Fine Feature Sensing and Restoration by Tactile Examination of PVDF Sensor

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Abstract: An important signal processing problem in PVDF sensor is the restoration of surface information from electric sensing signals. The objectives of this research are to design a new texture sensing system and to develop a new signal processing algorithm for signals from the sensor to be tangibly displayed by tangible interface systems. The texture sensing system is designed to get surface information with high resolution and dynamic range. First, a PVDF sensor is made of piezoelectric polymer (polyvinylidene fluoride) strips molded in a silicon rubber and attached in a rigid cylinder body. The sensor is mounted to a scanning system for dynamic sensing. Secondly, a new signal processing algorithm is developed to restore surface information. The algorithm consists of the two-dimensional modeling of the sensor using an identification method and inverse filtering from sensing signals into estimated surface information. Finally the two-dimensional surface information can be experimentally reconstructed from sensing signals using the developed signal processing algorithm.

Keywords: PVDF, tactile sensor, signal processing, texture, restoration, inverse filtering

1. INTRODUCTION

Recently, cyberspace enables computer users to do the Internet shopping or communication at home and also to obtain entertainment and educational information. But it is possible to experience just visual environments in the cyberspace which does not give sufficient information such as tactile feeling, taste, and smell. That is, the cyberspace has been limited in reflecting our physical environments because of the lack of tangibility such as tactile, tasty, and smelling sensibility. Thereby a new project called TSI (tangible space initiative) has been launched by the KIST (Korea institute of science and technology) to overcome the problem of the cyberspace and to explore a new digital life society [1]. The tangible space has a different concept from the visual cyberspace in that it introduces tangible agent (TA). The tangible agent transfers real world information to computer environment. The real world information includes video, texture, sound, and smell which cannot be experienced due to time and space limits. Also it goes directly to some place and does tasks on behalf of human. For the TA, there are technologies such as mobile robot manipulation, real-time stereoscopic video, and tactile sensing technologies. With the TA, a key technology for the implementation of digital life is TI (tangible interface) which gives human various feelings and information. These two technologies are organically coupled with the cyberspace and build the tangible space. For example, in the tangible space, it is possible for computer users at home to see, smell, touch, and select apples in a remote market or to feel the texture of fabric in a clothing shop and buy it.

For the TA to gather the information of physical objects tangibly, previous tactile sensing technologies such as the measurement of contact normal force and frictional force and the identification of contact position have limitations due to low sensing resolution and the lack of information such as varying frictional coefficient, roughness, damping property, and compliance. For this reason, the development of a texture sensor to obtain much information with very high resolution is necessary. In this research, texture is defined as physical property containing friction, roughness, damping property, compliance related to pressure. As a starting point of our research, we develop a texture sensor using PVDF (polyvinylidene fluoride) piezoelectric polymer strips to extract varying friction coefficient by scanning the surface of objects. The sensor has advantages such as flexibility, long durability, high force resolution, and high dynamic range. In previous studies on texture sensing except for tactile sensing researches, Kawabata developed the commercialized Kawabata evaluation system for the standardization of fabric [2]. Shinoda et. al proposed a texture sensor using pneumatic pressure and phase shift of microphone has been developed [3]. Howe and Cutkosky have proposed dynamic texture sensing using PVDF strips [4, 5], but only one-dimensional restoration algorithm for texture sensing is developed. Thus the development of a two-dimensional inversion algorithm is needed. Park et. al have developed texture sensing system to sense roughness and compliance using non-contact laser and a force torque sensor [8]. There is an important signal processing problem in sensing by using PVDF sensors, that is, the restoration problem of surface information from the electric sensing signals because the PVDF strips are located inside of silicon skin and because the contact is not a point but area [4, 6, 7].

The objectives of this research are to design a new texture sensing system and to develop a new signal processing algorithm appropriate for the sensor signals to be registered in an object modeler in cyberspace and to be tangibly displayed by tangible interface systems (for example, haptic devices) as shown in Fig. 1. The texture sensing system is designed to get surface information with high resolution and wide dynamic range. First, a texture sensor is made of piezoelectric polymer (polyvinylidene fluoride) strips molded in a silicon rubber and attached in a rigid cylindrical body. The sensor is fixed to a scanning mechanism for dynamic sensing which implies that the sensor moves on the surface of objects. Second, a new signal processing algorithm for the restoration of surface information is developed. The algorithm consists of two-dimensional modeling of the sensor using an identification method and inverse filtering that changes sensed signals into estimated surface information. Finally the two-dimensional surface information can be obtained on-line by using the developed signal processing algorithm.

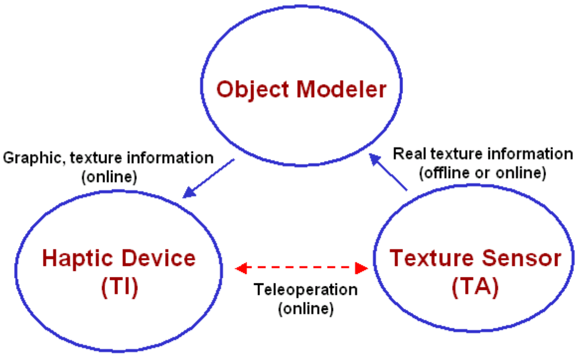


Fig. 1 Connection diagram with other technologies of a proposed texture sensor in the tangible space.

2. BACKGROUND

2.1 Advantages of sensors using PVDF

Sensor using PVDF polymer is a kind of tactile sensor, which contacts to the surface of objects and obtains the information about the objects. The operation of the sensor is similar to the movement of human hand when sensing surface of an object. Also silicon rubber wrapping the PVDF polymer strips is also similar to human outer skin. Thus the information obtained from the sensor is very appropriate to give naturally touch feeling to human. Also the sensor generates sensitive signals in spite of small changes of test surface and thus can detect fine surface features with high-resolution. While computer vision sensors give the global information of surface, the PVDF sensors can give local and detailed information and also physical properties such as friction, roughness, damping property, and compliance related to stress. The sensing performance is independent of changes of test material brightness unlike computer vision sensors and has advantages such as wide dynamic range, durability, and no use of external voltage source [7]. For example, PVDF sensors can be used as an off-line texture registration device for fabric, furniture, or apples like commercial barcode scanners in shopping malls and they can be attached to the finger of robot hand to touch and sense in real-time the surface of products in this case the robot agent goes to the place where the products are located.

2.2 Definition of impulse response in elastic materials and a measuring method using PVDF sensor

In this subsection, a simplified definition of impulse response in elastic materials is explained with Figs. 2 and 3 for easy understanding, which is restricted to the case of impulse response of z stress due to a normal impulse force in the z direction under the plain strain condition as in [4]. Figure 2 shows an elastic material when a normal impulse force $\delta(x)$ in the z direction is applied. Assuming that the horizontal position is fixed at z_0, the sequential stresses $\sigma(x_1,z_0)$, $\sigma(x_2,z_0)$, $\sigma(x_3,z_0)$ measured at the points x_1,x_2,x_3 are impulse responses at the points. If impulse responses for all x are gathered, they become the impulse response $\sigma(x,z_0)$ of the elastic material. By the way if we want to measure the responses, many sensors are required at the each position, which is impractical. Thus an approximate measuring method of the impulse response using PVDF sensor as shown in Fig. 3 can be used. When sequential impulse forces are applied to the material at the points x_1,x_2,x_3, sequential signals measured in a PVDF strip located at the point $(x=0, z=z_0)$ are approximately the same values as the rate of the stresses measured in Fig. 2 because the relative distances denoted by arrows are approximately the same as the length of arrows on Fig. 2 (Note that the elastic materials in Figs. 2 and 3 can be flattened on the x axis by pressing action). If responses for all x are gathered, they become the approximate impulse response $m_1(x)$ of the elastic material.

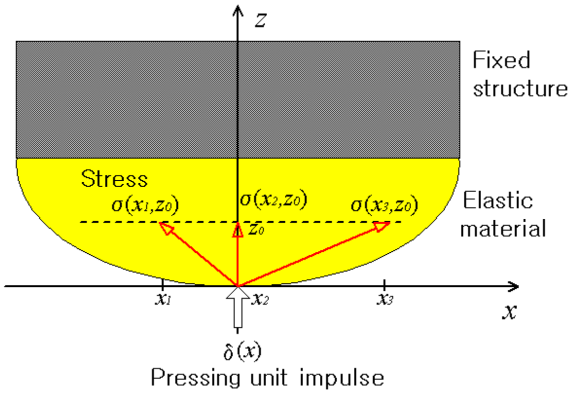


Fig. 2 An elastic material when a normal impulse force in the z direction is applied.

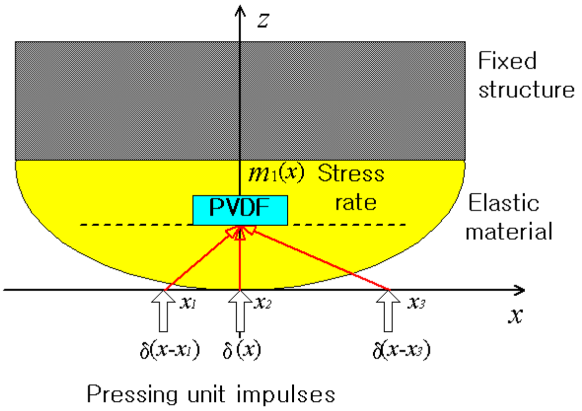


Fig. 3 A measuring method of the impulse response in an elastic material using PVDF sensor.

2.3 Theoretical modeling of elastic material and problems in PVDF sensors

PVDF sensors have complicated interaction between the sensor and surface, which makes analysis difficult. There are two different components on surface forces: a normal direction component in the z direction perpendicular to the surface, denoted f_z; and a shear component in the x direction parallel to the surface, denoted f_x. The theoretical relation between the sensor voltage and surface impulse force is represented by the following impulse response equation [4]:

$$v(x) = A_r R_f u\left(\frac{-2}{\pi z_0}\right)\frac{d}{dx}\left\{\left(k_3+\frac{k_2}{2}\right)\frac{1+\mu(x/z_0)}{\left[1+(x/z_0)^2\right]^2} + \left(k_1+\frac{k_2}{2}\right)\frac{(x/z_0)^2+\mu(x/z_0)^3}{\left[1+(x/z_0)^2\right]^2}\right\} \quad (1)$$

where v is the output voltage, A_r is the film strip area,

R_f is the OP amp feedback resistance, u is the sliding motion velocity, z_0 is the depth where the sensor is located, k_1, k_2, k_3 are the piezoelectric constants, μ is the dynamic coefficient of friction, and x is the relative position from a point where the impulse is applied to an interesting sensing point. Because of the derivative in this expression it is more convenient to work with the integral of the impulse response. The signal $v(x)$ corresponds to the stress rate applied to the PVDF polymer. Because of inherent derivative property of PVDF sensor, output signal decays to zero for constant load. Thus a circuit for integration is needed to measure the load value in steady state.

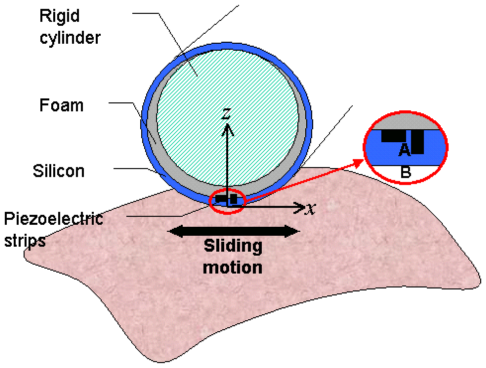


Fig. 4 Cross sectional view of a sensor module and the scanning motion.

Table. 1. Design specifications of proposed sensing system

Spatial resolution	Force resolution	Dynamic range	Hysteresis
1-10micron	1gf	4000:1	negligible hysteresis
Monotonicity	Durability	A/D sampling rate	A/D resolution
linear	compliant& durable	10KHz	12 bits
Range of scan velocity	Range of tension for fabric	Dimension of test object	Scanning distance
10mm/s-100mm/s	20-100gf	200mm*200mm	100mm
Dimension of sensor module	Contact load		
50mm long 25mm radius	50gf-2Kgf		

3. PROBLEM FORMULATION

3.1 Objectives of this research

In this research, a PVDF sensor module similar to one developed in [4] as shown in Fig. 4 is used to obtain two line forces and varying coefficient of friction according to movement on the surface of objects. The sensor module is made of rigid cylinder wrapped with foam and silicon rubber in that piezoelectric strips are molded. To obtain the texture information, a new scanning system and a novel two-dimensional restoration algorithm are developed. The restoration problem is to transform from stress rate signals of the PVDF strips at the location A into two estimated surface line forces (f_x, f_z) at the location B. We extract only the two line forces and varying coefficient of friction in the several physical properties representing texture as a starting point. Note that the proposed algorithm is not based on theoretical modeling but on experimental data which reflect correlated noise. Thus it does not need parameters of PVDF strips and electric circuit, and can outperform the algorithm based on the theoretical modeling in [4].

3.2 Design specifications

We set design specifications of proposed sensing system as shown in Table 1, which satisfy the guideline for tactile sensors in [6]. The scanning system and restoration algorithm are developed to satisfy the specifications.

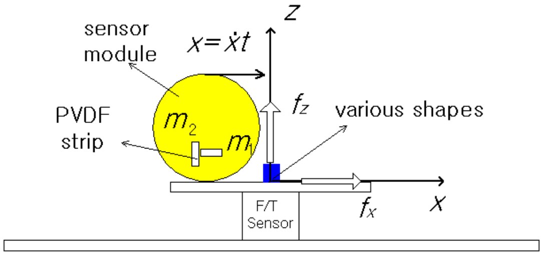
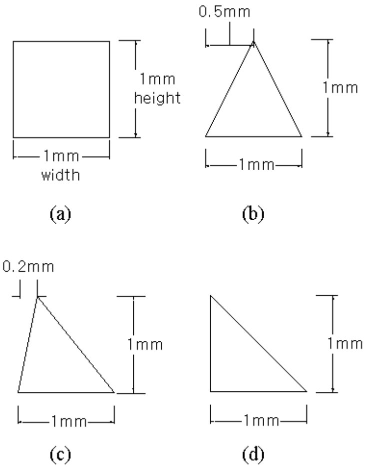


Fig. 5 A new test system to obtain impulse response matrix.



(a) (b)

(c) (d)

Fig. 6 Cross sectional view of raised metal edge examples.

4. RESTORATION ALGORITHM

4.1 Measurement of impulse responses and transfer function matrix

In this section, we design a new test system to obtain impulse responses and transfer function matrix as shown in Fig. 5. The transfer function matrix $G(z)$ can be obtained by the following equation and some mathematical derivation

$$M(z) = G(z)F(z) \tag{2}$$

where $M(z)$ is the Z-transformed result of measured voltage signals $m_1(x), m_2(x)$ from the PVDF sensors, $F(z)$ is the

Z-transformed result of force signals $f_x(x), f_z(x)$ measured by a force/torque sensor with high resolution,

$$M(z)=\begin{bmatrix} M_1(z) \\ M_2(z) \end{bmatrix}, G(z)=\begin{bmatrix} G_{11}(z) & G_{12}(z) \\ G_{21}(z) & G_{22}(z) \end{bmatrix}, F(z)=\begin{bmatrix} F_x(z) \\ F_z(z) \end{bmatrix}.$$

Note that though the force signals (f_x, f_z) are measured for experimental modeling in this step, they must be estimated by a proposed signal processing algorithm in restoration step without the force/torque sensor. Mathematically, at least two independent impulse vectors (f_x, f_z) are required to obtain four elements of the transfer function matrix. For example, through twice scanning results using raised metal edges shown in Fig. 6, two independent vectors can be generated as:

$$F(z)=\begin{bmatrix} F_x \\ F_z \end{bmatrix}=\begin{bmatrix} 0.6 \\ 0.9 \end{bmatrix}, \begin{bmatrix} 0.2 \\ 1.0 \end{bmatrix}, \qquad (3)$$

which imply two coefficients of friction.

4.2 Two-dimensional inversion algorithm

In this subsection, a novel two-dimensional inversion algorithm is proposed, which transforms measured sensor signals into surface force signals. Once we have obtained the transfer function matrix in the previous section, surface force signals can be estimated by using a multi-channel inversion algorithm for room acoustics applications [9-13] which can give an inverse filter for the sensor. Let $\hat{F}(z)$ denote Z-transform of the estimated surface force signal. The inverse filter gives the following relation:

$$\hat{F}(z)=H(z)M(z)=H(z)G(z)F(z)\ . \qquad (3)$$

We want to find an inverse filter $H(z)$ so that $\hat{F}(z)$ be as similar as possible to $F(z)$. Figure 7 shows the diagram of the inversion process.

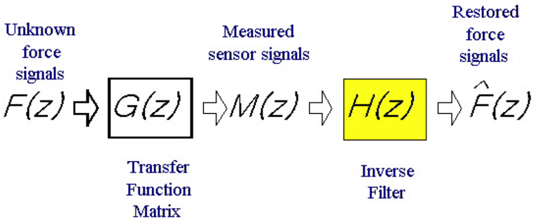


Fig. 7 Diagram to explain the inversion process.

Merely inverting the samples of the FFT (fast Fourier transform) matrix G yields a poor estimate of H because of singularities related to the non-minimum phase character of G. A better estimate can be computed by the regularized inversion formula [9, 11, 12], in which a small constant β is added to each eigenvalue of G before inversion:

$$H=(G^{*}G+\beta I)^{-1}G^{*}, \qquad (4)$$

where G^{*} is the Hermitian of G. The inverse transfer function H can be computed by sampling the spectrum of G using FFT and inverting matrix at each frequency.

5. EXPERIMENTS

5.1 Design of PVDF sensor module

Figure 8 shows a fabrication process of the PVDF sensor film in detail, which is similar to that in [14]. As a raw material, polyvinylidene fluoride pallets (supplied by Shine-Tsu Chemical Co. Ltd.) are used and they are prepared by using hot-press. In the hot-press process, the PVDF pallets are pressed with a high pressure for 1-2 minutes between two pieces of polymide film at high temperature. Quenching out the press before the films are removed from polymide films follows those samples. To perform the poling treatment of the films, aluminium electrodes are attached to both sides of the PVDF film and the electric field is applied by using a high-voltage power supply. It is carried out without changing the process temperatures. We fabricate several films while varying the poling voltages and optimal processing conditions are determined according to the experimental data. After polling the films had piezoelectric properties. Also, silver electrodes are made by silk-screen technique with silver on both sides of the film according to the desired electrode pattern. Finally, the silicon rubber is coated on the both sides of the films to prevent the damage externally. Figure 9 represents the picture of a developed sensor module with two PVDF strips, which is attached to cylindrical rigid rod as Fig. 4. An electrical differential amplifying circuit similar to one in [15] is connected to the electrode of the PVDF sensor module, which amplifies signals from the sensor module and rejects common mode noise.

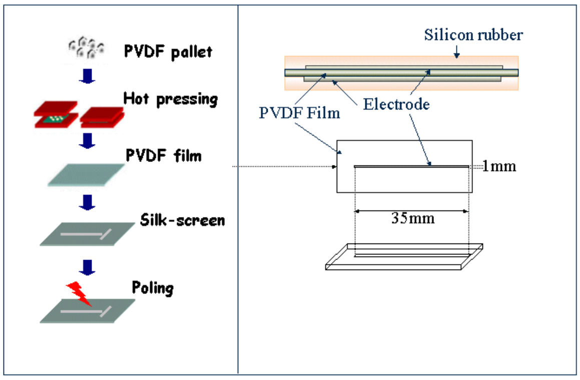


Fig. 8 Process to fabricate PVDF film strip into silicon rubber.

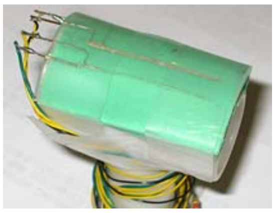


Fig. 9 PVDF sensor module.

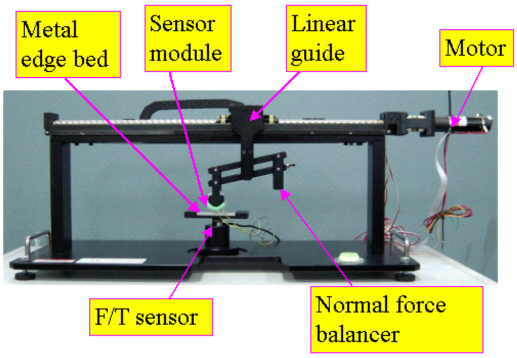


Fig. 10 Scanning mechanism for measuring impulse responses.

5.2 Measurement of impulse responses and reconstruction

In this subsection, we measure impulse responses to obtain an inverse filter matrix by using the proposed algorithms in section 4 and restore the applied impulses which result in two surface forces and coefficient of friction. Figure 10 shows a developed scanning mechanism for measuring impulse responses and impulse forces. In the mechanism, the developed sensor module is equipped to a link connected to a normal force balancer and moved by a linear guide and a geared motor along a raised metal edge bed. The raised metal edge bed can be changed according to the edge shapes as shown in Fig. 6. The F/T sensor can measure surface shear and normal forces. Figures 11 and 12 show the measured impulse responses to the raised metal edges as shown in Figs. 6 (a) and (b), respectively (Notice that the responses are not the integral of voltage signals but original electrical signals). The measured signal contains noise and is thus conditioned by a moving average method. It is difficult to see directly surface normal and shear forces from the Figs. 11 and 12. Thus the signals must be processed by a signal processing algorithm and the two forces must be restored. In the each case, the Fourier transforms of forces measured by the F/T sensor to the two raised edges are as follows:

$$F^a(z)=\begin{bmatrix}F_x^a(z)\\F_z^a(z)\end{bmatrix}=\begin{bmatrix}0.6\\0.9\end{bmatrix},\ F^b(z)=\begin{bmatrix}F_x^b(z)\\F_z^b(z)\end{bmatrix}=\begin{bmatrix}0.2\\1.0\end{bmatrix} \quad (5)$$

where the superscripts “a” and “b” denote the raised edges in Figs. 6(a) and 6(b), respectively. From (2), we can derive the following relation to calculate $G(e^{j\omega})$ at each frequency:

$$\begin{bmatrix}G_{11}\\G_{12}\\G_{21}\\G_{22}\end{bmatrix}=\begin{bmatrix}F_x^a & F_z^a & 0 & 0\\0 & 0 & F_x^a & F_z^a\\F_x^b & F_z^b & 0 & 0\\0 & 0 & F_x^b & F_z^b\end{bmatrix}^{-1}\begin{bmatrix}M_1^a\\M_2^a\\M_1^b\\M_2^b\end{bmatrix} \quad (6)$$

where the components of the matrix and vectors are (real or complex) constant at each frequency. Note that at least two independent vectors as (5) make the matrix in (6) be full-ranked and the transfer matrix $G(e^{j\omega})$ can be obtained from (6). Then for each frequency, a regularized inverse filter matrix is calculated from (4) with $\beta=10^{-4}$ and G obtained by (6). Finally the resulting impulse responses of the inverse filter matrix are given by using the inverse Fourier transformation as shown Fig. 13. Using the inverse impulse responses, we can restore the surface forces to the two raised metal edges as shown in Fig. 14 where the magnitude of the forces become smaller than those in (5) but the coefficients of friction are very similar to those in (5). Also the reconstructed forces are shifted by 25 [mm] from the initial position –12.5 [mm] and noises are generated in both sides. In the future, these problems should be solved. The reconstruction filter can be utilized in restoration for arbitrary fine rigid objects and fabric by using the devices as Figs. 15 and 16. The devices can fix the objects on the beds in arbitrary angle by the rotating mechanism and the tension for fabric can be manually controlled by the tension tuning part. And the sensor module can be moved along the surfaces of objects in a velocity.

6. CONCLUSIONS

In this research, we have designed a new texture sensing system and developed a new signal processing algorithm for tangible interface systems. This texture sensing system is designed to get surface information with high resolution and bandwidth. First, a texture sensor is made of piezo-electric polymer (polyvinylidene fluoride) strips molded in a silicon rubber and attached in a rigid cylinder body. The sensor is fixed to a scanning system for dynamic sensing. Second, a new signal processing algorithm for restoration of surface information is developed. The algorithm consists of two-dimensional modeling of the sensor using an identification method and inverse filtering from sensing signals into estimated surface information. Finally the two-dimensional surface information can be experimentally reconstructed from sensing signals using the developed signal processing algorithm.

The result in this research can be a fundamental technology for tangible agent area and also a new experimental solution of the two-dimensional restoration problem in PVDF sensors. This solution gives varying frictional coefficient and its reconstruction performance is better than that of analytical method because it reflects correlated noise and is set up on small number of assumptions. In the future, a system integrated with a tangible interface will be developed and other properties of texture will be considered.

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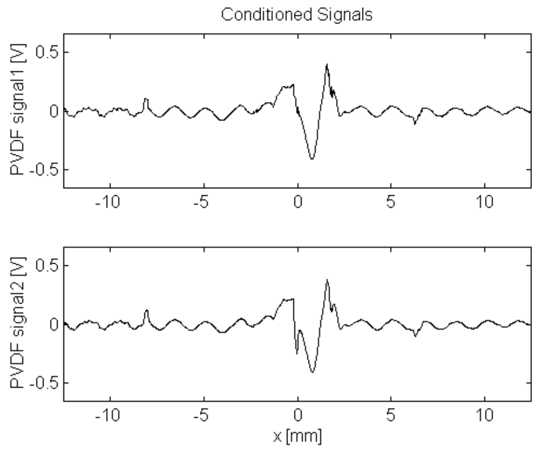

Fig. 11 Impulse responses $m_1(x)$ and $m_2(x)$ according to scanning along the first raised metal edge (Fig. 4 (a)).

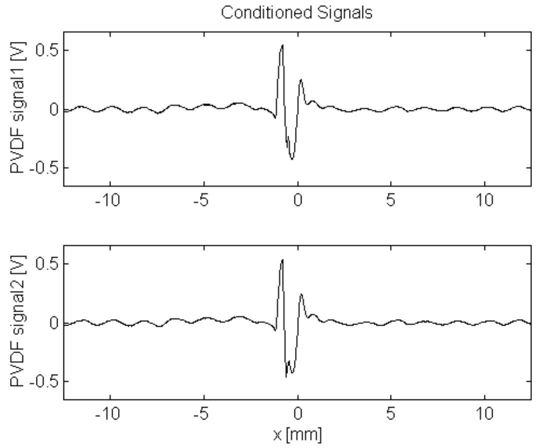

Fig. 12 Impulse responses $m_1(x)$ and $m_2(x)$ according to scanning along the second raised metal edge (Fig. 4(b)).

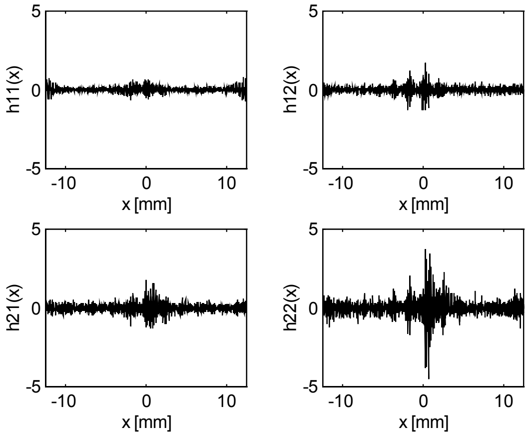

Fig. 13 Inverse filter $h_{11}(x), h_{12}(x), h_{21}(x), h_{22}(x)$ using regularized inversion.

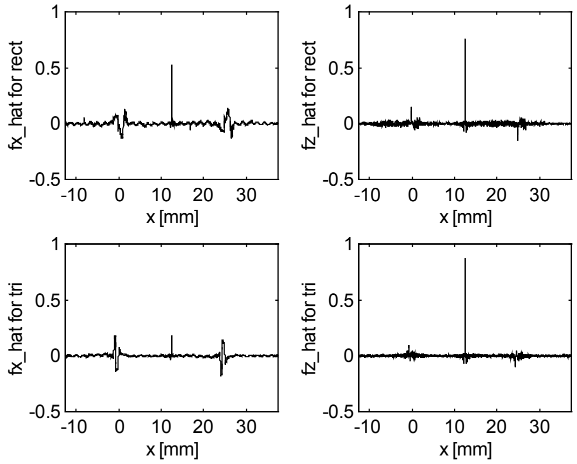

Fig. 14 Reconstruction results for the first and second raised edges.

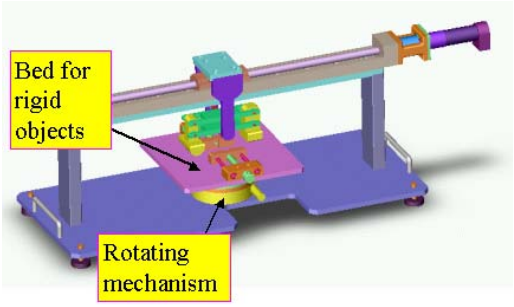

Fig. 15 Three-dimensional model of experimental setup for scanning metal objects.

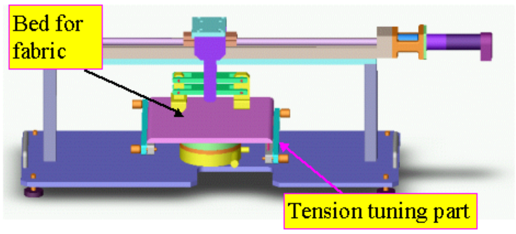

Fig. 16 Three-dimensional CAD model of experimental setup for scanning fabric.