Journal of the Korea Academia-Industrial cooperation Society
Vol. 15, No. 11 pp. 6399-6405, 2014

http://dx.doi.org/10.5762/KAIS.2014.15.11.6399
ISSN 1975-4701 / eISSN 2288-4688

# Development of a PVDF sensor for detecting over-load and impact on large-scale mechanical structures

**Dong-Bae Kang[1], Jung-Hwan Ahn[1], Gang-Yeon Kim[2], Seong-Min Son[2*]**
[1]School of Mechanical Engineering, Pusan National University
[2]School of Mechanical Engineering, Ulsan College

# 대형 기계 구조물의 과부하 및 충격 측정을 위한 PVDF 센서 개발

강동배[1], 안중환[1], 김강연[2], 손성민[2*]
[1]부산대학교 기계공학부, [2]울산과학대학교 기계공학부

**Abstract** An external overload or impact is an important factor affecting the safety of large-scale structures. The proposal of this paper is the development of a system for detecting overload and impulse using a single PVDF film sensor. In large-scale structures, the load causes the structure to be deformed and the impulse generates vibration on the structure. Generally, low frequency deformation or bending of a structure is measured with a strain gauge and the high frequency vibration is detected by an accelerometer. On the other hand, a single sensor that can detect both deformation and vibration has not been developed. In this study, the development of a detection system integrated with a polyvinylidene fluoride (PVDF) film sensor, amplifier, and software was attempted to monitor deformation and impact through a single sensor. The system was verified by the possibility of detecting overload and impulse, and the two filtered signals of the PVDF were compared with a conventional strain gauge and an accelerometer.

**요 약** 오늘날 작업능률 및 운용효율의 향상을 위해 장비의 대형화 추세가 진행되고 있으나 이와 더불어 사고 발생 시에는 많은 인명 피해와 함께 크나큰 경제적인 손실을 초래하게 되어 대형장비의 안전성 문제에 대하여 많은 연구가 진행되고 있다. 대형구조물의 안전성 감시를 위해 외부의 부하에 따른 구조물의 변형은 스트레인게이지로, 순간적인 충격에 의한 진동은 가속도 센서를 이용한다. 본 연구에서는 고분자 압전 필름센서인 PVDF(PolyVinyliDene Fluoride)를 이용하여 구조물의 변형에 대한 측정뿐만 아니라 충격에 대해서도 민감하게 반응하여 하나의 센서로 부하와 충격을 모두 검출하여 산업적 효율성과 실효성 향상을 도모하였다. 개발된 센서는 스트레인 게이지의 출력값에 대해 14% 이내의 오차를 나타내고 가속도 센서와는 충격에 대해 동일한 패턴의 충격신호를 나타내었다.

**Key Words :** Impact, Large-scale structure, Structural health monitoring, Over-load, PVDF

## 1. Introduction

Artificial structures such as buildings, airplanes, bridges, construction machinery and other equipments are becoming bigger and larger due to advancing technologies. Since the damage or collapse of those structures may cause a serious loss of life and property, the monitoring on health of large structures is very important. For this reason, many researchers have been studying for various subjects on the structural health monitoring.

Structural health monitoring system is widely applied to the long-span bridges in several countries [1-4]. Damage detection of wind turbine blades was

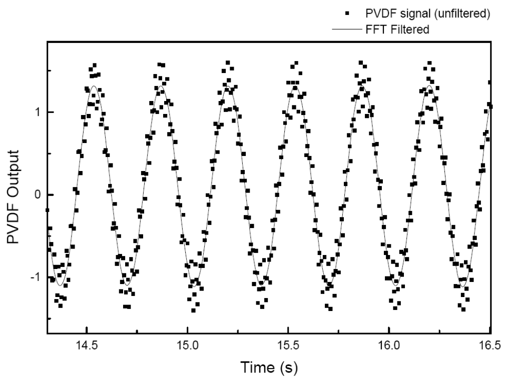
*Corresponding Author : Seong-Min Son(Ulsan College)
Tel: +82-52-279-3104 email: semson@uc.ac.kr
Received October 8, 2013 Revised (1st September 30, 2014, 2nd October 20, 2014) Accepted November 6, 2014

attempted using a piezoelectric patch [5]. The structural health evaluation for 3D surface-cracked structures was also reported [6]. As described above for applications, structural health monitoring is a technology which examines the factors affecting safety of structures such as erosion, crack, deformation, impact, and fatigue caused by external load. Load and impact are the basic factors in the case of structural health monitoring, because physical structures are deformed by external load and vibrated with resonant frequency by impact. Those two factors are usually measured by strain gage and accelerometer. Stain gages adhered to structure measure the stain rate when the structure is deformed by external force and accelerometers detect the acceleration by impact.

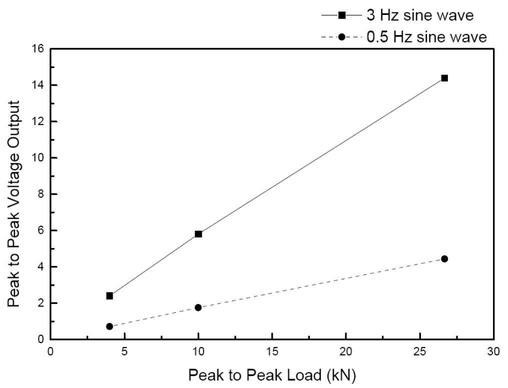
In this study, a PVDF based sensor, which is able to detect deformation and acceleration at the same time, is proposed to monitor the load and impulse on large structures. And the experiments are conducted to evaluate the characteristics of the proposed PVDF sensor by comparing the detection performance for two basic factors.

Polyvinylidene fluoride, which is a kind of fluoropolymer, is generally used in the case of requiring highest purity, strength, and resistance to solvents, acids. Compared to other fluoropolymers, a PVDF has the properties of relatively low density, low cost, a very wide frequency range, and a vast dynamic range. Strong piezoelectricity was observed in PVDF and it is 10 times larger piezoelectric coefficient than other polymers [7]. PVDF film sensors, which have been applied for this study, are piezoelectric element with physical flexibility. Since the sensor can measure not only strain but also acceleration, strain gauge and accelerometer are able to be substituted with one PVDF film sensor.

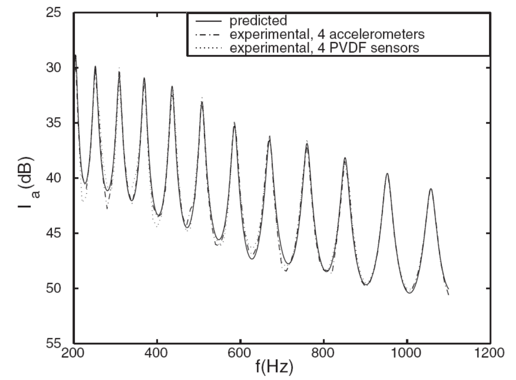
Vodicka and Galea reported the characteristics of PVDF film sensor for detecting damage by applying sinusoidal load [8]. From the Fig. 1, it can be seen that the PVDF film is precisely tracing strains with low frequency. This means PVDF can replace strain gage when detecting the deformations of a constant frequency. However, PVDF film shows the different sensitivities for various frequencies of the deformation due to the property of piezoelectric element as shown in the [Fig. 2].




[Fig. 1] FFT filter applied to PVDF signals




[Fig. 2] PVDF output for input frequency change of load




[Fig. 3] Output comparison for PVDF and accelerometer

On the other hand, Audrain reported that the signal outputs from accelerometer and PVDF are almost same in the cantilever test as shown in Fig. 3 [9]. Other researchers also conducted to detect the damage of structures by applying piezoelectric elements [10-12].

From previous researches, it is clear that PVDF can measure load and impulse at the same time if the sensitivity for various frequencies is calibrated in a low frequency range.

## 2. PVDF sensor design

### 2.1 Sensor circuit design

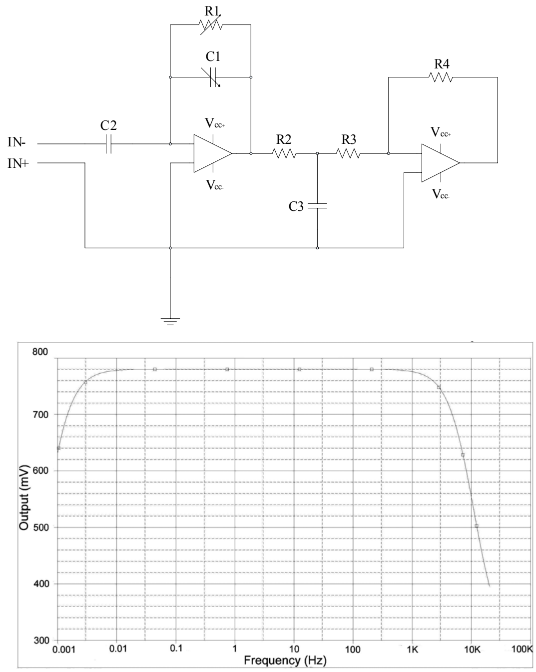
When a piezoelectric element with effective Area $A_p$ and thickness $t_p$ is subjected to in-plane strains, $\varepsilon_x$ and $\varepsilon_y$, the charge developed in the film is given by $Q$. The relation between output voltage ($\overline{V}$) of open circuit and strains is expressed as:

$$\overline{V}(t) = \frac{Q(t)}{C_P} = \frac{t_p}{A_p \varepsilon_{33}} \int_{A_p} (e_{31}\varepsilon_x + e_{32}\varepsilon_y)dxdy = C_x \overline{\varepsilon}_x + C_y \overline{\varepsilon}_y$$

$$C_x = \frac{t_p e_{31}}{\varepsilon_{33}}, C_x = \frac{t_p e_{32}}{\varepsilon_{33}}$$

where $C_x$, $C_y$ are sensor constants, $\varepsilon_{33}$ is permittivity in the thickness direction, $e_{31}$ and $e_{32}$ are the piezoelectric constants, and $\overline{\varepsilon}_x$, $\overline{\varepsilon}_y$ are average strains in $x$ and $y$ direction, respectively[13]. Then the strain of measuring object is able to be calculated from the sensor signal of piezoelectric element by the equation.

Since the equivalent circuit of piezoelectric element with input resistance in an electronic interface has high pass filter characteristics, basic algorithm circuit is not proper to detect the low frequency load. Therefore, an electronic circuit was designed to maintain the sensitivity for a wide range of frequencies. Fig. 4 shows the equivalent circuit of PVDF based sensor with linear response from 0.1 Hz to 1 kHz.

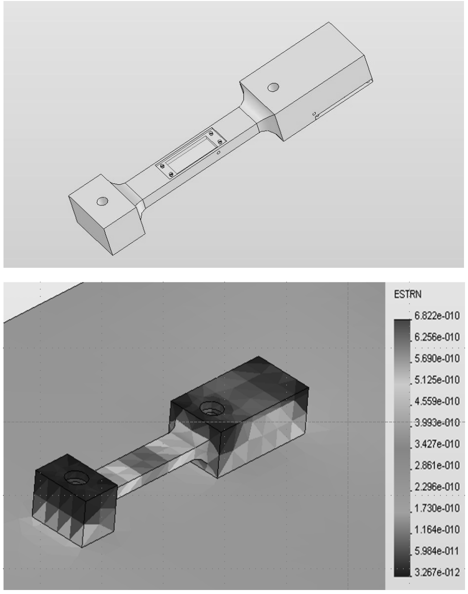



[Fig. 4] Equivalent circuit of PVDF sensor and frequency characteristics

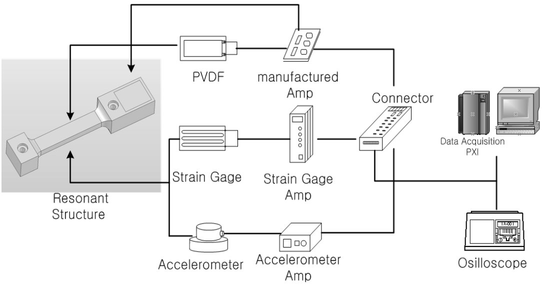
### 2.2 Sensor structure design

In a point of view to measure signal without any interference or distortion, it is ideal that a sensor is directly attached on the surface or inside of a measuring object. But the sensors should be protected from harsh environment for the purpose of guaranteeing the reliable health monitoring in a long-term observation on large structures. Consequently, the PVDF film with an amplifier was embedded in an optimally designed structure.

Fig. 5(a) shows the prepared sensor including a PVDF element and an amplifier. The sensor can be attached to the flat target of monitoring structure without any changing its shape. The deformation in load and the vibration in impact were considered in the design of sensing unit structure. The structure material is aluminum and the strain transmitted from measuring object is concentrated on the area of attached PVDF element as shown in Fig. 5(b).



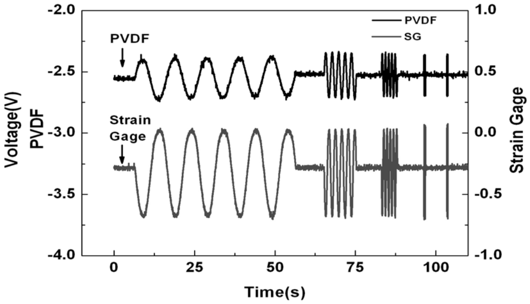

[Fig. 5] Structure of PVDF based sensor



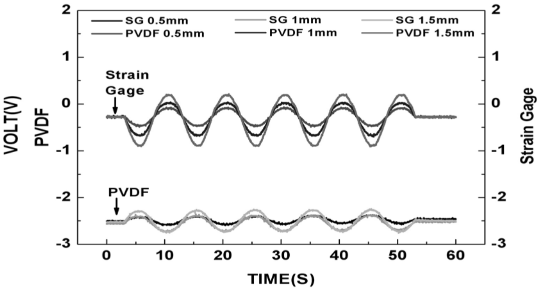

[Fig. 6] Schematic for PVDF sensor evaluation

[Table 1] Relative error for strain frequency

| Frequency (Hz) | 0.1 | 0.5 | 1 | 10 | 15 |
|---|---|---|---|---|---|
| Relative error (%) | 7.1 | 5.8 | 0.1 | 13.6 | 10.5 |




[Fig. 7] Sensor output for various strain frequencies




[Fig. 8] Sensor output for various input level

## 3. Experimental results

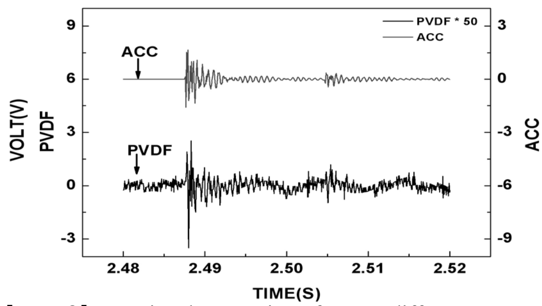
### 3.1 Sensor signal for strain

Experiments were conducted in two ways with the main variables such as strain speed and amplitude under the experimental setup as shown in figure 6. The output signal from PVDF film sensor was compared to the signal from a strain gauge.

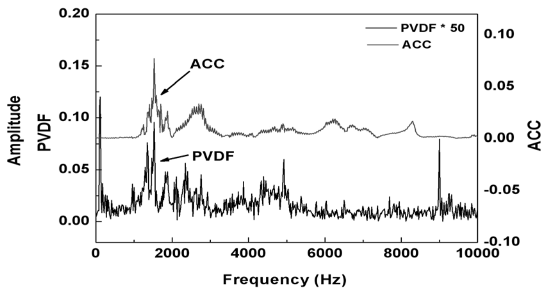
In the experiment for various strain frequencies, sinusoidal input signal, which ranged from 0.1 Hz to 15 Hz, was used as substitute of strain speed. The signal error between a stain gage and a PVDF film sensor was investigated. Fig. 7 and Table 1 show the results. Since the sensors were attached opposite to each other, the sign of signal from the PVDF film sensor was reversed to that from the strain gage. The amplitude of the PVDF signal was 50% for the strain gage signal.

The errors without software calibration for input frequency are quite large due to piezoelectric drift but the output can trace even a slowly changing load of 0.1 Hz.

The frequency was fixed at 1 Hz and the amplitude of input signal was varied from 0.5 to 1.5 mm in the experiments for strain level. Fig. 8 show the results for various amplitudes. The error is decreased down to 2.2% from 5% with increase of amplitude. The PVDF sensor signal has a much lower amplitude than that for the strain gage is caused by the application of resistance and the capacitance for improving low-frequency properties of the sensor.




[Fig. 9] Raw signal comparison for two different sensors



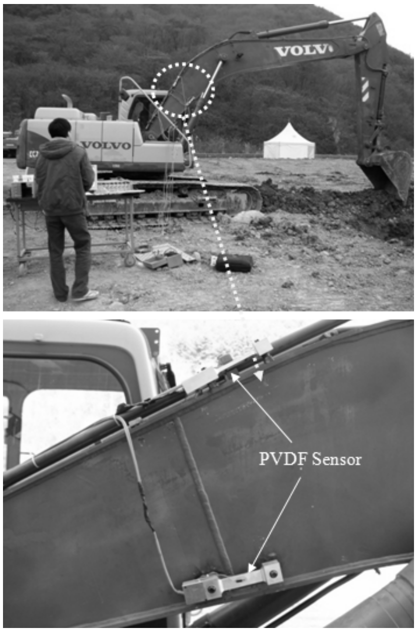

[Fig. 10] FFT results for two different sensors

### 3.2 Sensor signal for impact

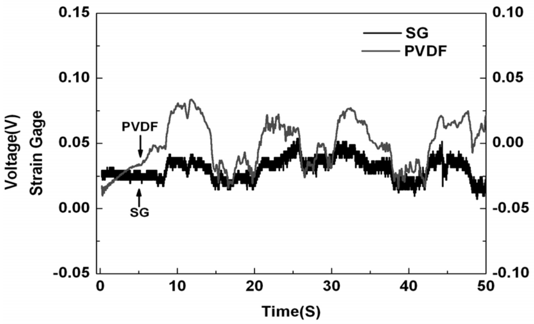
The sensitivity of the PVDF film sensor for impact was investigated by the comparison with accelerometer signal. The accelerometer used in this experiment also consists of piezo materials the same as a PVDF film sensor, but the output signals showed different characteristics in details. The output signal from the PVDF film sensor was so weak as to need amplification. Nevertheless, the main function as a sensor was almost equal to each other as shown in the Fig. 9 and 10. The high amplitudes around 5 kHz and 9 kHz are the resonant frequencies of the sensor structure including the PVDF film and the amplifier.

### 3.3 Application to excavator

The capabilities of the developed PVDF sensor were tested in a large-scale engineering vehicle, which was an excavator of 22,300 kg operating weight. The sensors were attached on the boom as shown in Fig. 11, and an accelerometer and a strain gauge also attached in order to compare each other. Fig. 12 shows the signals from the PVDF sensor and the strain gauge during digging work of the excavator. The boom repeats micro extension and recovery depending on loading-unloading of the bucket. The output signals express well those phenomena, and the signal from the PVDF sensor is very clear as well.

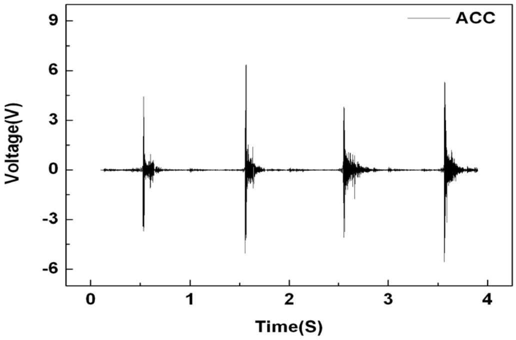



[Fig. 11] Developed PVDF sensors attached on excavator

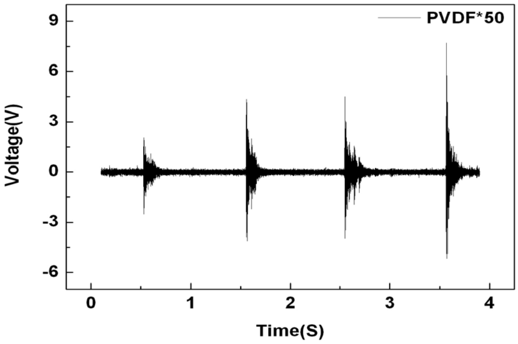



[Fig. 12] PVDF sensor and strain gauge signals at digging work of excavator

The test for an impact was conducted through crushing work, and the acquired signals from the PVDF sensor and the accelerometer are shown in Fig. 13. The figure definitely proves that the developed PVDF sensor is able to substitute for an accelerometer in detection of an impact force.




(a)




(b)

[Fig. 13] Signals at crushing work of excavator (a) By Accelerometer (b) By PVDF sensor

## 4. Conclusions

APVDF based sensor for detecting over-load and impact was proposed. The structure adequate to measure the two factors was designed and the electric circuit able to linearize the raw signals of the PVDF film sensor was designed. In this study, the signals from the PVDF film sensor were compared to those from a strain gage and an accelerometer, and the conclusions are as follows:

1) The PVDF sensor, which can be attached on a large-scale structure for health monitoring, was developed. The sensor includes an amplifier as well as a PVDF film, and the load and impact from measuring object are concentrated on the area of the attached PVDF element.
2) The PVDF sensor nearly traces strain variables, and the error against a strain gage was maintained within 14% in the range of 0.1~15 Hz without software calibration.
3) The PVDF film sensor is substitutable for an accelerometer to detect impulse signal through magnifying signals and removing noise.

## References

[1] J.M. Ko and Y.Q. Ni, Technology developments in structural health monitoring of large-scale bridges, Engineering Structures, Volume 27, Issue 12, October 2005, Pages 1715-1725
DOI: http://dx.doi.org/10.1016/j.engstruct.2005.02.021
[2] Anun Patjawit and Worsak Kanok-Nukulchai , Health monitoring of highway bridges based on a Global Flexibility Index, Engineering Structures, Volume 27, Issue 9, August 2005, Pages 1385-1391
[3] M W Nam, O Y Yang, Y S Lee and M K Oh, Development of Realtime Bridge Safety Monitoring System, Journal of the Korea Academia-Industrial Cooperatin Society, Vol. 11, No. 1, pp. 79-84, 2010
DOI: http://dx.doi.org/10.5762/KAIS.2010.11.1.079
[4] JH Ahn et.al, Development of sensor for over-load and impulse in large structure, Proceeding of KSPE Spring Conference, 2007
[5] Anindya Ghoshal, Mannur J. Sundaresan, Mark J. Schulz, P. Frank Pai, Structural health monitoring techniques for wind turbine blades, Journal of Wind Engineering and Industrial Aerodynamics 85 (2000) 309-324
DOI: http://dx.doi.org/10.1016/S0167-6105(99)00132-4
[6] Joon-Seong Lee, Integrity Evaluation for 3D Cracked Structures(II), Journal of the Korea Academia-Industrial Cooperatin Society, Vol. 14, No. 1, pp. 1- 6, 2013
DOI: http://dx.doi.org/10.5762/KAIS.2013.14.1.1
[7] Kawai, H., The Piezoelectricity of Polyvinylidene Fluoride, Japan. J. Appl. Phys., 8 (1969) 975.

DOI: http://dx.doi.org/10.1143/JJAP.8.975

[8] Vodicka, R., and Galea, S.C., Use of PVDF Strain Sensors for Health Monitoring of Bonded Composite Patches, DSTO Airframes and Engines Division Aeronautical and Maritime Research Lab., Technical Report, 1998.

[9] Audrain, P. et al, The Use of PVDF Strain Sensing in Active Control of Structural Intensity in Beams, Journal of Intelligent Material Systems and Structures, 15(5) (2004) 319-327.
DOI: http://dx.doi.org/10.1177/1045389X04039936

[10] Kim, I.G et al, Impact demage detecting in composite laminates Using PVDF and PZT sensor signals, Journal of Intelligent Material Systems and Structures, 16(11-12) (2005) 1007-1013.
DOI: http://dx.doi.org/10.1177/1045389X05053918

[11] Egusa, S. et al, Piezoelectric paints as one approach to smart structural materials with health-monitoring capabilities, Smart Material and Structures, 7 (1998) 438-445.
DOI: http://dx.doi.org/10.1088/0964-1726/7/4/002

[12] Chiu, W. K. et al, The use of Piezoelectric Thin Film Sensors for Structural Integrity Monitoring, Journal of Intelligent Material Systems and Structures, 5(5) (1994) 683-693.
DOI: http://dx.doi.org/10.1177/1045389X9400500513

[13] In-Gul Kim, Hong-Young Lee and Jin-Won Kim, Impact Damage Detection in Composite Laminates Using PVDF and PZT Sensor Signals, Journal of Intelligent Material Systems and Structures, Vol. 16–November/December 2005 1007-1013

**Dong-Bae Kang** [Regular member]

- Feb. 2003 : Pusan National Univ. MS
- Mar. 2004 ~ current : Pusan National Univ. PhD
- Mar. 2008 ~ current : DMJ Systems, CEO

<Research Interests>
Control Engineering, Automation

**Jung-Hwan Ahn** [Regular member]

- Feb. 1997 : KAIST, MS
- Feb. 1998 : University of Tokyo. PhD
- Mar. 1980 ~ Current : Pusan National University, Professor

<Research Interests>
Manufacturing Engineering, Monitoring/Diagnosis

**Gang-Yeon Kim** [Regular member]

- Aug. 2002 : Gwangju Institute of Science and Technology, Dept. of Mechatronics, MS
- Feb. 2011 : Gwangju Institute of Science and Technology, Dep. of Mechatronics, PhD
- Jan. 2011 ~ Aug. 2011 : LG Electronics Inc., Inspection & control system Dept., Senior Research Engineer
- Sep. 2011 ~ current : Ulsan College, Assist. Professor

<Research Interests>
Machine Vision, CAD/CAM, System Operating S/W Development

**Seong-Min Son** [Regular member]

- Feb. 1999 : Pusan National Univ. MS
- Feb. 2004 : Pusan National Univ. PhD
- Nov. 2004 ~ Feb. 2007 : National Univ. of Singapore Research Fellow
- Mar. 2008 ~ current : Ulsan College, Associate Professor

<Research Interests>
Micro/Non-conventional Machining, Manufacturing