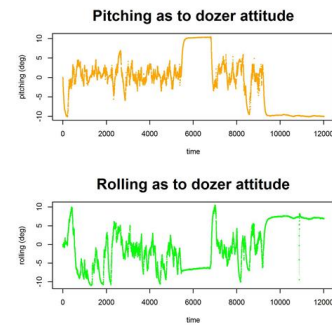

Figure 6. Dozer attitude in time series and the histogram

3.4 Productivity Control

Figure 7 shows dozing trajectory and the area, and the progress gauge of the operation. The progress gauge represents progress rate to the target value.

Kernel density estimation is a nonparametric method for estimation of probability density functions. An axis-aligned bivariate normal kernel is utilized to estimate the dozed area.

Wrap-up of lesson learned from Figure 7 is listed below.
(1) Objectives: Visualization of dozing trajectory and the area, and progress rate of the operation.
(2) Hazard clarified: None
(3) Dangerous operation identified: None
(4) Early precautionary message: None
(5) Reflective description on lesson learned:
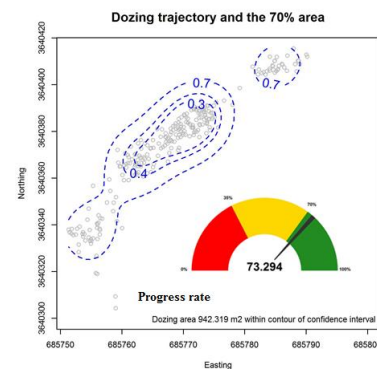Dozing and compacting are being operated as scheduled.

Figure 7. Dozing trajectory and the area, and progress rate of the operation

3.5 Quality Control

3.5.1 Compacting Trajectory and the Compacted Density

Weighted Kernel density Estimate method is utilized to visualize compacting trajectory and the compacted density, where the weight is impulse values. Figure 8 shows compacting trajectory and the compacted density.
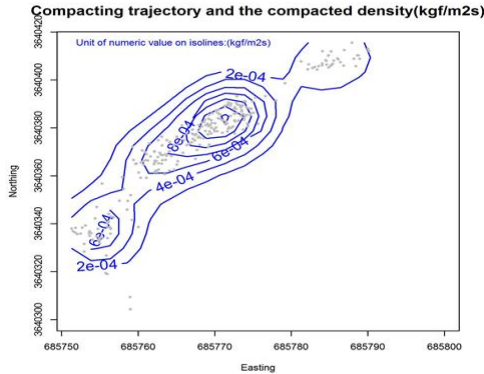
Figure 8. Compacting trajectory and the compacted density

Wrap-up of lesson learned from Figure 8 is listed below.
(1) Objectives: Visualization of compacting trajectory and the compacted density.
(2) Hazard clarified: None
(3) Dangerous operation identified: None
(4) Early precautionary message: None
(5) Reflective description on lesson learned:
    Compaction is filled in all the required area.

3.5.2 Grasp of Loading Surface Displacement

Nonlinear dynamical behavior as to loading surface displacement consists of transient term and stationary term.

If the damping ratio $\zeta < 1$, the former is given as

$$, \qquad x(t) = \exp(-\xi\omega_0 t)\frac{v_0}{\omega}\sin\omega t \qquad (2)$$

where v_0 is the running speed. The latter is expressed as

$$x(t) = A\sin(\omega t - \phi), \qquad (3)$$

$$A = \frac{x_{st}}{\sqrt{(1-\lambda^2)^2 + 4\xi^2\lambda^2}}, \qquad (4)$$

$$\tan\phi = \frac{2\xi\lambda}{1-\lambda^2}, \qquad \text{and} \qquad (5)$$

$$\lambda = \sqrt{1-\zeta^2} \quad , \qquad (6)$$

where x_{st} is static displacement.

Relationship between the damping ratio ζ and the logarithmic decrement δ is expressed as

$$\delta = \frac{2\pi\xi}{\sqrt{1-\xi^2}} \quad , \qquad (7)$$

If and when the damping ratio $\zeta \ll 1$,

$$\delta \cong 2\pi\xi \qquad (8)$$

In addition, the relationship between the natural frequency ω_0 and the damped natural frequency ω is presented by the following equation.

$$\omega = \omega_0\sqrt{1-\zeta^2} \quad . \qquad (9)$$

The natural frequency can be obtained from the zero-crossing rate of the 3-axis composition values in time series. And then, the damped natural frequency is calculated.

In this study, the logarithmic decrement δ is obtained from the jerk of the 3-axis composition value. First, Empirical Mode Decomposition (EMD) is applied to the jerk, and then we can obtain the 5-th intrinsic mode function (IMF). This sifting process is shown on the left in Figure 9. We could find carriers with amplitude decay envelope in the close-up of 5-th IMF on the right in Figure 9.

By finding local extrema (e.g., maxima and minima), the logarithmic decrement δ can be obtained and then the damping ratio ζ can be given.
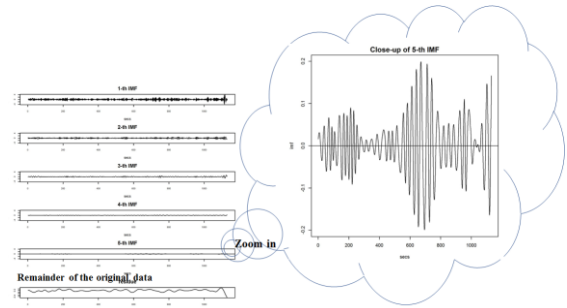

Figure 9. Sifting process of the EMD

Figure 10 shows changes in the loading surface displacement. The solid blue line and the dashed green line are local polynomial regression and the 95% confidence interval, respectively, in the upper illustration of Figure 10. Change points as to the mean and variance of the loading surface displacement in the lower illustration of Figure 10.

Wrap-up of lesson learned from Figure 10 is listed below as follows.
(1) Objectives: Visualization of the loading surface displacement.
(2) Hazard clarified: None
(3) Dangerous operation identified: None
(4) Early precautionary message: None
(5) Reflective description on lesson learned:
    Phenomena of spreading fill materials and stepping on them is continuously repeated. The fill material here is lime-stabilized andosol. Unexpected event in this operation is not occurred.
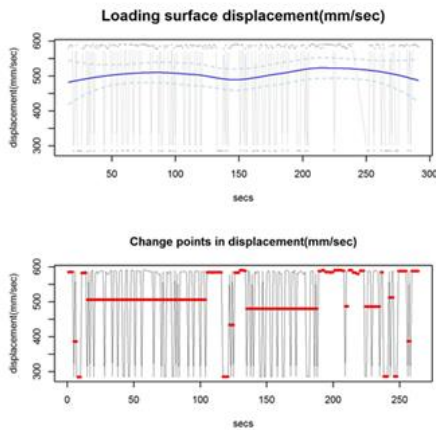
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Figure 10. changes in the loading surface displacement

3.5.3 Visualization of Underground Stress

Steinbrenne's stress solution is shown as follows [4]:

$$\sigma_z = \frac{2p}{\pi}[\frac{abz}{D}\frac{a^2+b^2+2z^2}{D^2z^2+a^2b^2}+\sin^{-1}\frac{ab}{\sqrt{a^2+z^2}\sqrt{b^2+z^2}}] \qquad (9) \text{ and}$$

$$D^2 = a^2 + b^2 + z^2 \quad , \qquad (10)$$

where σ_z is stress at the depth z, the shoe width is 2a, the shoe length 2b, and p is impulse per unit of area.
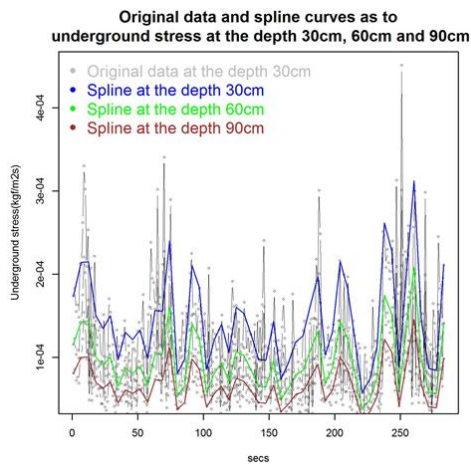

Figure 11. Underground stress in time series

Wrap-up of lesson learned from Figure 11 is listed below.
(1) Objectives: Visualization of the 1 Underground stress in time series.
(2) Impact clarified: None
(3) Hazard identified: None
(4) Message: None
(5) Reflective description on lesson learned:
   Although the waveforms of those underground stresses have almost same shape, the deeper its position is, the smaller the stress value become. Besides the smaller the dispersion gets.

4 Concluding Remarks

The infographics play role in the following matters:
(1) Feedback of physical cues related to machine behaviour,
(2) Spatiotemporal visualization of hazards latent in in-situ earthwork process,
(3) To pick a set of building block of information at the right level of abstraction,
(4) To provide oneself with the opportunities to reflect on their own bearings as facing their own works at hand,
(5) To take timely and quickly correct actions based on detailed visibility of appearances and motions of mobile entities in a whole unmanned construction process, and accordingly, and
(6) To reduce likely mental stress burden to oneself in the remote-control room.

Taken together, these enhancements of conscious awareness of actions would be able to provide operators with the opportunities to reflect on their own bearings as facing their own works at hand.

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