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Authors
Jung, Hwee-Kwon
Park, Gyuhae
Todd, Michael D

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Structural impact detection with vibro-haptic interfaces

Hwee-Kwon Jung[1], **Gyuhae Park**[1] **and Michael D Todd**[2]

[1] School of Mechanical Engineering, Chonnam National University, Gwangju, South Korea
[2] Department of Structural Engineering, University of California San Diego, California, Lajolla, USA

E-mail: zerguringhk@gmail.com, gpark@jnu.ac.kr and mdtodd@ucsd.edu

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Abstract

This paper presents a new sensing paradigm for structural impact detection using vibro-haptic interfaces. The goal of this study is to allow humans to ‘feel’ structural responses (impact, shape changes, and damage) and eventually determine health conditions of a structure. The target applications for this study are aerospace structures, in particular, airplane wings. Both hardware and software components are developed to realize the vibro-haptic-based impact detection system. First, L-shape piezoelectric sensor arrays are deployed to measure the acoustic emission data generated by impacts on a wing. Unique haptic signals are then generated by processing the measured acoustic emission data. These haptic signals are wirelessly transmitted to human arms, and with vibro-haptic interface, human pilots could identify impact location, intensity and possibility of subsequent damage initiation. With the haptic interface, the experimental results demonstrate that human could correctly identify such events, while reducing false indications on structural conditions by capitalizing on human’s classification capability. Several important aspects of this study, including development of haptic interfaces, design of optimal human training strategies, and extension of the haptic capability into structural impact detection are summarized in this paper.

Keywords: structural health monitoring, acoustic emission, piezoelectric transducers, haptic interface, impact detection

(Some figures may appear in colour only in the online journal)

1. Introduction

Structural health monitoring (SHM) is the process of measuring the dynamic response of a system and determining from these data the current state of the system’s ‘health’ in near real time. This process is typically carried out by comparing the dynamic response of an undamaged, baseline structure to that of the current, potentially damaged structure [1, 2].

SHM can improve the safety and increase the service life of many engineered structures. Additionally, SHM works to shift the maintenance of these structures from a time-basis to a condition-basis. By repairing structures on a condition-based schedule, their operating costs and potential for failure will be significantly reduced.

In this paper a novel approach of incorporating haptic interfaces into SHM is developed for applications in aerospace structures. Current paradigms of SHM or structural dynamics research efforts have focused on developing techniques that take little use of human intelligence. In general, statistical pattern recognition is typically employed to autonomously determine the presence of structural damage by comparing a new measurement to baseline data. The statistical pattern recognition SHM paradigm is a multi-step approach consisting of the sequence of operational evaluation, data acquisition and cleansing, feature extraction, and statistical model development [1]. While this methodology has resulted in great improvements in SHM capabilities, this autonomous sensing paradigm usually take little use of human inspectors’ judgment during the monitoring process. However, human classification capabilities often exceed those of contemporary classification algorithms [3], and are capable of better adapting to new situations. Therefore, in this work, we propose the development of a new semi-autonomous SHM paradigm in which novel human–machine interfaces are

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used to leverage the computational precision and humans' adaptability and classification capabilities. Our focus for this study will be impact detection of airplane wings, which may cause important problems during operation.

Impact detection has been a recurrent research topic that attracts many researchers [4–8], especially for composite structures. Composite structures are increasingly used in aerospace applications due to their lightweight characteristics. However, they are vulnerable to impact loads, which is the main source of catastrophic structural failures. Furthermore, due to their anisotropic nature, existing impact detection methods have shown some limitations on impact localization. In order to overcome such limitations, several new methods are also developed [9–14]. It should be pointed out that all of these algorithms are carried out autonomously without human intervention.

It is David *et al* [15, 16], who first proposed the new haptic-based sensing network paradigm for SHM with collaboration of human and computer. They use a haptic glove to transmit haptic-feedbacks, containing damage detection and classification signals, from a four-story structure. After 20 min of training, human could detect damage only using haptic signals. Even though the accuracy of damage detection was lower than that of using optical information, the results indicate that the haptic interface system could improve multitasking capabilities if optimization of human training strategies and design of haptic signals are made. Mingsian *et al* [17] studied localization of impacts on a thin touch panel by using haptic signals. They installed voice coils as actuators to edges of a panel and generated haptic signals using time reverse method. After a few tests, it was demonstrated that human subjects could accurately detect location of an impact occurred at the center of a panel. Haptic vibration for these applications could have some advantages over other senses such as vision and audition. While vision and audition could be completely passive in the sense that they only receive the signals and hence be suitable for receiving structural information from SHM hardware, the haptic vibration could be efficiently used to leverage human's classification capability because these signals are unobtrusively provided to human for training and the classification could be done in an unconscious manner, as described later in this paper.

We believe that haptic interfaces could provide several advantages to the current SHM practice. Many SHM techniques are designed to fit into expectable situations. However, if unforeseen circumstance occurs, human intelligence could actively deal with the new situations and find a solution faster and more accurate, than SHM detection algorithms [18]. Furthermore, human tends to rely on the sense of touch under unconscious conditions, which make this application ideal for human pilots, whose visual and auditory information is overloaded during the flight. In order to capitalize on these characteristics, we designed and implement an impact detection system based on haptic interfaces. It should be emphasized that this work describes a preliminary effort to integrate a sensing networks with a haptic interface. In addition, this work is not intended to replace the current SHM sensing and processing systems with the proposed haptic interfaces. Instead, we believe that the performance of SHM could be enhanced by integrating with the haptic interface for certain applications.

In this study, the target applications considered are unmanned aerial vehicles, unmanned vehicles, and some applications where the operators have only a limited information regarding the structures' conditions. For experiment and demonstration, a wing shape structure was designed and the method of source localization on anisotropic plates proposed by Kundu *et al* [12] was adopted. Haptic signals are then designed and wirelessly transmitted to human arms to provide the necessary information on impact events, locations, and intensity. In order to test the feasibility of this approach, several human subject tests are also performed and the results are summarized in the following sections.

2. Concept of SHM with haptic interface

The impact detection scheme with haptic interface in this study is shown in figure 1. Three key features that will be required to identify for this system are (i) impact detection, (ii) impact location and (iii) impact intensity. Piezoelectric sensors are deployed to measure the high-frequency waves caused by impact events. The measured data are processed by an on-board computer. Unique haptic signals are then generated and wirelessly transmitted to the haptic interface, which is connected to human arms. The haptic motors to provide vibro-haptic stimulation are those typically used in cell phones. They provide vibration in the range of 150 Hz, which is designed to maximize human reception.

In this study, the processes for haptic-based decision making process are divided into two levels; Level 1 and Level 2. Level 1 haptic is defined as that all the necessary signal processing is carried out by a computer and only the result of computation is delivered to human arms via haptic interfaces. In Level 2 haptic, only pre-processed data are delivered using haptic interface, and human will make a decision based on this delivered information. In this study, the impact detection and localization are carried out by Level 1, and result confirmation and impact intensity estimation are done by Level 2. In this approach, human can compare the results of Level 1 and Level 2 and then determine whether computer's result is reliable or not in order to improve the detection capability. These Level 1 amd 2 haptic processes are integrated in this study for efficient impact detection.

The three key features are delivered sequently in steps as shown in figure 2. If the sensors measure the impact events, the data are processed in computer and sent the information on impact detection (step 1, Level 1) and impact location (step 2, Level 1). After this step, pre-processed data based on time-difference-of-arrival, detailed in the next section, (step 2, Level 2) are delivered in order for human to reason where the impact is located. In the final step (step 3, Level 2), the impact intensity is analyzed by humans by comparing the impact intensity to a pre-defined threshold level to find out if subsequent damage could be caused by the impact. In order to realize this concept, a series of experiments and human

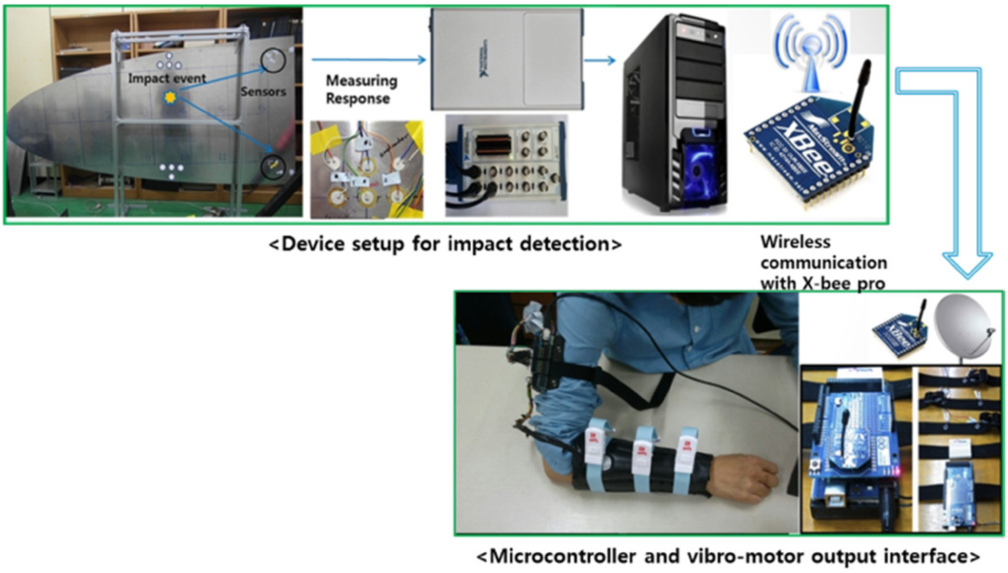


Figure 1. Haptic based impact detection.

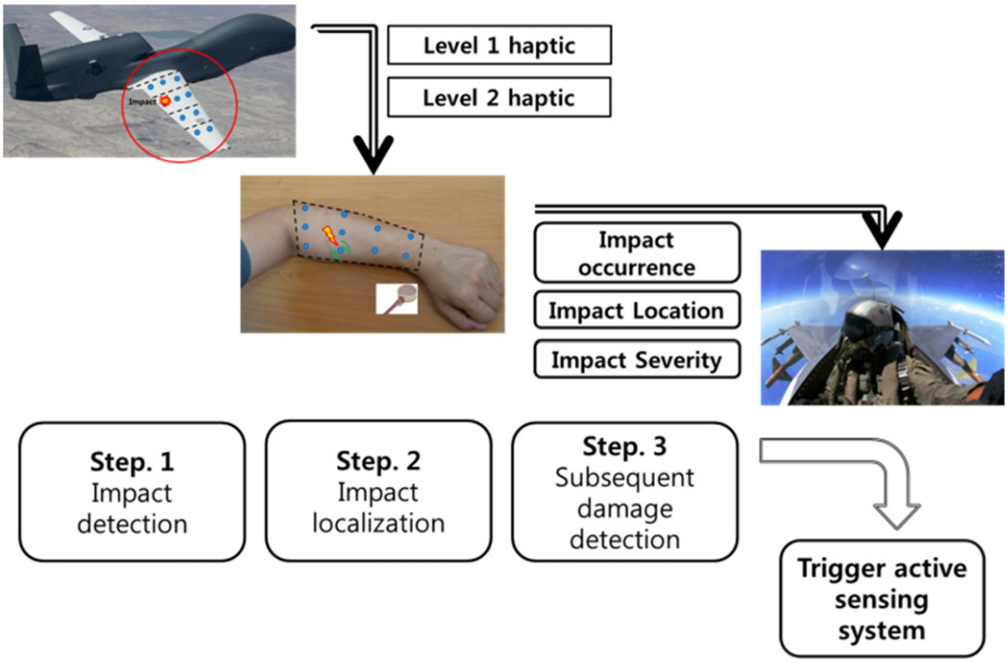


Figure 2. Flow of haptic signals for impact detection.

training were performed and each component, including impact detection using piezoelectric transducers, haptic signals generation for Levels 1 and 2, haptic interface construction, human training, and the results, is outlined in the following sections.

3. Impact detection

3.1. Impact detection

Source localization method developed by Kundu *et al* [12, 13] is used in this study. This method could localize an acoustic source in an anisotropic plate with only six receiving sensors. This method does not require the direction dependent velocity profile in a plate. Three receiving sensors 1–3 are deployed on a plate, as shown in figure 3. The coordinates of three receiving sensors (sensor 1, 2, 3) are defined as (x_1, y_1), (x_2, y_2) and (x_3, y_3). It is clear that $x_2 = x_1 + d$, $x_3 = x_1$, $y_2 = y_1$ and $y_3 = y_1 + d$. The coordinate of the acoustic source is given by (x_A, y_A). The distance d between the sensors is much smaller than the distance of the acoustic source (A) and the sensor cluster (D). Therefore, the inclination angles (θ) of A and sensor 1, A and sensor 2 and A and sensor 3 could be assumed to be

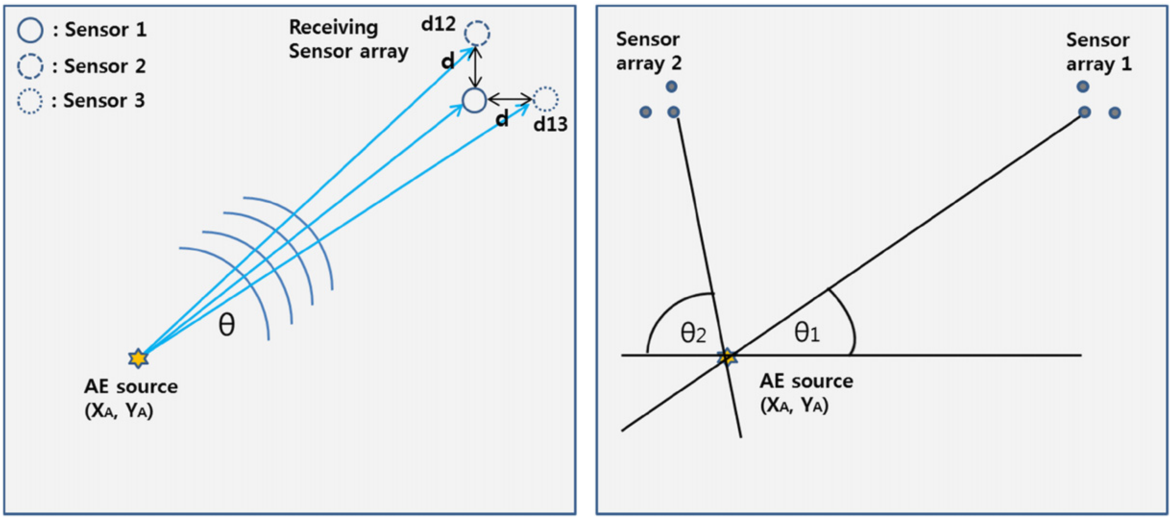


Figure 3. Source localization method using L-shape sensor array.

approximately same, and could be expressed as

$$\theta = \tan^{-1}\left(\frac{X_A}{Y_A}\right) \approx \tan^{-1}\left(\frac{X_A + d}{Y_A}\right) \approx \tan^{-1}\left(\frac{X_A}{Y_A + d}\right). \tag{1}$$

The time-difference-of-arrivals between each sensor are given by

$$\Delta t_{12} = \frac{d\cos(\theta)}{\text{wave speed}_{\text{at }\theta}},\ \Delta t_{13} = \frac{d\sin(\theta)}{\text{wave speed}_{\text{at }\theta}}. \tag{2}$$

From equations (1) and (2), one can easily obtained

$$\theta = \tan^{-1}\left(\frac{\Delta t_{12}}{\Delta t_{13}}\right). \tag{3}$$

From equation (3), the direction of wave propagation could be obtained experimentally only with the measured TDOA between sensors. By deploying another sensor array (sensor array 2) another angle of arrival (θ_2) could be identified using the same procedures, and the intersection point of these lines could be the location of an impact. As described, this method only requires the knowledge of TDOA, one could obtain accurate results even on anisotropic plates or complex shaped structures. The full description of the method could be found in the [12, 13].

3.2. Experimental investigation

Experiments were performed to demonstrate the performance of the source localization method. A wing shape structure, measured 1200 × 2400 mm, was used. Two aluminum plates (4 mm thickness) are jointed together, where inner spars are installed inside, as shown in the figure, in order to introduce non-isotropic characteristics. Two piezoelectric sensor arrays are then installed at the top and the bottom of the structure, as shown in figure 4. The distances between sensors are maintained at 10 mm. Figure 5 shows the entire experimental setup, which consists of the wing shape structure, data acquisition system. NI-6366 is used for data acquisition with the sampling rate of 2 MHz.

When an impact occurs at the lower-left corner (shown in figure 6), the time difference of arrivals of sensor 1 and 2 and 1 and 3 are estimated 4.5 μs and 8.5 μs, respectively, which results in the arrival angle of 31.7°. With the same procedure, the arrival angle at sensor array 2 is estimated as 14.8°. By finding out the intersection point of these two lines, the actual impact location was accurately identified with less than 1% errors. The rest of pictures in figure 7 show the results of impact localization at various locations. As we could see, the method shows overall high accuracy of impact localization with 5% maximum errors at this somehow non-isotropic plates.

4. A vibro-haptic interface

4.1. An arm wearable haptic interface design

A haptic interface aims to capitalize on the human sense of touch to provide information of structural impacts. The haptic interface designed in this study is arm-wearable one, which could provide haptic stimulation to pilots' arm during operation. This haptic interface consists of 12 vibro-motors, which are controlled by an on-board microcontroller and wireless telemetry. As shown in figure 8, twelve vibro-motors are positioned as corresponding to twelve structural sections. These vibro-motors are targeting Pacinian corpuscles in forearms. These corpuscles dominate the response for vibrations in range of 100–1 kHz [19–22]. These motors are typically used for cell phones, vibrating at a fixed frequency of 180 Hz, as shown in figure 9, which is most sensitive to human skin [23]. These motors are installed with at least 4 cm apart for human to distinguish the location of haptic vibration.

Since these motors are only operated as on and off conditions, their frequency and amplitude cannot be directly

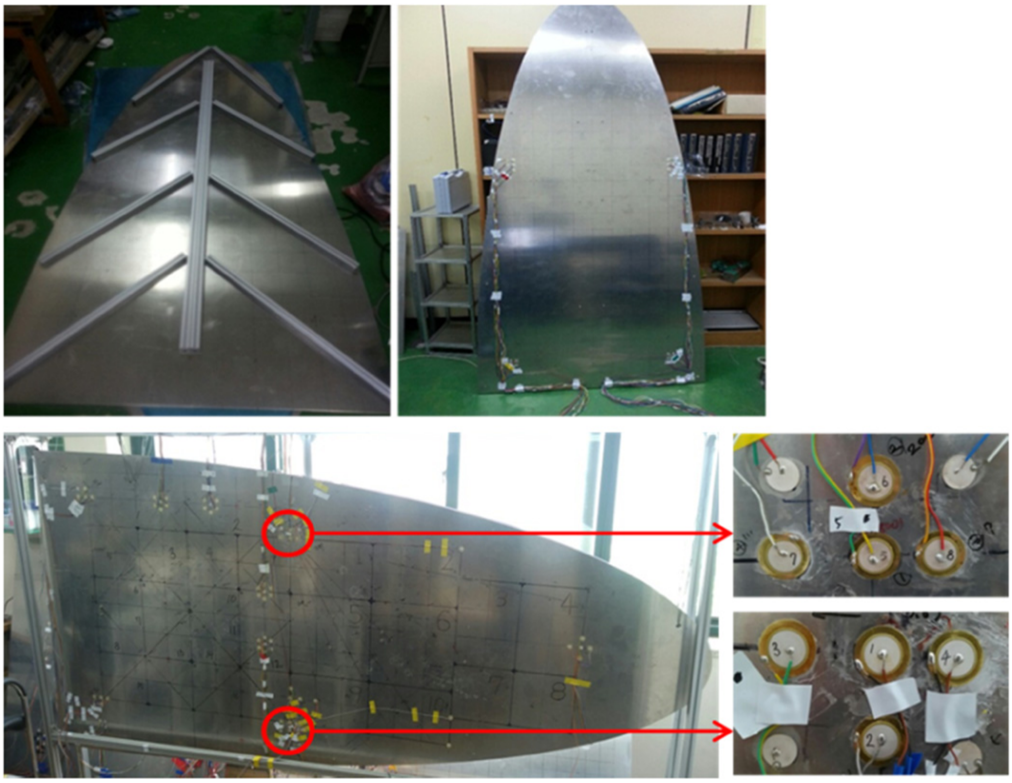


Figure 4. A wing shape structure.

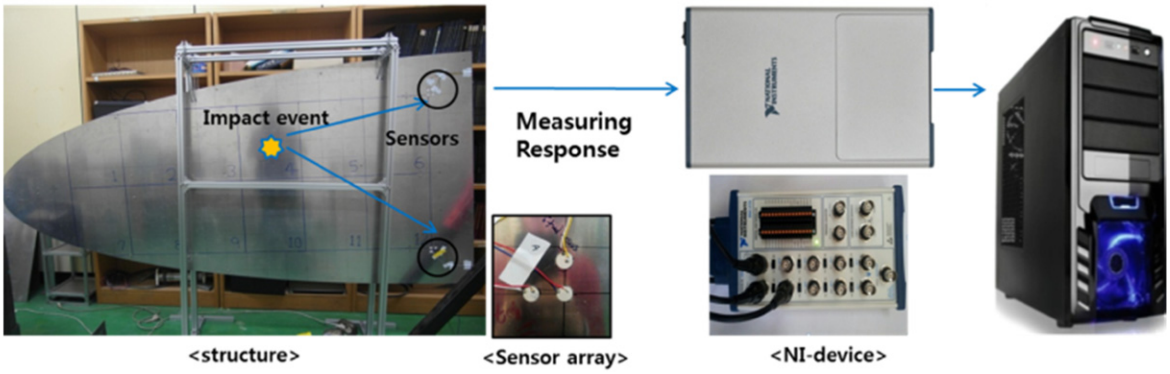


Figure 5. Experiment setup for impact detection on a wing shape structure.

modulated to emulate various waveforms. Therefore, pulse width modulation (PWM) is used. PWM is a modulation scheme whereby complex waveforms can be stimulated in electric motors by adjusting the duty cycle of the motor. Because the period of this PWM scheme is approximately 14 ms, the human subject does not perceive each motor turning on or off. Instead, the length of the pulse transmits a feeling of intensity such that the amplitude and frequency characteristics of the waveform of haptic signals could be simulated. Controlled motors have the intensity range of 0–5 V. A microcontroller (Arduino 2560) was used to control motors individually. After haptic signals are generated from the microcontroller, a pair of X-bee wireless telemetry is used to transmit and receive haptic signals for the arm wearable haptic interface. The X-Bee is chosen because, for this or aerospace applications, it only needs to transmit the data from the controller to the pilot arm usually confined a cockpit area.

4.2. Design of haptic signals

In order to deliver the necessary information on impact occurrence, impact location, detection result validation and impact intensity, haptic signals are generated in the following sequence. Haptic signals are converted into a physical modulation that can be presented to the human nerve system.

(1) Step 1, impact detection (Level 1).
(2) Step 2, impact localization (Level 1).
(3) Step 2, impact localization (Level 2).
(4) Step 3, impact intensity (Level 2).

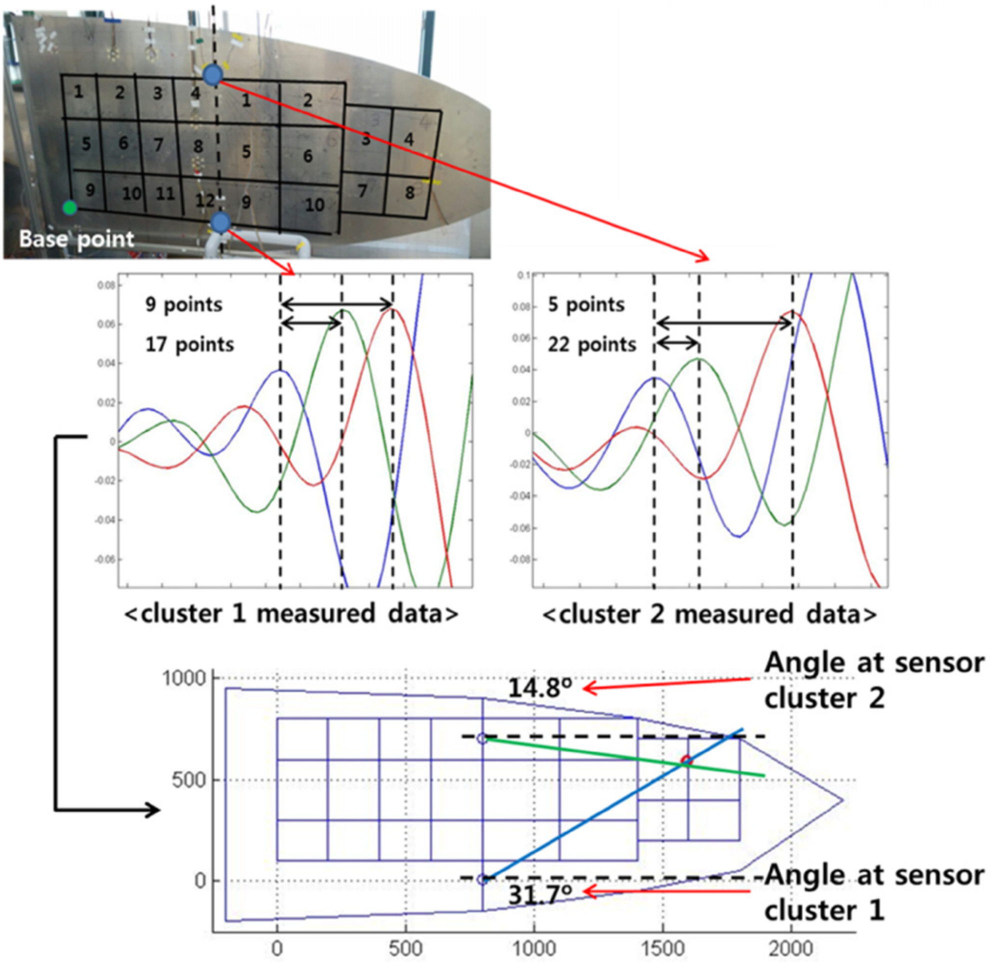


Figure 6. Procedures of impact localization.

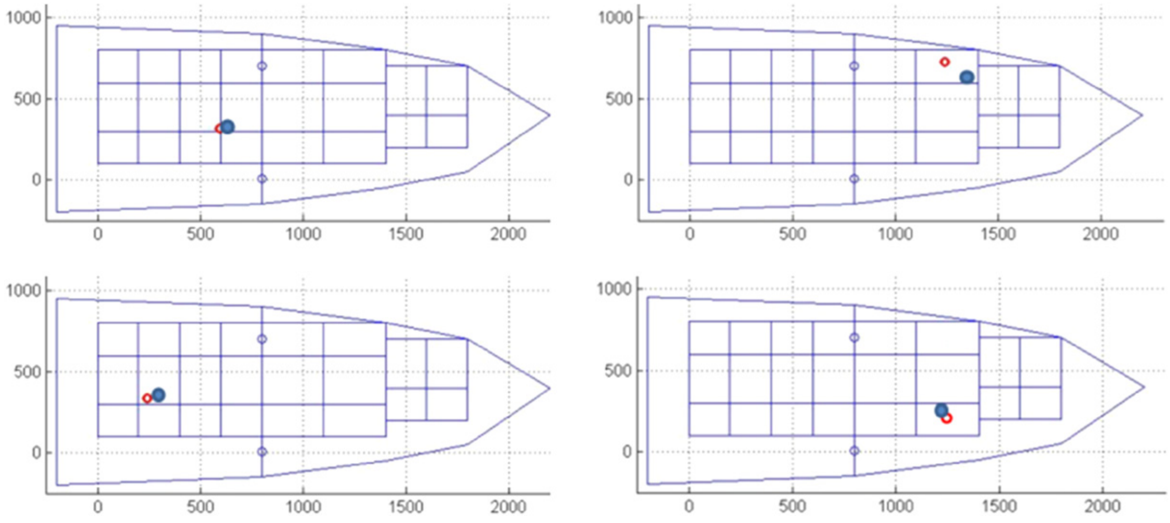


Figure 7. Results of impact detection.

When an impact event occurs, the piezo-sensors measure the high-frequency wave data. After the measurement, a haptic code, which activates haptic motor line-by-line, is generated and delivered to inform human about the event. Then, Level 1 and 2 haptic signals are transmitted for impact localization. First, the haptic motors near the corresponding impact locations are dynamically activated so that human could identify the impact section, as a Level 1 haptic. For instance, if an impact occurs at section 4 in figure 10, then the pair of haptic-motors of 7 and 8 are activated first to indicate

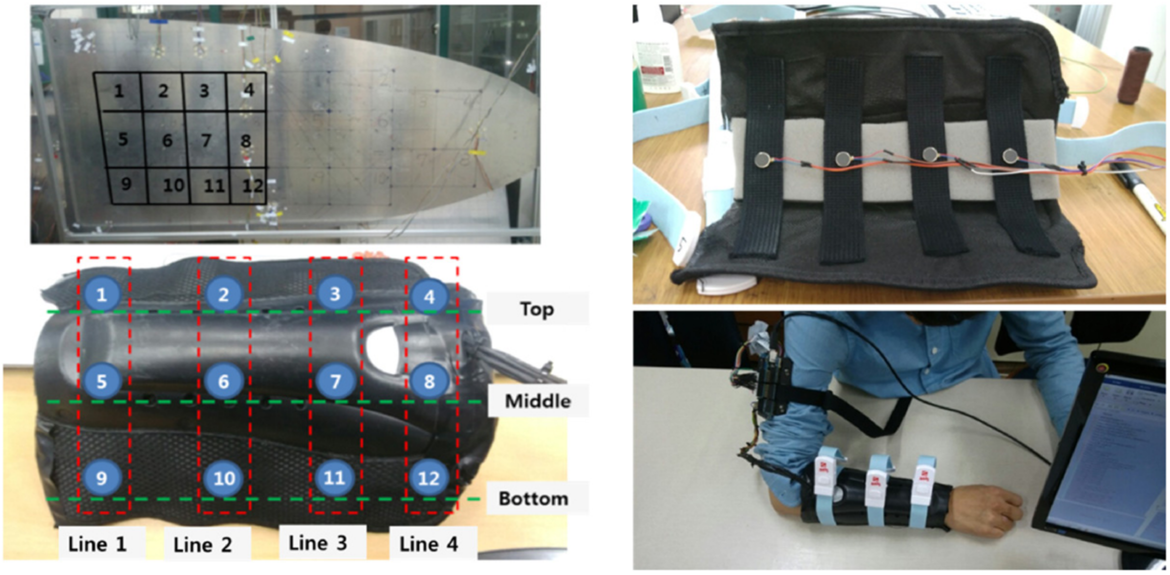


Figure 8. Position of motors on an arm wearable output interface.

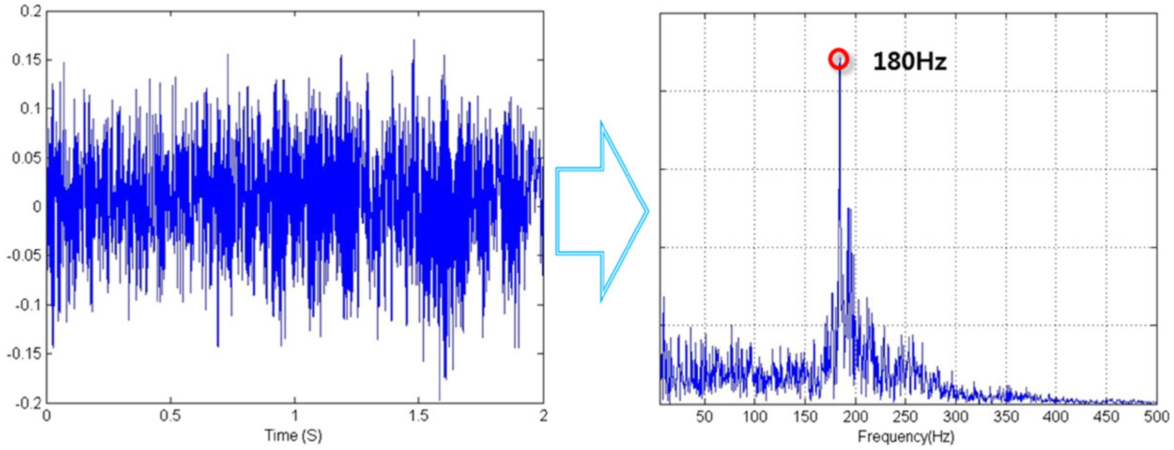


Figure 9. Time and frequency domain representations of haptic actuator's vibration.

the impact occurrence in the right side of the wing, and then the pair of 8 and 4 are activated to inform that the impact occurs at that specific section. If an impact occurs at section 10, then the pair of motors 5 and 6, and then 6 and 10 are activated in sequence. The haptic signals are delivered dynamically, rather than a single motor vibrating at one location because human could more easily identify the location of vibration.

Level 2 haptic for impact localization consists of TDOA between each sensor. The vibro-motors are activated with the time delay proportional to estimated angle of arrival. After this haptic stimulation, human could estimate the angle of arrival from two sensor arrays and reason the actual impact locations, as shown in figure 11. Because Level 1 haptic was delivered earlier, this process could be used for human to confirm (or reject) the information delivered from computer.

As the final step, haptic signals on impact intensity are transmitted. As shown in figure 12, reference (threshold) intensity is first presented and then the current impact intensity is transmitted. With this signal, a user could judge whether this impact intensity is over the pre-defined threshold limit and may take additional actions to estimate if the impact causes any structural damage. It should be pointed out that the impact intensity here does not mean the impact magnitude or impact energy quantification, which may require a more sensing and processing effort. Rather, this step is to check the impact magnitude is higher than a certain threshold limit, where the impact may cause some structural damage. The threshold limit should be carefully selected empirically or with the reference data for actual applications.

It is a well-known fact that human's sense of touch easily gets used to a static stimulation. Also, human skin is not ideal for magnitude calibration. For example, even though the same intensity of vibration is applied to more than two different points of skin, human percepts them as different vibration intensities. Therefore, when generating and transmitting haptic stimulation, all of these signals consist of dynamics signals that several motors are activated in sequence to enhance the accuracy on source localization and magnitude estimation.

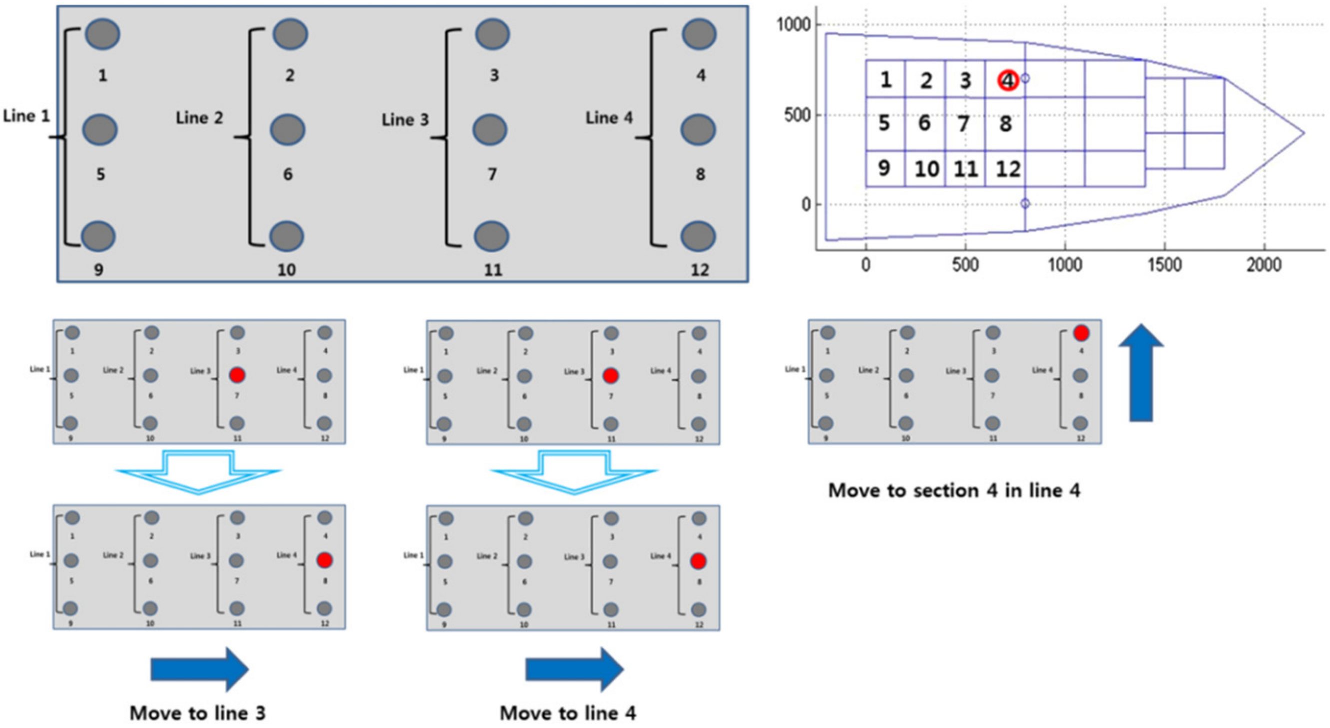


Figure 10. Level 1 signal for impact section.

5. Human training and performance test

5.1. Human training and performance test protocol

In order to test the feasibility of the haptic-based impact detection scheme, several human subject tests were performed. The impacts were given to the wing structure, and the subsequent responses are measured from the piezo-sensor array. These data are stored and used for training. When an impact event occurs, the overall process including data measurements, signal processing for impact localization, haptic signal generation and transmission takes less than 2 s, which allows the proposed process to be implemented in real-time impact detection.

As a first step, a human training procedure was developed. In this study, human subjects who took part in human training and performance test will be called as trainee. The human training and performance test protocol is summarized as follows. Since trainees need to estimate impact locations (section) by using the angles of arrival which is stimulated by haptic motors, they study and memorize the relationship between the section and the pair of angle of arrival, which is summarized in table 1 as a first step. Then individual haptic signal training was implemented for each step. During the training, the haptic signals are also provided visually to enhance the learning process.

Total eight people whose ages range in 23–29 took part in human training and performance test as novice. In addition, three people as expert group were then chosen from the novice group, taking additional training. The test supervisor controls the training and testing from impact detection interface, allowing them to send various impact cases to haptic interface or stop all interface vibrations if necessary. The time needed for training is summarized in figure 13. In average, it takes approximately 39.04 min to complete the entire training process with standard deviation of 7.81. Almost 50% of the training time (19.45 min) is needed to memorize table 1. Therefore, the total training time will be drastically shortened, if the difficulty of this level could be reduced, which will be one of future research works. Once the training process was finished, the performance test was implemented.

5.2. Results

Tests were performed to demonstrate the possibility that human could detect impact events of wing structures by only using haptic interface. The results are summarized in tables 2 and 3. For impact event detection (step 1), there is 100% correct identification.

For step 2 (impact localization, Level 1 haptic) the average correct score was 94%, and, for step 3 (impact localization, Level 2 haptic) the average accuracy was 87.5%. For impact intensity estimation (step 4), all but one trainee gets 100% average accuracy. Because impact intensity signals are very simple and clear, the highest value of accuracy was derived. Haptic signals for impact localization also have relatively straightforward pattern signals. Thus it also has higher than 90% of accuracy. The most difficult part of training and the associated results are for step 3. However, even with relatively lower accuracy, trainees pointed neighboring sections of actual impact locations.

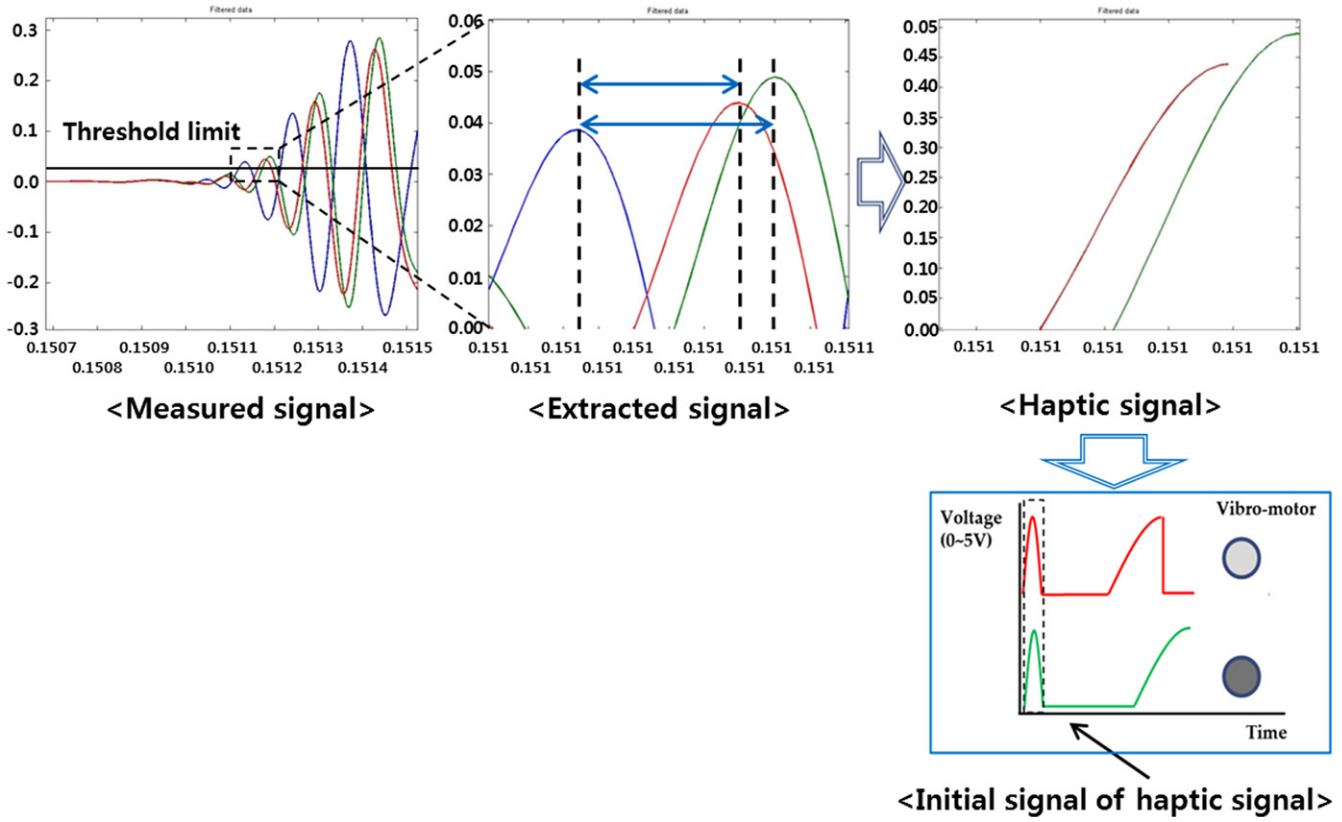


Figure 11. Level 2 signal for impact angle.

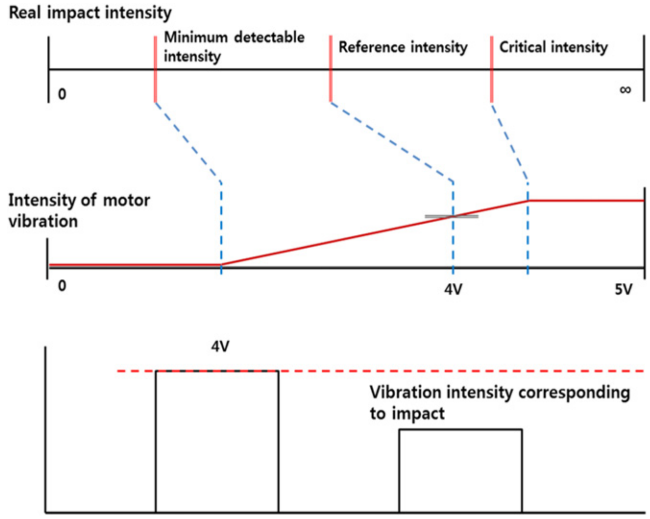


Figure 12. Haptic signal for impact intensity.

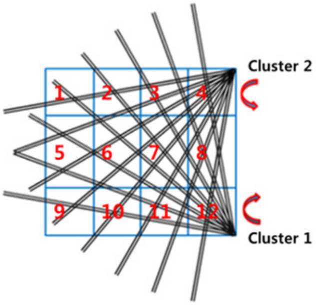
It should also be noted that, there is no clear relationship between the time spent for training and accuracies of the test for each trainee. One trainee spent a short period of time on training and overall accuracy is higher. However there are some trainees who spent a long period time on training but acquired very low accuracy from the tests. For example, trainee 5 and 6 had only 34 and 28.5 min of training but they had the lowest accuracy.

In table 3, novice group and expert group are compared. Training time was decreased by 20%–66%. In addition, there is a substantial increase in accuracy. It could be envisioned that, with increase in training time or process, the overall accuracy could be improved and the impact events could be correctly identified by pilots during the flight operation. Another remarkable result to point out is that, more than few occasions, trainees could notice abnormality of signals by feeling improper haptic signals. Usually these signals are caused by low signal to noise ratio, improper impact excitation, or DAQ failure. An algorithm processes these data without having any cleansing process and leads false indication on structural impact condition. However, by using haptic interface which capitalizes on human's reasoning capacities, this types of false indications on structural condition could be drastically reduced, which could be a clear advantages of the proposed technique

6. Discussion

A haptic interface based impact detection system is described. While the proof-of-concept experiments demonstrate the potential of the proposed technique, there are still more research efforts need to be performed.

Table 1. Angle and section table.



1	2	3	4
(40, 10)	(50, 10), (50, 20)	(60, 10), (60, 20), (60, 30), (70, 10), (70, 20), (70, 30)	(80, 10), (80, 20), (80, 30), (80, 40), (80, 50), (80, 60)
5	6	7	8
(20, 30), (30, 20)	(30, 40), (40, 30)	(40, 50), (40, 60), (50, 40), (50, 50), (50, 60), (60, 40), (60, 50)	(60, 70), (70, 60), (70, 70), (70, 80), (80, 70), (80, 80)
9	10	11	12
(10, 40)	(10, 50), (20, 50)	(10, 60), (20, 60), (30, 60), (10, 70), (20, 70), (30, 70)	(10, 80), (20, 80), (30, 80), (40, 80), (50, 80), (60, 80)

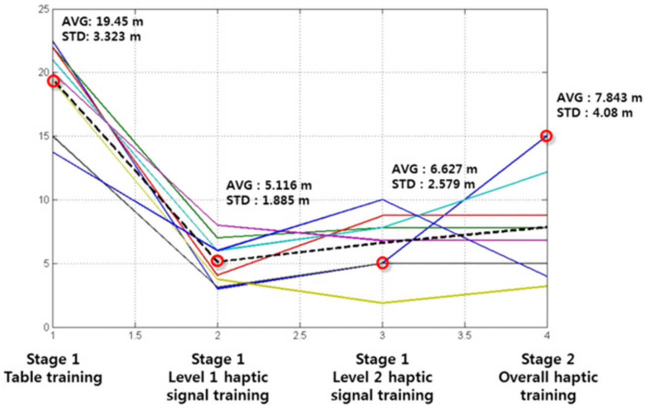


Figure 13. Training time at each step.

Table 2. Average accuracy on each test items of overall signal test.

Trainee number	Impact localization	Result confirmation	Impact intensity
1	93.33%	86.67%	100%
2	96.67%	83.33%	100%
3	96.67%	90%	100%
4	96.67%	86.67%	100%
5	93.33%	73.33%	100%
6	93.33%	100%	93.33%
7	90%	86.67%	100%
8	93.33%	80%	100%

First, one must note that there is high level of uncertainty associated with the sense of touch because it is somehow correlated to the current state of both physical and emotional health conditions. The detection capability of an individual user itself is varied under different physical and environmental conditions. Although pilots belong to a relatively homogeneous group in terms of their specific training, the performance could be different depending on each individual's status. Therefore, a detailed statistical analysis from large data set users is needed to quantify the uncertainties in the proposed study. The trainee data set needs to be significantly increased where the statistical measures could establish the reliability of the proposed method. One possible drawback of the proposed system is that the human training procedure is required to memorize the look up table. The detection performance may significantly depend on this procedure, and further, depend on the structure geometry. In order to overcome this limitation, our future works include the design of a haptic system relying more on human instinct rather than memories, which would require the optimization of human training strategy and the intelligent selection of the section and the pair of angle of arrivals, instead of using those in table 1.

Finally, our study is aim to introduce a new sensing paradigm that a human could feel structural responses (impact, shape change, damage) and human's classification capabilities could be integrated with computers' algorithms for better SHM performance. Yet, this study only presents the impact detection studies. Other parts on shape change and damage detection are being carried out by other research teams. After studies on individual haptic interface systems are conducted, an integrated haptic interface system for various structural responses will be developed to assess the feasibility of the proposed concept.

Table 3. Total training time and performance of expert group.

Trainee number		Total training time	Impact localization	Result confirmation	Subsequent damage assessment
1	Novice	44 min	93.33%	86.67%	100%
	Expert	15 min	100%	95%	100%
2	Novice	28.5 min	96.67%	90%	100%
	Expert	23 min	99%	99%	100%
3	Novice	42 min	93.33%	73.33%	100%
	Expert	34 min	95%	98%	100%

7. Conclusion

In this study, a new sensing paradigm for detecting impacts on structures by using haptic interface is introduced. Distributed sensors, computer's processing algorithms, and human's classification capabilities are integrated using a haptic interface for efficient impact detection. Both software and hardware components are developed, especially focused on applications in aerospace structures. Piezoelectric sensors are deployed in an L-shape for impact localization in a wing shape structure. A haptic interface was designed to generate and transmit haptic signals to human subject. These haptic signals were generated into two levels in order to improve the accuracy and to utilize human's detection capability. After human training, human could detect impact events, location, and intensity only using a haptic interface with relatively good detection rate. Also measurement errors and algorithm failures of sensing systems could be identified by improper haptic signals.

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References

[1] Farrar C R, Doebling S W and Nix D A 2001 Vibration-based structural damage identification *Phil. Trans. R. Soc.: Math. Phys. Eng. Sci.* **359** 131–49

[2] Worden K and Dulie-Barton J M 2004 An overview of intelligent fault detection in systems and structures *Int. J. Struct. Health Monit.* **3** 85–98

[3] Schwamb M E *et al* 2013 Planet hunters: a transiting circumbinary planet in a quadruple star system *Astrophys. J.* **768** 127

[4] Park I, Jun Y and Lee U 2014 Lamb wave mode decomposition for structural health monitoring *Wave Motion* **51** 335–47

[5] Kim J K, Kwon O Y and Kang Y K 2003 A practical method of acoustic emission source location in anisotropic composite laminates *J. Korean Soc. Nondestruct. Test.* **23** 237–45

[6] Kim J K, Kwon O Y and Won Y K 2003 Acoustic emission source location in filament wound CFRP pressure vessel *J. Korean Soc. Nondestruct. Test.* **23** 395–401

[7] Han B H and Yoon D J 2011 Damage detection method of wind turbine blade using acoustic emission signal *J. Korean Soc. Nondestruct. Test.* **31** 68–76

[8] Han B H, Yoon D J, Huh Y H and Lee Y S 2013 Source location on full-scale wind turbine blade using acoustic emission energy based signal mapping method *J. Korean Soc. Nondestruct. Test.* **33** 395–401

[9] Kundu T, Das S and Jata K V 2007 Point of impact prediction in isotropic and anisotropic plates from the acoustic data *J. Acoust. Soc. Am.* **122** 2057–66

[10] Hajzarberbashi T, Kundu T, Martin S A and Jata K V 2008 Locating point of impact in anisotropic fiber reinforced composite plates *Ultrasonics* **48** 193–201

[11] Aljets D, Chong A, Wilcox S and Holford K 2010 Acoustic emission localization in plate-like structures using a closely arranged triangular sensor array *J. Acoust. Emiss.* **28** 85–98

[12] Kundu T, Nakatani H and Takeda N 2012 Acoustic source localization in anisotropic plates *Ultrasonics* **52** 740–6

[13] Kundu T 2012 A new technique for acoustic source localization in an anisotropic plate without knowing its material properties *6th European Workshop on Structural Health Monitoring (Dresden, Germany, 3–6 July)*

[14] Kundu T, Yang X, Nakatani H and Takeda N 2015 A two-step hybrid technique for accurately localizing acoustic source in anisotropic structures without knowing their material properties *Ultrasonics* **56** 271–8

[15] Mascarenas D, Choi Y, Kim H, Pekedis M, Hong S, Lee J and Farrar C R 2013 Development of a novel human–machine interface exploiting sensor substitution for structural health monitoring *The 22nd IEEE Int. Symp. on Robot and Human Interactive Communication (Gyeongju, Korea, 26–29 August)* pp 334–5

[16] Mascarenas D, Plont C, Brown C, Cowel M, Jameson N J, Block J, Djidjev S, Hahn H and Farrar C R 2014 A vibro-haptic human–machine interface for structural health monitoring *Struct. Health Monit.* **13** 671–85

[17] Mingsian R B and Tsai Y K 2010 Impact localization combined with haptic feedback for touch panel applications based on the time-reversal approach *J. Acoust. Soc. Am.* **129** 1297–305

[18] Jones L A and Sarter N B 2008 Tactile displays: guidance for their design and application *Hum. Factors J. Hum. Factors Ergon. Soc.* **50** 90–111

[19] Morioka M and Griffin M J 2005 Thresholds for the perception of hand-transmitted vibration: dependence on contact area and contact location *Somatosensory Motor Res.* **22** 281–97

[20] Hale K S and Stanny K M 2004 Deriving haptic design guidelines from human physiological, psychophysical and neurological foundations *IEEE Comput. Graph. Appl.* **24** 33–9 Haptic Rendering-Beyond Visual Computing

[21] Barghout A, Cha J and Saddikk A E 2009 Spatial resolution of vibrotactile perception on the human forearm when exploiting funneling illusion *IEEE Int. Workshop on Haptic Audio Visual Environments and Games (Lecco, 7–8 November)* pp 19–23

[22] Zadeh M H, Wang D and Kubica E 2008 Perception-based lossy haptic compression considerations for velocity-based interactions *Multimedia Syst.* **13** 275–82

[23] Lee B, Park H and Myung R 2004 JND-based mobile phone optimal vibration frequency *J. Korean Inst. Ind. Eng.* **30** 27–35