Development of Advanced Artifact-Metrics Authentication System Using Carbon Nanotube Composite Papers*

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Artifact-metrics authentication is a method to authenticate artifacts that have measurable intrinsic characteristics like microscopic random patterns produced in the manufacturing process. In this study, we use a single-walled carbon nanotube (SWCNT) composite paper that is a composite material made from the mixture of the SWCNTs and the pulp (paper materials), as the material of a new artifact-metrics authentication. Advantages of using SWCNT-composite papers, for example, are easy to handle and to make, and impossible to replicate the patterns. As authentication methods, we focus on the use of Raman spectroscopic characteristics of the SWCNTs, and use features of the distinctive SWCNT patterns in each paper, for authentication “keys.” The estimated result of error rate $= 10^{-5}$ or less was obtained from an experiment that used combination data obtained from specific Raman peaks of the SWCNTs. Our SWCNT-composite papers also have the other usable properties that can be used for authentication keys, thus we are able to improve authentication accuracy more using those keys.

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I. INTRODUCTION

Nowadays, advanced authentication technology is required with the development of the information society. Currently, biometric authentication is often used as an authentication technology [1, 2]. The biometrics is an authentication system that uses physical features of humans such as fingerprints, irises, and veins. This authentication system is possible to authenticate a high level, but problems also exist. For example, privacy concerns due to the use of physical characteristics, and counterfeiting of vulnerability of biometric features has been pointed out. Actually, in experiments using fingerprint identification device commercially available, the result that artificial finger made of gelatin was authenticated as genuine high probability, has been reported [3].

As a technology to solve these problems, an artifact-metrics authentication has been proposed [4]. The artifact-metrics authentication is an authentication system that uses specific features of the artifacts. Typically, specific random patterns of the artifacts are used for verification as a “fingerprint” of the artifact. In general, this authentication system is possible to improve the complexity by combining the physical characteristics, and it is possible to advance the secure level of authentication compared with a biometrics authentication. Examples of the artifact-metrics authentication that has been proposed in recent years, e.g., utilizing the magnetic properties of the magnetic fiber [5] or using infrared transmitted light image of the paper [6], are presented.

In this study, as the material for a new artifact-metrics authentication, we focused on single-walled carbon nanotube (SWCNT) composite papers [7]. SWCNTs are cylindrical materials consist of only carbon atoms and its diameter is nm scale. The SWCNTs have various characteristics, e.g., high electrical conductivity and high thermal conductivity [8, 9].

For use in authenticating the SWCNTs, we here use the SWCNT-composite-paper that is prepared by mixing the pulp and the SWCNTs. Advantages of using the SWCNT-composite paper that standardization of artifact is easy, preparation is easy, replication is impossible, and so on, are described [10]. We focused on specific Raman spectroscopic characteristics of the SWCNTs [11], performed an authenticity judgment using keys obtained by Raman mapping from the SWCNT-composite papers. Further, we used a calculated correlation-coefficient and pattern-matching in the comparison of the authentication data.

In this paper, we aim to further advancement of the artifact-metrics authentication using our SWCNT-composite papers, examined complication of authentication keys.

II. BASIS OF ARTIFACT-METRICS AUTHENTICATION SYSTEM

Figure 1 shows a basic configuration of artifact-metrics authentication system described in Ref. [12]. This system...
FIG. 1. The schematic diagram of the general artifact-metrics authentication system [12].

Consists of two phases that are enrollment and verification. In enrollment phase, specific features of the artifact are measured and stored as enrollment data in a database. On the other hand, in verification phase, the artifact is measured again to authenticate, and verification is performed against the registered data.

In addition, we evaluate the similarity between the samples using a correlation-coefficient and pattern-matching scores in verification. We search a position by pattern matching process where the largest correlation-coefficient of the two data is obtained. We use Eq. (1) to calculate the correlation coefficient, and use Eq. (2) for the pattern-matching as shown below, respectively.

$$r = \frac{N \sum P_{ij}Q_{ij} - \sum P_{ij}Q_{ij}}{\sqrt{N \sum P_{ij}^2 - (\sum P_{ij})^2} \sqrt{N \sum Q_{ij}^2 - (\sum Q_{ij})^2}}.$$  

(1)

$$R_{ZNCC} = \frac{N^{M-1} \sum \sum_{i=0}^{N-1} (I_{ij} - \bar{I})(T_{ij} - \bar{T})}{\sqrt{\sum_{i=0}^{N-1} \sum_{j=0}^{M-1} (I_{ij} - \bar{I})^2 \times \sum_{j=0}^{M-1} \sum_{i=0}^{N-1} (T_{ij} - \bar{T})^2}},$$

(2)

where $N, M$ denote the numbers of sampling points and $I_{ij}, T_{ij}$ are strength of peaks in coordinates $i, j$.

Moreover, in order to evaluate the accuracy of this system, evaluating indexes of FMR (false match rate: rate of judging that match incorrectly), FNMR (false non-match rate: rate of judging that non-match incorrectly) are estimated as used in evaluation of the biometrics [6]. EER (equal error rate) that is an equaled point both FMR and FNMR is also used as a typical index of the authentication accuracy. Relationship with FMR, FNMR, and EER is shown in Fig. 2. If EER is small, authentication accuracy is assumed to be high.

III. BASIS OF CARBON-NANOTUBE-COMPOSITE PAPER

The SWCNT-composite paper is a composite material made by mixing the pulp and the SWCNT. The CNTs are a cylindrical substance constituted by a six-membered ring structure of carbon atoms. Its diameter is nm order and a length is μm order. A SW (Single-walled) CNT and a MW (Multi-walled) CNT are present. The SWCNTs have the excellent physical and chemical properties. In particular, we have here focused on Raman spectroscopic characteristics of SWCNTs. We create authentication keys based on the difference of peaks by the presence density of SWCNTs in the composite-papers. Typical Raman spectra of SWCNTs are shown in Fig. 3.

IV. EXPERIMENTAL METHODS

A. Fabrication methods for Carbon-nanotube-composite papers [7]

In this study, we use SWCNT-composite papers as a material for a new artifact-metrics authentication. Fabrication methods for our SWCNT-composite papers are shown below. Furthermore, a schematic diagram of the paper fabrication methods is shown in Fig. 4.

1) Preparation of the pulp suspension by soaking and dispersing pulp materials in pure water.
B. Authentication key generation methods

In order to obtain authentication keys, we use Raman mapping data of our SWCNT-composite papers. The Raman mapping is an imaging technique obtained by taking the averaged values of the peak intensity of the spectra in each measurement point. The measurement should be performed twice for each sample because obtaining process for the enrollment data and the verification data is required. The sample of the Raman mapping image of SWCNT-composite papers is shown in Fig. 5. The bright colored points indicate high intensity of peaks, and the dark points indicate low intensity of peaks. We use a laser having a wavelength of 532 nm (diode-pumped Nd:YVO$_4$ laser, Showa Optronics Co., Ltd.) for this measurements. In this measurement, the laser spot size is 5 $\mu$m$^2$, the laser strength is $10^6$ W/cm$^2$, and the exposure time is 0.6 sec.

C. Authentication procedures

Obtaining the data from SWCNT-composite papers at the first performs as verification data. We here show the flow of the verification as follows.

a) Data read
Read the enrollment data and the verification data obtained from the Raman mapping.

b) Pattern-matching process
The pattern-matching is a method to determine the place that appears a particular pattern. We use a numerical formula called ZNCC (zero-mean normalized cross-correlation) as shown in Eq. (2) to gain a rate of similarity.

c) Calculation of the correlation-coefficient

After identifying the position having high similarity by pattern matching, the correlation-coefficient at that position is calculated. We use Eq. (1) for its calculation. If the calculated correlation-coefficient is near 1, it means that the measured article is expected to be genuine. In contrast, if the correlation-coefficient is near 0, it is counterfeit. We perform the authentication judgment as described above.

V. RESULTS AND DISCUSSION

A. Fabrication of SWCNT composite paper

First, we fabricated SWCNT composite papers to use for measurement. We here used SWCNTs (NanoIntegris Inc.) for the paper. The SWCNT concentration for making our composite paper was 0.05 wt% as a function of the pulp weight. The thickness of the composite paper was about 100 $\mu$m. The fabricated SWCNT-composite paper was shown in Fig. 6. In this time, we cut out 100 samples from this SWCNT-composite paper, and used for measurement.

B. Authentication using only G-band

First, we were carried out an experiment in the case of using only G-band because an observed peak of G-band was the strongest in the whole of the Raman spectra of SWCNTs. By previous work [13], related usefulness of the data and spectral analysis range were described. Based on...
FIG. 6. The fabricated SWCNT-composite paper. Uses SWCNTs manufactured by NanoIntegris Inc. for the paper. The SWCNT concentration was 0.05 wt% as a function of the pulp weight.

This, we set spectral analysis range at 1500 ~ 1680 cm\(^{-1}\). The obtained mapping image is shown in Fig. 7. Different characteristic patterns depending on samples were obtained successfully. It is impossible to confirm these patterns by a microscope and naked eyes.

We calculated correlation-coefficients from these authentication keys, and derived the authentication accuracy. Figure 8(a) shows a histogram created from the obtained correlation-coefficients. In this experiment, these results that the correlation-coefficient was able to obtain high values between genuine and genuine. On the other hand, the correlation-coefficient was low between genuine and counterfeit. In addition, FMR/FNMR curves are shown in Fig. 9(a). Lines were estimated curves from results. The obtained EER was 3.0 \(\times\) 10\(^{-4}\). Our authentication system was able to be set a clear threshold value about 0.55 for example.

C. Authentication using only RBM-band

RBM-band is one of specific Raman spectra observed from only SWCNTs as described in Sec. III. It is possible to obtain the various peaks by using many types of SWCNTs because the position of peaks varies depending on the diameter of SWCNTs. We here were carried out an experiment in the case of using the SWCNT that only one type of diameter. In the same way as in the case of G-band, by previous work [13], related usefulness of the data and spectral analysis range were described. Based on this, we set spectral analysis range at 140-200 cm\(^{-1}\). Different characteristic patterns depending on samples were also obtained successfully as same as Sec. V B described. It is also impossible to confirm these patterns by a microscope and naked eyes.

We calculated correlation-coefficients from these authentication keys, and derived the authentication accuracy as same as Sec. V B described. Figure 8(b) shows a histogram created from the obtained correlation-coefficients. In the same way as in the case of G-band, these results in this experiment that the correlation-coefficient was able to obtain high values between genuine and genuine. On the other hand, the correlation-coefficient was low between genuine and counterfeit. In addition, FMR/FNMR curves are also shown in Fig. 9(b). Lines were estimated curves from results. The obtained EER was 5.0 \(\times\) 10\(^{-4}\). Our system was also able to be set a threshold value clearly.

D. Combination of G-band and RBM-band keys

For aiming to improve the authentication accuracy, we tested the use of a combination data of G-band and RBM-band as multiple keys. We integrated the data using values of the correlation-coefficients. The obtained FMR/FNMR curves from experimental data are shown in Fig. 9(c), and EER was 1.0 \(\times\) 10\(^{-5}\). As a result, we succeeded that the EER reduced comparing with two experimental results as described previously. By increasing the number of the authentication keys, we succeeded to
We believe that by increasing authentication keys using the others Raman peaks of SWCNTs, it is possible to improve authentication accuracy more and more. In particular, we consider the use of 2G-band and G'-band, or the use of other RBM-bands obtained by adding other kinds of SWCNTs with different diameters will provide more secure system. In previous work [14], evaluation of the authentication accuracy using simulation has been described. According to this study, authentication accuracy can be improved to $5.0 \times 10^{-8}$ by a combination of four peaks. Therefore, by adding authentication keys, we think that the improvement of authentication accuracy of about two orders can be expected also in the experiment.

VI. CONCLUSIONS

In this study, we aimed to apply the SWCNT-composite papers to an artifact-metrics authentication as artifacts generating authentication keys. We focused on specific Raman spectroscopic characteristics of SWCNTs as produced authentication keys. In concrete, we used Raman mapping patterns obtained from our SWCNT-composite papers. As results of experiments, we confirmed our authentication system had good secure level comparing with the biometrics system. Moreover, by optimizing measurement parameters and SWCNT-composite papers’ parameters, authentication accuracy had improved significantly. In this time, we used two Raman spectra, i.e., G-band and RBM-band, and confirmed our system improved its secure level. We can also use the others spectra of SWCNTs. Therefore, it is possible to further improve the authentication accuracy. We will confirm the improvement of the accuracy in the future work.

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