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Development of support system for estimation of earthquake fault plane with hypocenter data

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Abstract. Effective data visualization techniques are required in order to support efficient earthquake analysis. So far, earthquake analysis experts have only been able to imagine 3D structures from typical 2D expressions. However, we consider that experts would be able to understand 3D structures more accurately and efficiently by providing them with an intuitive and interactive 3D display system. We focused on immersive projection technology (IPT) systems, more specifically on the CAVE system, to develop an effective support system for earthquake data analysis. We also developed an IPT oriented bimanual input based control interface for the support system to enable intuitive user interaction with the 3D display. In addition, we implemented a support tool for estimating fault planes in the earthquake phenomenon using the Spatio-Temporal Kriging method.

Keywords: Earthquake, Fault plane, IPT, Control interface, Spatio-Temporal Kriging

1. Introduction

In recent years, there is a consensus that a large earthquake will occur in the Tokai or Nankai region of Japan in the near future, and concerns about earthquake disaster prevention have grown. As a result, several research centers have been attempting to clarify the earthquake mechanism[1]. In general, hypocenter or seismic wave data which are obtained soon after the earthquake have been used for analysis, and reliability of various numerical simulation about quantitative prediction and seismic activity of the earthquake occurrence process are improved. In the Japanese islands where earthquakes are occurred frequently, measuring and

analyzing earthquake data plays important role for building a safe social infrastructure.

In order to execute an efficient analysis on earthquake data, effective data visualization techniques are crucial. For instance, we could find abnormalities in earthquake activities and therefore estimate the ground structures and active faults from the visualization results of hypocenter data sets. So far, earthquake analysis experts have only been able to imagine 3D structures from typical 2D expressions, such as hypocenter distribution map and cross section diagram. In addition, the criteria in analysis result is often different among these experts, and there is no consensus about the best methods for such estimations. In this research, we suggest the support system for experts to understand 3D structures of seismic activities more effectively and accurately with providing an intuitive and interactive 3D display technology.

We have proposed a support system for analyzing earthquake phenomenon with immersive 3D environment[2]. We focused on immersive projection technology (IPT) such as CAVE[3] system. Earthquake experts can be immersed in a virtual space of hypocenter data distribution to understand the 3D structure more intuitively by using high presence 3D display system with IPT. In addition, we have developed a bimanual input based control interface for IPT systems[4] to enable an intuitive user interaction with 3D displayed data. Moreover, we focused on a support tool for estimating fault planes based on hypocenter data distribution. The earthquake is caused by destruction around the dislocation which is occurred when energy saved in the earth crust is released with plate sinking, and the shape of fault plane can be estimated with hypocenter data distribution. Estimating and analyzing the fault plane plays an important role on performing prediction and disaster prevention of earthquake.

Our system have implemented support tool for estimating fault planes only with spatial information of hypocenter data. In this paper, we newly implemented estimation method with not only spatial but temporal information of hypocenter data to verify the effectiveness of our system. In our system, the countour can be displayed on the fault plane estimated with hypocenter data by means of Spatio-Temporal Kriging method[5] which is an interpolation technique widely used in the geostatistics field. We expect that our system can be powerful tool for discovering the new active fault and spatio-temporal change of ground structure which were not easily achieved when using traditional 2D display techniques.

2. Related works

In this section, we explain about some of the traditional visualization techniques for hypocenter data. Sumitomo et al.[6] have described both the advantages and disadvantages of some traditional visualization techniques which have been used by the experts during earthquake analysis. The authors tried to investigate and improve visualization methods for quantifying this analysis information. The traditional hypocenter distribution map, spatio-temporal distribution map, and accumulated curve are shown in Figure 1. The hypocenter distribution

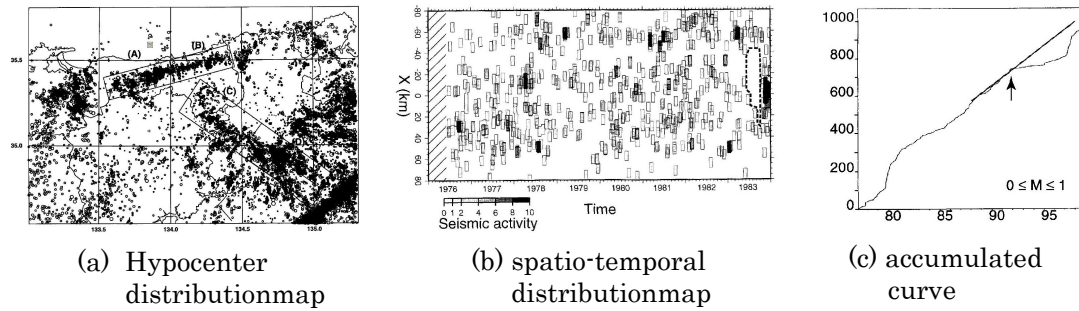


Figure1: Representative visualization technique of earthquake data [6]

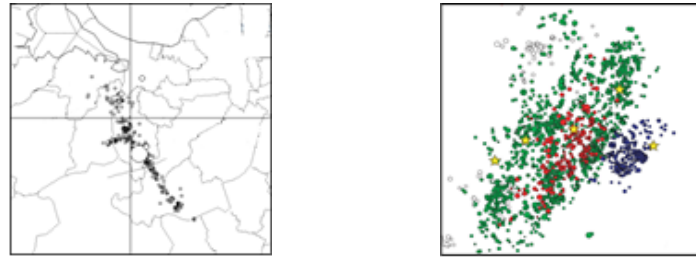
map of Figure 1(a) shows all hypocenters of an earthquake in some specific time period. We can verify that some local characteristic such as the seismic activity along the active fault is clearly distinguished. The spatio-temporal distribution map of Figure 1(b) represents the distribution of the hypocenter positions projected onto a 1D space, and shows its temporal response. It is possible not only to express the spatial distribution of hypocenters but also to analyze along the temporal response. The accumulated curve of Figure 1(c) shows the accumulated number of earthquakes which were larger than a magnitude set as the minimum. These techniques are suitable when using paper sheets or traditional 2D displays by converting 3D data into 2D or 1D data. However this process is still insufficient for an intuitive estimation of the 3D structure.

On the other hand, there already exists earthquake analysis system using 3D display. Kaito et al.[7] have proposed a 3D visualization system which uses time series analysis for the distribution of hypocenter point group. In addition, they have evaluated visibility in stereoscopic viewing using liquid-crystal shutter glasses. In this paper, we propose an IPT oriented displaying system which enables 3D visualization of hypocenters and their interactive analysis by using a newly developed control interface. Our proposed system differs from the aforementioned system in the point which it supports earthquake fault plane estimation with spatio-temporal statistic analysis techniques.

3. Fault plane estimation method

We implemented a support tool for fault plane estimation using hypocenter data distribution. The accumulated distortion in the base rock is dissolved by the surrounding region of the fault being destroyed. As a result, the region on which many hypocenters concentrate shows roughly the fault shape. The fault shape estimated by this method can be used for earthquake disaster prevention in various ways such as the earthquake movement forecast.

So far, earthquake experts have worked on 3D structures from typical 2D hypocenter distribution map and estimated the shape of fault planes. For instance, the hypocenter distribution map of the Western Tottori Prefecture Earthquake in 2000 is shown in Figure 2(a).



(a) Western Tottori prefecture Earthquake (b) Mid Niigata prefecture Earthquake

Figure2: Example of 2D hypocenter distribution map

In the case of the Western Tottori Prefecture Earthquake, the fault plane was a simple structure which consists of one plane (segment), therefore easy to estimate from this 2D hypocenter distribution map. However, another example, the Mid Niigata Prefecture Earthquake in 2004 shown in Figure 2(b), shows that when two or more fault planes intersect each other, the estimation task becomes complicated. This therefore shows the difficulty in understanding the fault plane shape only from the 2D hypocenter distribution maps.

In our proposed system, earthquake experts are able to understand the 3D structure of hypocenter distribution intuitively by immersively visualizing the hypocenter data using IPT systems. Moreover, the contour display of estimated fault plane is also possible by applying the Spatio-Temporal Kriging method which is one of interpolation technique widely used in geostatistics area.

3.1. 3D display of hypocenter data

The hypocenter data applied in this research include oscillation time, latitude, longitude, depth and magnitude of each shock. In proposed system, each shock is expressed as a sphere in 3D space. The position of sphere is determined by latitude, longitude and depth. In addition, the scale and color of the spheres are determined by the magnitude. Visualization results of Mid Niigata prefecture earthquake data is shown in Figure 3.

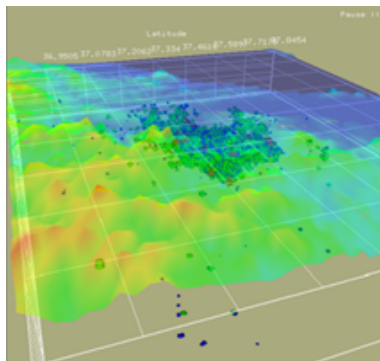


Figure3: Example of visualization results on 2D display(Mid Niigata prefecture earthquake)

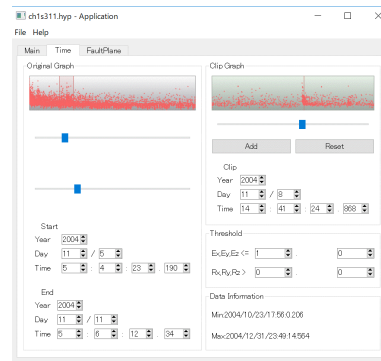


Figure4: Specifying data page GUI

The hypocenter data contains a large amount of shock over a long term. Therefore, users may overlook the part that should be paid attention, when the entire data is displayed at the same time. To avoid this problem, in our system the users can specify the necessary data using the GUI on the wearable computer through the newly developed user interface (Section 4.2) shown in Figure 4. The left graph shows the data at whole period where the horizontal axis shows time and the vertical axis shows magnitude. Users can select the region of interest by clipping it with the slider. The region specified in the left graph is expanded in the right graph. Users can specify the time for estimating the fault plane on the right graph.

3.2. Spatio-Temporal Kriging method

Kriging method is one of the main techniques used in geostatistics. The spatio-temporal phenomenon is modeled as a continuous space and time probability field, and the values at any position in the probability field can be estimated from observed data such as hypocenter data at any irregular position. Among the Kriging methods, Ordinary Kriging is the best linear unbiased estimation method for probability fields with the intrinsic stationarity. The probability field Z has the intrinsic stationary when the following two conditions are satisfied.

For any position and time $(s_1, t_1), (s_2, t_2) \in D$

$$E\{Z(s_1, t_1) - Z(s_2, t_2)\} = 0 \quad (1)$$

$$Var\{Z(s_1, t_1) - Z(s_2, t_2)\} = 2\gamma(s_1 - s_2, t_1 - t_2) \quad (2)$$

2γ depends only on the relative position and is called variogram, and γ is called semivariogram. The semivariogram parameters are estimated by applying existing models to the measurement data. The spatio-temporal estimation with Ordinary Kriging method is executed using the estimated semivariogram. For appropriate weights $\omega = [\omega_1, \dots, \omega_n]'$, the linear estimation value is

$$\hat{Z}(s_0, t_0) = \sum_{i=1}^n \omega_i Z(s_i, t_i) = \omega'Z \quad (3)$$

The aforementioned "best" means that the following mean square prediction error is minimized

$$\sigma^2(s_0, t_0) = E\left\{\left|\hat{Z}(s_0, t_0) - Z(s_0, t_0)\right|^2\right\} = -\omega'\Gamma\omega + 2\omega'\gamma_0 \quad (4)$$

where $\gamma_0 = [\gamma(s_1 - s_0, t_1 - t_0), \dots, \gamma(s_n - s_0, t_n - t_0)]'$, $\Gamma = \{\gamma(s_i - s_j, t_i - t_j)\}_{ij}$. By solving simple simultaneous equations, the weights ω are calculated.

$$\omega = \Gamma^{-1}\gamma_0 + \left(\frac{1 - 1'\Gamma^{-1}\gamma_0}{1'\Gamma^{-1}1} \right) \Gamma^{-1}1 \quad (5)$$

The estimation plane at the time of t_0 is obtained by repeatedly excuting this linear estimation by changing the s_0 value in the Equation(3).

3.3. Fault plane estimation process flow

3.3.1. Selecting a fault plane from hypocenter distribution

At first, users should select hypocenters which are supported to be a part of the fault plane from the 3D hypocenter distribution map diplayed in the 2D display (wearable computer). Then, users should select the time zone wanting to observe (Detailed in section 3.1). After that users should select hypocenter data used for fault plane estimation through the pen touch operation(Figure 5).

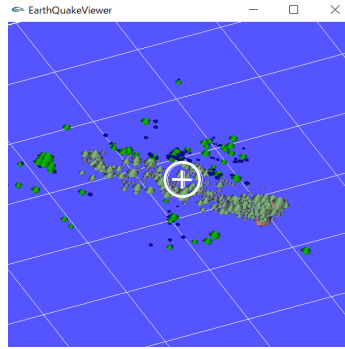


Figure5: Selection of hypocenter data

3.3.2. Estimating semivariogram model

As a pre-processing of spatio-temporal estimation using Ordinary Kriging method, the semi-variogram should be estimated from the selected hypocenter data by following steps.

1. Remove the outliers from the histogram (Horizontal axis: Magnitude) (Figure 6(a)).
2. Remove the outliers from the variogram cloud (Horizontal axis: Distance/Time between the hypocenters, Vertical axis: Magnitude difference between hypocenters) (Figure 6(b)).
3. Obtain the empirical semivariogram using the variogram cloud by specifying the number of division(Figure 6(c)).
4. Select the semivariogram model and estimate the parameters based on the empirical semivariogram.

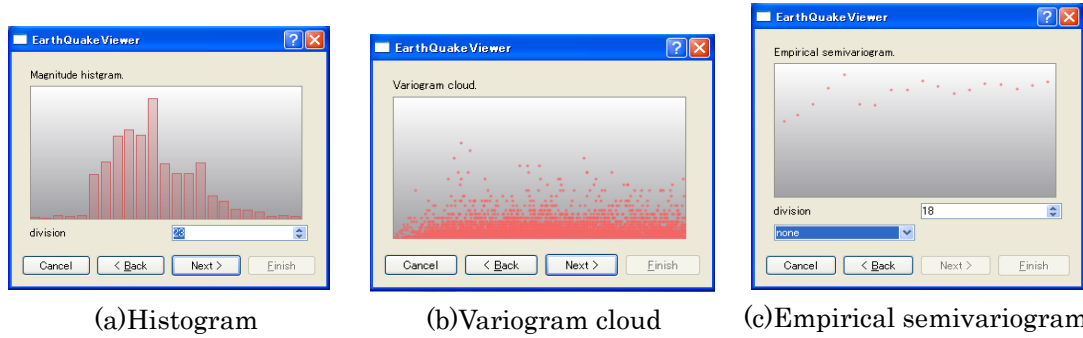


Figure6: Flow of estimating the semivariogram model

We implemented six models (nugget effect, linear, power, spherical, exponential, Gaussian model) for the selection in step 4. Users can specify the model to estimate semivariogram parameters. We implemented the optimization algorithm proposed by Brunell[8] to solve the nonlinear optimisation problem.

3.3.3. Displaying a fault plane

A fault plane is calculated from the 3D coordinates of hypocenter data. We applied the least square method to estimate the fault plane. The weights ω are calculated from the semivariogram estimated in 3.3.2 and then the spatio-temporal estimation using Ordinary Kriging method is executed from magnitudes of selected hypocenter data. The contour color of the estimated fault plane is estimated by the position and specified time with GUI(Figure4). Because hypocenter data has the current of the times, only hypocenter data before specified time is used for estimation. Example of estimation results with only changing specified time for same hypocenter data is shown in Figure7. Examples of some estimated fault planes are shown in Figure 8. We consider that it is possible to assist user's analyse by displaying the fault plane in 3D and giving the color of the contour using space interpolation.

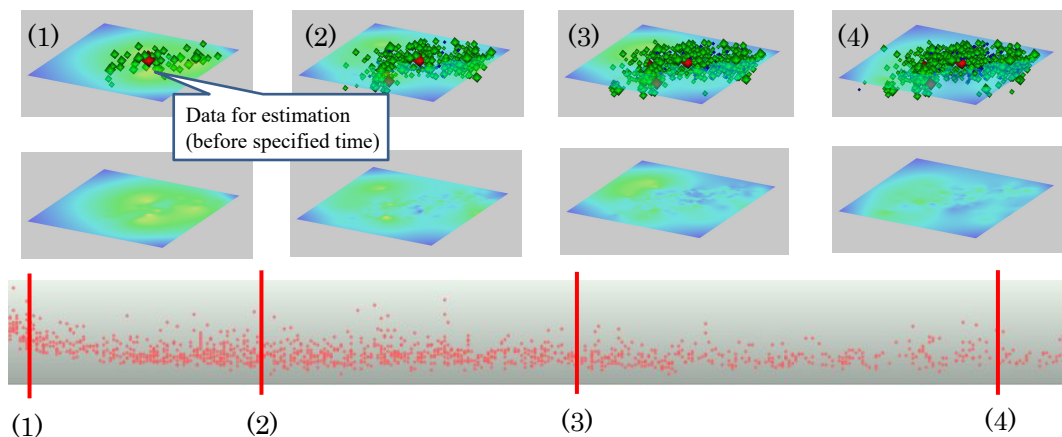


Figure7: Example of estimation result with changing specified time

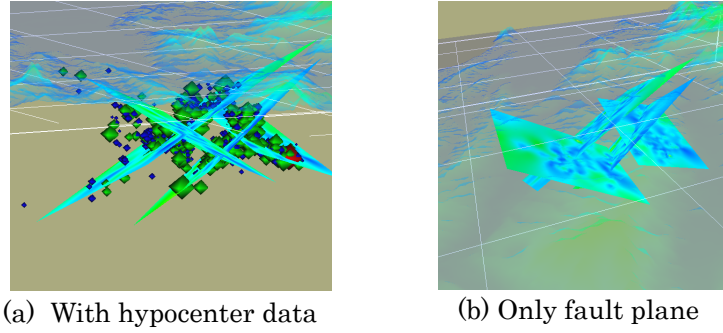


Figure8: Example of estimating fault plane (Mid Niigata prefecture earthquake)

4. System configuration

In this section, we detail the configuration of the proposed support system for earthquake analysis.

4.1. Overview of the proposed system

The outline of our proposed system is shown in Figure 9. The system consists of an IPT system and the CAVE-Ring, our developed novel control interface for IPT system. Our system is implemented using CAVE Library[9] for developing IPT application and QUANTA[10] for networking.

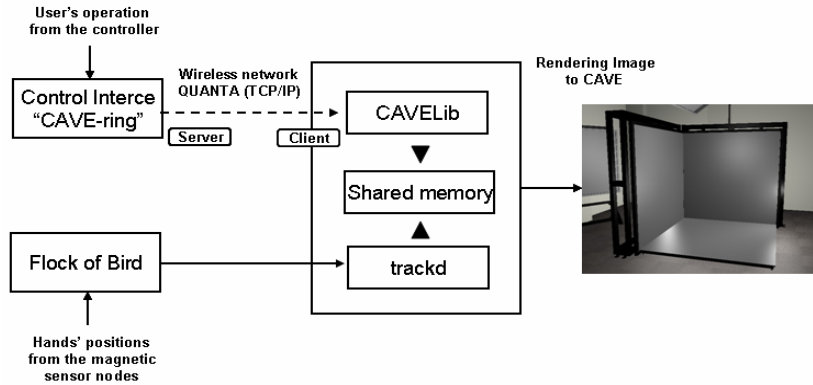


Figure9: Configuration of proposed system

4.2. CAVE-Ring: a control interface

We developed a novel control interface for IPT system which we named "CAVE-Ring". Wanda is generally used for control interface for IPT systems such as CAVE or Immer-saDesk. Wanda has 3 buttons and a joystick and users operate them by one hand. Moreover Kukimoto et al.[11] proposed the control interface with PDA(Personal Digital Assistance) for changing parameters and anotation to VR space easily in visualization works with IPT system. Control interfaces which have been proposed for IPT are designed for one handed ma-

nipulation. Considering that we manipulate various objects using both hands in our daily life, we think that bimanual manipulation can be more effective than one handed manipulations in IPT systems since it can avoid the lack of realism. Therefore, we developed a bimanual control interface for IPT systems and named it as "CAVE-Ring".

Figure 10(a) shows the input system for the CAVERING system. The proposed system consists of a pair of input devices which have ring shape, a control unit and a wearable computer. The input device has a joystick and a button(Figure 10(b)). The operation with input devices are detected with a control unit and the detected information is transmit to IPT sytem from wearable computer via wireless LAN. Moreover, the positions of user's hands are detected with magnetic sensors, and the detected information is transmitted to the trackd program on the host computer connected with IPT system. From the above, application developers can detect user control information and positions of user's hands in their applications.

Figure 11 shows the sisutation that an user wears CAVE-Ring system actually. Users wear the input devices which have ring shape with their forefingers of both hands. Various interactive controls with 3D displayed contents in IPT space are enable. In addition, the wearable computer also works as a user interface through its GUI(Graphical User Interface). Because the input devices are simply rings, users can therefore operate the GUI on the wearable computer using touch pen while wearing CAVE-Rings.

The advantage this user interface is its intuitive interaction with the 3D displayed contents with bymanual input devices which have ring shape. In addition, the 2D GUI provided by the wearable computer simplifeds some operations which become complex when using 3D displaying. The complete list of supported operations and functions are described in reference [4]. For the suppot system for earthquake analysis, we used CAVERings for walk-through in the 3D space and for fine-tuning the estimating fault plane. Especially, in our system, users can hold estimated fault planes with both hands and translate or rotate fault planes for confirming the hypocenter distribution map on them. In addition, 2D GUI was used for data file selection and partial specification of the hypocenter data.

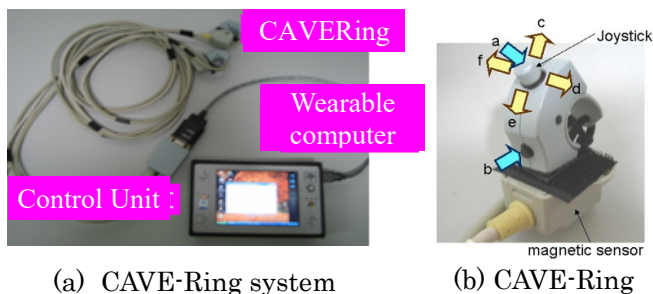


Figure10: Newly developed interface "CAVE-Ring"

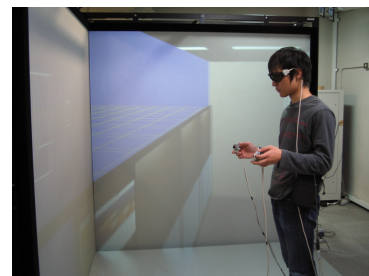
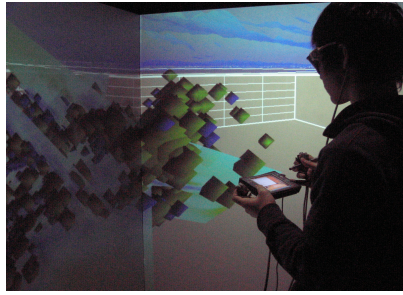


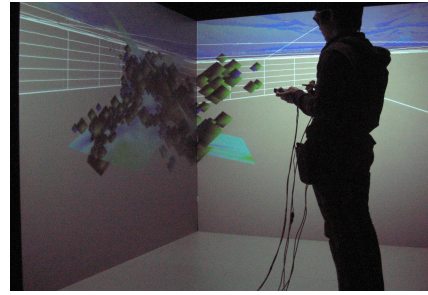
Figure11: The situation of wearing CAVE-Ring system

5. Implementation and results

We tried to display some past hypocenter data[1] with our system. Figure 12 shows a situation where a user observes past hypocenter data in an immersive environment. The user can select displayed hypocenter data interactively and estimated fault planes are displayed easily by intuitive pen touch on wearable computer (Figure12(a)). Moreover, users can observe internal data which was impossible to observe when using traditional 2D display and can analyze 3D hypocenter data interactively with using CAVE-Ring system (Figure12(b)). In experiment that earthquake analysis experts use our system, we received evaluation “3D position of hypocenter distribution can be understood intuitively”, “Complex fault plane structures can be observed easily by immersing into hypocenter data”.



(a) Using 2D GUI on wearable computer



(b) Using CAVE-Ring

Figure12: Situation of using proposed system

6. Conclusion and future works

In this paper, we proposed an IPT oriented support system for earthquake phenomenon analysis. Though IPT is inferior to recent high definition 2D display in terms of resolution, It turned out to be useful that users can detect overlapped fault plane group easily. Moreover, in this proposed system, users can select spatio-temporal hypocenter data with wearable computer in addition to 3D display with high presence. In addition, users can estimate fault planes from selected hypocenter data in an interactive speed. Hypocenter intensity distribution on the estimated fault plane can be estimated with spatio-temporal kriging method, too. Moreover, users can observe 3D hypocenter data from various view and analyze interactively by holding fault planes and moving them intuitively with CAVE-Ring system. We expect that our system enables to analyze fault plane position and hypocenter intensity distribution which plays an important role in prediction of earthquake and disaster prevention interactively, and it is useful for earthquake reserch which is necessary to build a safe and secure social infrastructure.

As future works, we should quantitatively evaluate the effectiveness of the implemented fault plane estimating method. Moreover, we are planning to develop an intuitive 3D inter-

face for assisting this fault plane estimation task, although our 2D GUI implementation has proven adequate. In addition, we are planning to expand the proposed system in order to enable the analysis of other kinds of data required in earthquake analysis, such as the earthquake wave speed structure. Finally, we plan to have this system evaluated by the earthquake analysis experts.

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