Effect of Multisensory Integration for Scientific Data Sensualization*

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In scientific computing, developing effective methods to display complex phenomena represented by numerical data is a key issue. In this study, virtual reality technology is applied to develop a multisensory data sensualization environment in which the user can use visual, acoustic, and touch sensations to understand scientific data. In particular, a prototype wind sensation display system was developed to generate touch sensation. In the multisensory data sensualization method, accurate and efficient transmission of data from the computer to the user is expected through the effective integration of several sensations. We conducted several experiments on the perception of scalar data and vector data in three dimensional space, using multisensory data sensualization methods, and verified their effectiveness in providing the user correct perceptions of data.

Key Words: Human Interface, Information Processing Equipment, Recognition, Scientific Visualization, Virtual Reality, Data Sensualization, Wind Sensation, Acoustic Sensation

1. Introduction

Recently, in scientific computing, advances in computer hardware and simulation technology have given rise to the existence of vast and complex numerical data. Therefore, developing effective methods to transmit scientific data from the computer to the user is a key issue. In several engineering fields such as structural dynamics or fluid dynamics, various data visualization methods have been studied and developed^{(1),(2)}. However, it is difficult to represent vast and complex data and transmitting physical phenomena to the user by the conventional data visualization methods.

In this study, virtual reality technology was applied to develop a multisensory scientific data sensualization method using several human sensations⁽³⁾.

Data sensualization methods using virtual reality technology have following significant features:

- Representing data in three dimensional space utilizing the interaction between the user and the data space.
- Representing data using multisensory information such as visual, acoustic and touch sensations.

With respect to the first feature, Bryson and others are developing a scientific visualizing system utilizing dynamic human interaction in three dimensional space⁽⁴⁾. As for the second feature, Smith and others used the acoustic information⁽⁵⁾, and Brooks and others showed the effectiveness of using touch sensation⁽⁶⁾. This study aimed at investigating the effectiveness of multisensory data sensualization method with the two features. Multisensory data sensualization environment was developed. In this environment, the user is able to represent and experience scientific data using visual, acoustic, and touch sensation with active interaction in three dimensional space. Figure 1 shows the concept of multisensory data sensualization proposed in this study, compared to the conventional data visualization methods.

This paper describes the several display devices

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Fig. 1 Concept of multisensory data sensualization

for visual, acoustic, and touch sensation, and explains the data sensualization environment. In addition, the effectiveness of multisensory data sensualization methods was discussed through the experiments on data perception.

2. Multisensory Information

2.1 Several human sensations

Table 1 shows the sensations used in this study and physiological classification of human sensations. In the ultimate data sensualization environment, all these sensations might be used to experience physical phenomenon virtually. However, in this study, basic human sensations such as visual, acoustic, and touch sensations were used to represent data. In this paper, we use the term of touch sensation in a broad sense which contains touch-pressure, warm, cold, and pain sensations. In this study, wind sensation, that will be mentioned in the latter part, was used as touch sensation.

In addition, it is necessary to utilize deep sensation to display data dynamically in three dimensional space. Deep sensation is felt by muscle, tendon, or joint, and is used to assist the human perception. For example, in the cases where a man turns his head to look at an object and hear a sound, or reaches out his hand to touch an object, deep sensation is used effectively. Therefore, various display devices which represent data using visual, acoustic, and touch sensations together with deep sensation are required. In this study, the following types of display devices were used to generate each sensation. Especially, a wind sensation display prototype was developed and used since existing devices were not effective for our purposes.

2.2 Visual display

A CRT and an HMD (VPL Eyephone) were used as visual display devices⁽⁷⁾. Since the HMD generates

Table 1 Sensations used in this study and physiological classification of human sensations

• Specific Sensation	Vision , Audition , Gustation, Olfaction, Otolithic Sensation
• Somatic Sensation	Touch Sensation (Wind Sensation)
• Cutaneous Sensation	<u>Touch-Pressure Sensation,</u> <u>Warm Sensation, Cold Sensation,</u> <u>Pain Sensation</u>
Deep Sensation	Kinesthesia, Deep Pain
• Visceral Sensation	Organic Sensation, Visceral Pain

○ means the sensation used in this study

3 D graphics using the effects of binocular vision and motion parallax, data can be displayed in three dimensional virtual space⁽⁸⁾. Thus, the user is able to see visual information corresponding to the data value in its actual existing position by moving his head. However, since HMD have a lower resolution compared to CRT, the data which has detailed variation and requires an accurate understanding would be effectively displayed by the CRT. In this study, the CRT and the HMD were used alternately according to the type of experiment.

2.3 Acoustic display

The Convolvotron (Crystal River Engineering) was used for acoustic display⁽⁹⁾. The Convolvotron is a digital signal processor board for the IBM personal computer which synthesizes spatial sound to the user's headphones using head related transfer functions⁽¹⁰⁾. Thus, the user can hear acoustic information corresponding to the data value from the data's actual existing position. For the sound source, a Musical Instrument Digital Interface (MIDI) driven synthesizer, cassette tapes, and compact discs were used depending on the experiments. The numerical data can be represented by the sound relating the displayed data value with the loudness or the sound frequency.

2.4 Wind sensation display

2.4.1 Principle and construction As for touch sensation display used in data sensualization, it is necessary to generate a sensation to touch and feel the numerical data value, and not to feel the geometrical shapes like CAD systems^{(11),(12)}. In this study, a wind sensation display prototype using air flow was developed and used to generate touch sensation⁽¹³⁾. Though wind sensation is not classified physiologically, it is considered to be a kind of touch sensation which compounds touch pressure, warm, and cold sensations in a broad sense. The wind sensation display is capable of creating a sensation which is representative of numerical data values by generating air flow pressure corresponding to the data value

Fig. 2 Structure of wind sensation display prototype

against the palm of the user's hand. Furthermore, since wind has two parameters, magnitude and direction of air flow, scalar data and vector data can be effectively represented through wind sensation.

Figure 2 shows the structure of the wind sensation display prototype. For wind sensation display, the functions of controlling both the magnitude and the direction of the wind output are required. In this display, wind currents are generated by the fans propelled by DC motors. Therefore, the magnitude of the wind is easily controlled by the spinning speeds of the fans. The maximum velocity of wind which can be generated on the wind sensation display is 4.47 m/s. The magnitude of the wind is controlled in 255 steps relating the displayed data value with the pressure of air flow. The spinning speed of each fan is controlled by the voltages applied to the DC motors, which are determined by displayed data values.

The direction of the wind is controlled by the perpendicular and the parallel components to the user's hand. The fans mounted to the right and left of the user's hand generate the perpendicular component of the wind and the fans mounted above and below the user's hand generate the parallel component. The parallel component generators consist of two fans to control the wind sensed by the palm and the back of the hand independently. For example, when the wind blows at a magnitude W , at an angle of direction θ ($0.0 \leq \theta \leq 90.0$), perpendicular and parallel components are calculated as follows:

$$w_1 = W \cos \theta : \text{Perpendicular Component (1)}$$

$$w_{2a} = W \sin \theta : \text{Parallel Component for the Front of the Hand (2)}$$

$$w_{2b} = W \cdot (\theta - 80.0) / (10.0) \quad (80.0 \leq \theta \leq 90.0).$$

$$: \text{Parallel Component for the Back of the Hand (3)}$$

When the angle of wind direction is between 80.0 degrees and 90.0 degrees, the parallel component for

Fig. 3 Mechanism of controlling wind direction

the back of the hand is gradually increased. Thus, the wind flow can change direction smoothly from the front to the back of the user's hand, or vice versa. This mechanism of controlling wind direction is shown in Fig. 3.

The position tracking sensor (a Polhemus 3 SPACE Isotrak) is mounted on the wind sensation display to determine the position and the orientation of the user's hand in three dimensional space. Thus, wind sensations according to the movement of the hand position and orientation can be generated three dimensionally. Though this wind sensation display prototype has only two dimensional expressive abilities along the plane perpendicular to the palm of the user's hand, this device can be used to represent three dimensional vector data by tracking the orientation of the user's hand and also displaying the two dimensional component along the display plane.

2.4.2 Estimation of generated wind sensation

To estimate the ability of generating wind sensation, an experiment to measure the perception of wind direction was conducted. In this experiment, the wind sensation display prototype was used to display wind from various directions in random fashion with a maximum magnitude of 4.47 m/s. The scales are set on the wind sensation display so that they can indicate the angles at five degree intervals. Subjects were asked to orally report the estimated direction of the displayed wind. Two conditions were tested to estimate the effect of free rotation of the user's hand. In the first condition, subjects were asked to hold their hand in a stationary position perpendicular to the floor while holding the wind sensation display prototype. In the second condition, subjects were allowed to rotate their hands freely while wearing the prototype.

Table 2 shows the results of five subjects. When the subject's hands were fixed, there were significant errors in the estimation of the direction. However, when the subjects were permitted to rotate their hands freely, the error decreased significantly. The

Table 2 Error of perceived wind direction by wind sensation display

	Fix Hand		Rotate Hand	
	Average Error	Maximum Error	Average Error	Maximum Error
Subject 1	16.39	90.00	7.50	20.00
Subject 2	19.17	60.00	15.56	40.00
Subject 3	17.78	60.00	14.31	30.00
Subject 4	22.50	90.00	16.25	40.00
Subject 5	20.56	60.00	11.53	30.00
Average	19.28	72.00	13.03	32.00

(degree)

average error was 13.03 degrees in the second condition compared to 19.28 degrees in the first condition. Based on these results, it was concluded that the free rotation of the user's hand allowed subjects to more accurately perceive the direction of the displayed wind currents. Hence, this type of wind sensation display with free rotation of the user's hand would be considered useful for the purpose of scientific data sensualization.

3. Multisensory Scientific Data Sensualization Environment

3.1 System architecture

Multisensory scientific data sensualization environment which included the above-mentioned display apparatuses has been constructed. Figure 4 shows the system architecture, and Fig. 5 shows the overall view in use. The data sensualization environment consists of the visual, acoustic, and wind sensation display subsystems and a tracking subsystem. The host computer is a Silicon Graphics IRIS SkyWriter graphics workstation. An IBM PC personal computer which contains the Convolvotron is also used to localize the virtual sound, and an NEC PC-9801 personal computer is used to control the sound source and the wind sensation display. These personal computers communicate with the host computer through RS 232 C serial interfaces.

The position and orientation of the user's head is tracked by the 3 SPACE Isotrak and is used to control the viewpoint of the graphical images and the sound location relative to the user's head. The user's hand position and orientation are also tracked. They are used to indicate the displayed data and to control the sound source and the wind information.

3.2 Applications of multisensory scientific data sensualization

In the multisensory data sensualization environment, displayed data is mapped onto three dimensional space. The user is able to get into the data

Fig. 4 System architecture of multisensory data sensualization environment

Fig. 5 Overall view of multisensory data sensualization environment

Fig. 6 Application to fluid dynamics data

space physically and recognize the data through the active exploration. In this environment, scalar data and vector data can be displayed. Therefore, this method can be applied to effectively represent scientific data in several engineering fields, such as structural or fluid dynamics.

An example of an application to fluid dynamics data is illustrated in Fig. 6. In this example, as for visual information, velocity data of the water current flowing over the obstacle is displayed via the three

dimensional arrows. The movement of the user's hand is visually displayed as a virtual hand. When the user put his hand into the virtual flow, the user is able to sense the data value at his hand position by means of acoustic and wind sensation information. As for acoustic information, loudness of the sampled sound of the real water flow is controlled according to the magnitude of velocity data. Wind information is represented controlling the magnitude and the direction of the displayed wind corresponding to the vector values of the velocity. Thus, in multisensory data sensualization environment, scientific data is displayed realistically representing data using visual, acoustic, and wind sensations in three dimensional space.

4. Integration of Multisensory Information

Effects on data perception using multisensory data sensualization methods were examined by psychophysical experiments. In particular, the accuracy of the perception of scalar data and vector data were tested.

4.1 Scalar data perception experiment

An experiment on scalar data perception using multisensory information was conducted. In this experiment, data which changes value along a single dimension were displayed to the subjects as shown in Fig. 7. The subjects were asked to draw a line graph of the perceived data while they were perceiving it. The length of the displayed data band was 50 cm in real space. The purpose of this experiment was to measure the improvement in data perception using multisensory information. Seven cases were tested using the following sensation:

1. Visual Sensation (CRT)
2. Acoustic Sensation
3. Wind Sensation
4. Visual+Acoustic Sensation
5. Visual+Wind Sensation
6. Acoustic+Wind Sensation
7. Visual+Acoustic+Wind Sensation

Fig. 7 Experiment on scalar data perception

For visual sensation, the color variations between green to red (using a RGB Color Model) corresponded to data values between 0.0 to 10.0. The data value 0.0 was represented by the color of RGB=(0.0, 1.0, 0.0), and the data value 10.0 was represented by RGB=(1.0, 0.0, 0.0). For acoustic sensation, sound frequency between two octave ranges from 130.81 to 523.25 Hz provided data from 0.0 to 10.0. And for wind sensation, the magnitude of the wind at constant direction perpendicular to the palm was varied from 0.0 to 4.47 m/s on a scale from 0.0 to 10.0.

Three types of data were displayed using the above mentioned methods for five subjects. The types of displayed data were a step line, a notched line, and a curved line. The subjects were given a sample experience for each stimulus which changes value linearly from 0.0 to 10.0 and learned the scaling of each sensation before the experiments. Figure 8 shows these data types and the chart of the average error and the standard deviation for each case and each data type. The error of the perceived data was estimated by the difference between the actual displayed data and the perceived data graph drawn by the subjects. Table 3 shows the average value of the errors for all data types. The numbers in parentheses are ratios of the average error values assuming that the value for Visual Sensation is a standard index of 1.00.

The accuracy of perception depended on the displayed data types. However, looking at the overall averages, we can see the following tendencies. In the cases where two or three sensations were integrated, such as Visual+Acoustic Sensation, Visual+Wind Sensation, Acoustic+Wind Sensation, or Visual+Acoustic+Wind Sensation, the perceived average

Fig. 8 Results of the experiment on scalar data perception

Table 3 Average error in the experiment on scalar data perception

Method of Data Sensualization	Average Error (Ratio)
1. Visual Sensation	0.891 (1.00)
2. Acoustic Sensation	1.197 (1.34)
3. Wind Sensation	0.897 (1.01)
4. Visual + Acoustic Sensation	0.658 (0.74)
5. Visual + Wind Sensation	0.694 (0.78)
6. Acoustic + Wind Sensation	0.686 (0.77)
7. Visual + Acoustic + Wind Sensation	0.600 (0.67)

(Error : 0.0 ~ 10.0)

error was less compared to the cases where each sensation was used alone. From these results, we can consider that multisensory data sensualization methods are very effective through the integration of several human senses. The improvement in accuracy ranged from 22 to 26 percent in the case where two sensations were used, and about 33 percent in the case of three sensations. With respect to the dependence on the displayed data types, the integration of three sensations significantly reduced the error in the case of the step line. However, in the case of the curved line, wind sensations were not so effective.

4.2 Vector data perception experiment

An experiment on vector data perception was conducted. In this experiment, three dimensional vector data were displayed to the subjects as shown in Fig. 9. This data were represented by the following sensations :

1. Visual (CRT) Sensation
2. Visual (CRT) + Wind Sensation
3. Visual (HMD) Sensation
4. Visual (HMD) + Wind Sensation

The visual information for vector data was represented by three dimensional arrows which were shaped in the form of a pyramid. A CRT and an HMD were used as visual display devices to compare each other. Wind sensation was represented by wind flow magnitude and wind direction. In this experiment, wind sensation display was used in combination with visual information due to the fact that the wind sensation display prototype had only a two dimensional expressive ability. The subjects were asked to orally report the estimation of magnitude of the displayed vector data on a scale from 0.0 to 10.0. For the direction of the vector data, the subjects were asked to indicate the direction by adjusting their hands to an orientation where the vector data arrow became normal to the planes of their palms. The orientation of their hands were measured by the 3 SPACE Isotrak sensor mounted on the wind sensation display.

Table 4 Average error in the experiment on vector data perception

Method of Data Sensualization	Magnitude Error (Ratio)	Direction Error (Ratio)
1. Visual (CRT) Sensation	0.78 (1.00)	13.57 (1.00)
2. Visual (CRT) + Wind Sensation	0.76 (0.97)	10.15 (0.75)
3. Visual (HMD) Sensation	0.78 (1.00)	12.16 (1.00)
4. Visual (HMD) + Wind Sensation	0.64 (0.82)	9.97 (0.82)

(Magnitude Error : 0.0 ~ 10.0, Direction Error : degree)

Fig. 9 Experiment on vector data perception

Five subjects were tested, and twenty data vectors with random magnitude and random direction were displayed to each subject for each experiment. The subjects were given a chance to learn the scaling of each sensation through practice sessions using sample data with a maximum magnitude of 10.0 and various directions before the actual experiments. Table 4 shows the average errors in magnitude and direction with respect to the perceived data for each experiment. The numbers in parentheses show the ratios when visual sensation was accompanied by wind sensations for CRT and HMD respectively.

These results showed the following tendencies with respect to the integration of several sensations. For estimation of magnitude, the combination of Visual (HMD) + Wind Sensation significantly reduced the error. Though the HMD has several advantages such as binocular vision and motion parallax compared to the CRT, the correct judgment of the size of the arrows is difficult because the arrow's appearance changes as the user moves while wearing the HMD. Therefore, with respect to the error using visual sensation alone, there was no noticeable difference between Visual (CRT) and Visual (HMD). However, the HMD functioned effectively together with the wind sensation display. In the case of Visual (HMD) + Wind Sensation, the improvement in accuracy with regard to the estimation of the magnitude was 18 percent compared to Visual (HMD) Sensation.

For estimates of direction, the combination of Visual+Wind Sensation significantly decreased the error in both cases of CRT and HMD. The improvements in accuracy were 25 percent for Visual (CRT)+Wind Sensation compared to Visual (CRT) Sensation, and 18 percent for Visual (HMD)+Wind Sensation compared to Visual (HMD) Sensation. With respect to the comparison between CRT and HMD, the HMD had a few advantages over the CRT. These results supports the effectiveness of the multisensory data sensualization methods.

5. Conclusions

In this study, the concept of multisensory scientific data sensualization method was proposed and a data sensualization environment which utilizes visual, acoustic, and touch sensations was developed. In particular, for the purpose of generating touch sensation, a wind sensation display prototype which utilizes air flow pressure was built and used. Multisensory data sensualization methods can be applied to display scientific data in various engineering fields. As an example, an application to fluid dynamics was illustrated. As for the effectiveness of multisensory data sensualization, accurate and efficient transmission of data from the computer to the user are expected. Experiments on scalar data and vector data perception were conducted, and the effectiveness of multisensory integration in perceiving data was shown by the experimental results.

Although this paper evaluated the effectiveness of the simple use of multisensory information, it is necessary to recognize the purpose of displaying scientific data. Future work will include investigating the effective data sensualization methods for different purpose in actual scientific data sensualization.

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