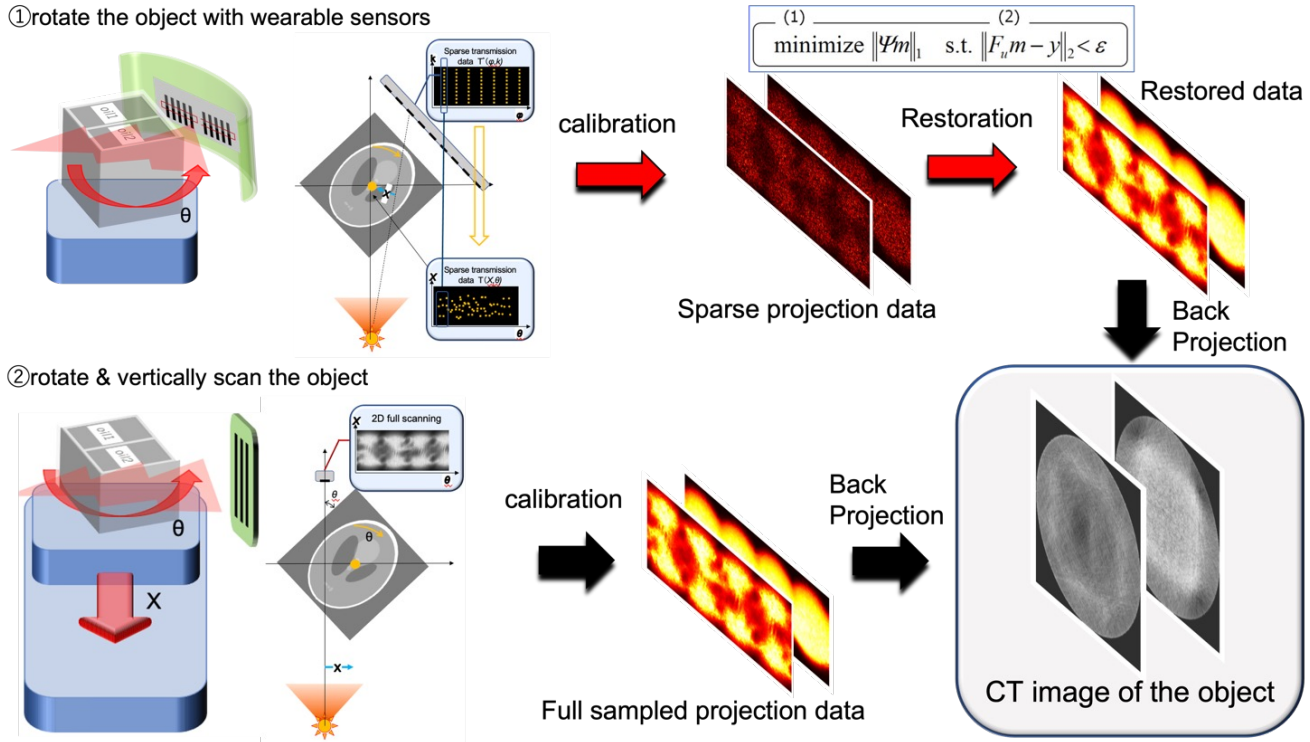
2023.08.16 THz CT論文進捗



参考1

Robot-assisted, source-camera-coupled multi-view broadband imagers for ubiquitous sensing platform

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Abstract

Multi-functional photo-imaging garners attention towards the development of universal safety-net sensor networks. Although there are urgent needs to comprehensively address the optical information from arbitrarily structured and located targets, investigations on multi-view sensitive broadband monitoring, being independent of the operating environment, are yet to be completed. This study presents a robot-assisted, photo-source and imager implanted, multi-view stereoscopic sensitive broadband photo-monitoring platform with reflective and transmissive switchable modes. A multifaceted photo-thermoelectric device design based on flexible carbon nanotube films facilitates the prototype demonstrations of non-destructive, target-structure-independent, free-form multi-view examinations on actual three-dimensional industrial components. Further functionalisation, namely, a portable system utilising three-dimensional printing and ultraviolet processing, achieves the unification of freely attachable photo-imagers and miniature photo-sources, enabling location-independent operation. Consequently, the non-destructive unmanned, remote, high-speed, omni-directional testing of a defective aerial miniature model winding road-bridge with a robot-assisted photo-source imager built into a multi-axis movable photo-thermoelectric monitor arm is demonstrated.

Non-destructive sensing and imaging techniques based on electromagnetic (EM) waves have garnered significant attention in both industry and academia. This is because of increasing demands for better performance, safety and quality assurance of industrial components, especially in the impending Internet of Things (IoT) society[1,2]. In particular, this situation requires multifaceted perspectives and comprehensive investigations of sensing devices dealing with composite multi-layered target objects of arbitrary structures or locations. Previous studies have reported rapid progress in imaging modalities by widening their application in certain regions of the EM spectrum, including visible light[3,4], infrared (IR)[5,6], terahertz (THz) and sub-THz wave[7–9] and millimetre-wave (MMW)[10,11]. Broadband photo-monitoring has been proven to be effective specifically in aggregating multi-spectral optical properties and information to test the composite material and layer structure[12,13]. Concurrently, bendable, flexible and easily attachable imager devices facilitate multi-functional sensing. Specifically, flexible and wearable scanner sheets have reflective and transmissive switchable modes that are comfortably applicable to any three-dimensional (3D) curvature through an adjustment of the device configuration with target structures. Moreover, the free-form imager setup yields multi-view stereoscopic visualisation[14], which can also be successfully applied in both flat and bent samples without forming blind spots. Additionally, the portability of sensing modules must be addressed and considered to overcome the limitation posed by the operation locations. The built-in implementation of photo-imagers and photo-sources is essential for designing a compact sensing module[15]. Here, uncooled device operation is indispensable for mobile systemisation and use in practical social scenes, being free from bulky cooling equipment. Moreover, the robot-assisted module can potentially govern ubiquitous sensing, where the unmanned remote high-speed photo-monitoring, which is independent of the operation environment, is feasible[16]. The transition from manned to robotic inspection can make operation safer and more sustainable. Some examples of robotic operation include disconnection testing of power-transmission lines with aerial modules, crack examination of sea bridges with wall-climbing units and exploring cramped environments with self-driving systems.

Thus, further efforts are needed to enable photo-imagers, which play an essential role in ubiquitous sensing platforms, with the following characteristics:

(i) Flexible switching of the multi-view stereoscopic system with reflective and transmissive sensing options with a proper choice of a freely attachable uncooled broadband photo-absorbent thin film.

(ii) Built-in implementation of miniature photo-sources in flexible multi-view stereoscopic photo-detector frameworks.

(iii) Target-location-independent, high-speed and omni-directional photo-monitoring via robot-assisted module driving.

To this end, several studies have investigated diverse systems, photo-sources and photo-imagers including functional unmanned remote sensing robotics[17,18], high-usability miniature photo-sources[19,20], flexible multi-view stereoscopic photo-imagers[21,22] and highly efficient uncooled broadband photo-absorbent materials[23,24]. In a related study, Yang et al. developed the thermo-phototronic effect[25], which is based on the combination of thermoelectric effect with the photoelectric effect in some semiconductor materials[26–29]. However, their functional integrations have not been adequately verified, hindering the fruition of a ubiquitous sensing platform.

In this study, we develop a robot-assisted, photo-source and imager implanted, multi-view and sensitive broadband photo-monitoring platform with switchable reflective and transmissive modes, demonstrating the aforementioned characteristic requirements. The proposed module employs (I) the freely attachable photo-thermoelectric (PTE) technique on uncooled sensitive broadband photo-imager sheets with physically and chemically enriched carbon nanotube (CNT) thin flexible films. The freely attachable photo-imager sheet enables the switching from reflective to transmissive modes and offers multi-view stereoscopic sensing operation. This free-form photo-monitoring not only allows comprehensive and non-destructive inspections of actual curvilinear industrial components (beverage bottles, gas or water pipes) but also provides a unique opportunity for the remote arbitrary hierarchical image extraction of multi-layered 3D structures via multi-frequency band sensing (sub-THz, near-infrared (NIR)). Simultaneously, the effective utilisation of the 3D printer and ultraviolet (UV) laser facilitates (II) the embedding of high-output-power miniature photo-sources. The resulting photo-source-implanted compact sensing module performs a portable 360°-view photo-monitoring. Finally, the portability of the photo-monitoring system leads to the built-in implementation of the present sensing module in a multi-axis movable-arm unit. Consequently, (III) the robot-assisted module operation verifies the non-destructive, unmanned, remote, high-speed and omni-directional photo-monitoring of the miniature model of an aerial defective winding road-bridge. These efforts potentially provide a roadmap for the materialisation of a ubiquitous sensing platform. Our results and the concept of this study could also be sued for a sustainable, long-term operable and user-friendly IoT system of a sensor network, including permanent and regular in situ inspections at construction sites and in line monitoring of fine-processed industrial products.

1. Background:

- Non-destructive sensing and imaging techniques based on electromagnetic (EM) waves are gaining attention in industry and academia.

- Increased demands for better performance, safety, and quality assurance of industrial components, especially in the impending Internet of Things (IoT) society.

- Emphasis on comprehensive investigations of sensing devices dealing with composite multi-layered target objects.

- Previous studies have shown progress in imaging modalities across various regions of the EM spectrum.

2. What is known:

- Broadband photo-monitoring has proven effective in aggregating multi-spectral optical properties to test composite material and layer structures.

- Flexible and wearable imager devices, such as scanner sheets, offer reflective and transmissive switchable modes applicable to 3D curvature.

- Free-form imager setups yield multi-view stereoscopic visualization applicable to various sample shapes.

- Portability of sensing modules is important, with a focus on uncooled device operation for mobile and compact setups.

- Robot-assisted modules can enable high-speed, independent photo-monitoring for safer and more sustainable operations.

3. What is unknown:

- The integration of diverse systems, photo-sources, and photo-imagers has not been adequately verified for creating a ubiquitous sensing platform.

- The functional integration of the thermo-phototronic effect and its application in sensing platforms is still uncertain.

4. Objective:

- Develop a robot-assisted, photo-source and imager implanted, multi-view and sensitive broadband photo-monitoring platform.

- Achieve switchable reflective and transmissive modes for multi-view stereoscopic sensing.

- Incorporate a freely attachable photo-thermoelectric (PTE) technique using uncooled sensitive broadband photo-imager sheets.

- Embed high-output-power miniature photo-sources using 3D printing and UV laser techniques.

- Implement the sensing module in a multi-axis movable-arm unit for non-destructive, unmanned, remote, high-speed, and omni-directional photo-monitoring.

- Verify the proposed platform's capabilities in various scenarios, including inspections of industrial products and construction sites.

1. Background:

電磁波を利用した非破壊センシングやイメージング技術が、産業界や学術界で注目を集めている。

特に、間近に迫ったモノのインターネット（IoT）社会において、工業部品の性能向上、安全性、品質保証に対する要求が高まっている。

複合多層の対象物を扱うセンシングデバイスの包括的な調査に重点が置かれている。

これまでの研究で、EMスペクトルの様々な領域におけるイメージングモダリティの進歩が示されている。

2. What is known:

広帯域フォトモニタリングは、複合材料や層構造をテストするためのマルチスペクトル光学特性の集約に有効であることが証明されている。

スキャナシートのような柔軟で装着可能なイメージャデバイスは、3D曲率に適用可能な反射・透過の切り替え可能なモードを提供する。

自由形状イメージャのセットアップにより、様々なサンプル形状に適用可能な多視点立体視が可能。

センシングモジュールの可搬性は重要であり、移動可能でコンパクトなセットアップのための非冷却デバイス操作に重点を置いている。

ロボットアシストモジュールは、より安全で持続可能な操作のために、高速で独立したフォトモニタリングを可能にする。

3. What is unknown:

ユビキタス・センシング・プラットフォームを構築するために、多様なシステム、光源、フォトイメージャーの統合は十分に検証されていない。

サーモフォトロニック効果の機能的統合とセンシング・プラットフォームへの応用はまだ不確かである。

4. Objective:

ロボット支援、光源とイメージャー埋め込み、マルチビュー、高感度広帯域フォトモニタリングプラットフォームの開発。

多視点立体センシングのための反射・透過モードの切り替えを実現する。

非冷却高感度広帯域フォトイメージャーシートを使用した、自由に取り付け可能なフォトサーモエレクトリック（PTE）技術を組み込む。

3DプリンティングとUVレーザー技術を用いて、高出力小型光源を組み込む。

非破壊、無人、遠隔、高速、全方向フォトモニタリングのための多軸可動アームユニットにセンシングモジュールを実装する。

工業製品や建設現場の検査を含む様々なシナリオにおいて、提案されたプラットフォームの能力を検証する。

参考2

Although...(1 文)

Using○○,we achived...(1 文)

A flexible and wearable terahertz scanner

D. Suzuki, S. Oda and Y. Kawano*

Imaging technologies based on terahertz (THz) waves have great potential for use in powerful non-invasive inspection methods. However, most real objects have various three-dimensional curvatures and existing THz technologies often encounter difficulties in imaging such configurations, which limits the useful range of THz imaging applications. Here, we report the development of a flexible and wearable THz scanner based on carbon nanotubes. We achieved room-temperature THz detection over a broad frequency band ranging from 0.14 to 39 THz and developed a portable THz scanner. Using this scanner, we performed THz imaging of samples concealed behind opaque objects, breakages and metal impurities of a bent film and multi-view scans of a syringe. We demonstrated a passive biometric THz scan of a human hand. Our results are expected to have considerable implications for non-destructive and non-contact inspections, such as medical examinations for the continuous monitoring of health conditions.

Techniques that are based on the sensing and imaging of electromagnetic waves have proven beneficial as powerful visualization methods in science and technology[1–3]. In particular, the THz frequency region of the electromagnetic spectrum has attracted considerable attention because of its unique advantages, such as the strong ability of THz waves to penetrate into non-polarized objects and the fact that this region of the spectrum contains characteristic absorption bands of many materials and molecules[4]. THz technologies are therefore expected to be a powerful tool for non-destructive inspections in a variety of fields including security, the characterization of organic/inorganic materials, pharmaceutical quality control, agriculture and medical and biological inspection[5,6]. Motivated by these expectations, several types of THz imaging systems have been created based on the thermoelectric/pyroelectric effect, bolometer, Schottky barrier diode, quantum effect and so on[7].

However, most real samples exhibit three-dimensional curvatures; this hinders the accurate measurement of such samples using conventional THz imaging technologies, which are primarily suited to flat samples. For example, in current technologies, THz images for security examinations of human bodies are obtained by rotating THz detectors through 360°. This necessity makes THz imaging systems very bulky. Although several types of THz tomography techniques have been reported, they require complicated systems and lack portability[8,9]. To significantly expand the usable range of THz imaging for future applications, a flexible and portable THz scanner is in high demand.

Although several types of uncooled THz cameras that are based on arrays of detectors such as bolometers and Schottky barrier diodes have been reported[10,11], none of these cameras is based on mechanically flexible materials, restricting the types of samples that can be observed. The difficulty of room-temperature THz detection originates from the fact that THz frequencies are too high for conventional semiconductor technology and the photon energy of THz waves (a few millielectronvolts) is much lower than the thermal energy of 300 K (~26 meV). These conditions limit the materials and devices that can be used in uncooled THz detectors, which has made the development of flexible THz imagers a formidable task.

Here we present room-temperature flexible THz imaging devices that are based on macroscopic carbon nanotube (CNT) films. Nanocarbon materials such as graphene[12–15] and CNTs[16–23] have previously been applied in photodetectors for the visible, infrared and THz regions of the spectrum. Although some studies[12,22,23] reported THz detectors that are based on quantum effects, the operation of these detectors require cryogenic temperatures. Uncooled THz detectors were also developed[13–21], but their application in a flexible THz scanner has not yet been realized. Using our CNT-based THz scanner, we achieved THz imaging of bent materials and the passive imaging of a human hand with a wearable scanner, demonstrating the possibility of using this technology to develop convenient and portable THz inspection devices.

CNT THz detectors

Because of its mechanical strength, the CNT film used in our THz scanner can be easily bent over wide angles, unlike conventional semiconductor materials (Supplementary Fig. 1a). In addition, this macroscopic CNT film effectively absorbs THz waves over a broad THz range (Supplementary Fig. 1b), thereby eliminating the need for integration with planar antennas, as is typically required for micro- and nanoscale detectors. These features allowed us to fabricate a flexible CNT-array-based THz scanner.

Figure 1a shows the current–voltage characteristics of our CNT device and its response to THz irradiation at 0.14, 1.4 and 39 THz. Detectable signals were generated for all considered cases of THz irradiation, indicating that the CNT device functions as a wideband THz detector. We measured the noise density spectrum of the detector using a lock-in amplifier. Because the detector operates under zero bias voltage, as shown in Fig. 1a, the effects of shot noise and $1/f$ noise can be avoided. The noise spectrum presented in Fig. 1b demonstrates that the noise current of the detector was reduced to 52 pA $Hz^{-1/2}$, the theoretical value of the thermal noise limit given by $\sqrt{4k_B\Delta fT}/\sqrt{R}$, where k_B is the Boltzmann constant, Δf is the frequency bandwidth, T is the temperature and R is the resistance[24]. Therefore, this device serves as a low-noise THz detector. The irradiation power at the detector is 0.9 mW for 0.14 THz, 2.6 mW for 1.4 THz and 0.5 mW for 39 THz, respectively. Thus, the noise equivalent power (NEP) of this detector was calculated to be 8.4 nW $Hz^{-1/2}$ for 0.14 THz, 2.4 nW $Hz^{-1/2}$ for 1.4 THz, and 180 pW $Hz^{-1/2}$ for 39 THz.

We performed spatially resolved measurements of the THz response of the CNT devices (Fig. 1c). The results reveal that the THz response predominantly appeared at the interface between

1. Background:

- 電磁波の感知と画像化に基づく技術は、科学と技術の分野で強力な視覚化手法として証明されてきた。

- 特に電磁スペクトルのTHz周波数領域は、THz波が非偏極化した物体に浸透する能力や、多くの材料や分子の特徴的な吸収バンドを含むなどの独自の利点を持っており、注目を集めている。

- THz技術は、セキュリティ、有機/無機材料の特性評価、医薬品品質管理、農業、医療および生物学的検査など、さまざまな分野で非破壊検査の強力なツールとして期待されている。

2. What is known:

- 既存のTHzイメージングシステムは、熱電/熱誘電効果、ボロメータ、ショットキーバリアダイオード、量子効果などを基に作成されている。

- しかしながら、実際のサンプルは3次元の曲率を示すことが多く、これが平坦なサンプルに適した従来のTHzイメージング技術を用いた正確な測定を妨げている。

- 現在の技術では、人体のセキュリティ検査のためのTHzイメージは、THz検出器を360°回転させることで得られる。これにより、THzイメージングシステムは非常に大きくなる。

- いくつかのTHzトモグラフィ技術が報告されているが、これらは複雑なシステムを必要とし、携帯性に欠けている。

3. What is unknown:

- 柔軟かつ携帯可能なTHzスキャナの実現に関する情報が不明である。

- メカニカルに柔軟な材料に基づくTHzカメラが存在しないため、観察可能なサンプルの種類が制限されている。

4. Objective:

- 本研究では、マクロスケールの炭素ナノチューブ（CNT）フィルムを基にした室温可撓性THzイメージングデバイスを提案する。

- これにより、曲がった材料のTHzイメージングや、装着可能なスキャナを用いた人間の手の被写体イメージングを実現し、便利で携帯可能なTHz検査デバイスの開発の可能性を示す。

今回の論文

1. Background:

1. 非破壊センシングおよびイメージング技術の注目
2. 産業と学術の双方での需要の増加
3. (IoT社会における)産業部品の安全性と品質保証のニーズ増大

(トランスの油漏れ，化学工場で使ってる油のタンク等，家庭の油，石油メーカーのプラントのモニタリング，船舶の石油輸送のモニタリング)

2. What is known:

1. 可視光、赤外線、テラヘルツ、ミリ波のブロードバンドスペクトルの光モニタリングの有用性
2. カーボンナノチューブ（CNT）フィルムを使用した非冷却フォトディテクターの開発
3. 内部欠陥の非破壊的モニタリング(CT含む？)

3. 未知の情報:

1. テラヘルツCTの内部イメージングの課題(死角，コンパクト性)
2. 内部欠陥などの非破壊的な内部モニタリングの未解決の課題

(視角のない場所の局面に沿ったイメージング)

4. 目的:

1. 平行光を必要とせず、光源の発散を1つの配置されたセンサで捉え、光源側にレンズ系を必要としないコンパクトなCTイメージング法の開発
2. カーボンナノチューブフィルムを用いた非冷却ブロードバンドフォトディテクターを組み込んだテラヘルツCT光学システムのコンパクト化
3. センサーの絶対的な位置情報からサンプリングに必要な相対的な位置情報(角度+光軸からの垂直な距離)を算出してスパース投影データを取得する
4. 複雑な多層構造の内部可視化の実証(広帯域でも取れたことをアピールする．「単一ではなく２つの波長でreconstructionしたことで油の識別が可能になった」)(識別をアピールするのではなく，波長ごとに違って見えたこと自体をアピールする方向に)

新規性

- objectに沿う形でセンサーを装着する
- センサーとobjectを共に回転させる

上記２つの要求を満たす新しいCT測定系を確立した.

センサーの配置を柔軟に変更できることは，実験系をコンパクトにするだけでなく，物体により近いところで計測できることによるS/N比の向上効果もある

上記のようなモバイルなCTの計測でも、これまでのセンサー固定型のCTのように内部(オイル)を識別した画像が得られることを実証できた

・測定制約を利用したイメージング:

一般の圧縮センシングカメラだと素子のgeometryが二次元配列に固定されているので、撮影してから間引いて圧縮するシミュレーションは多くされている。

CNTセンサーは素子のgeometryの自由度は高いものの縦長の構造のため、前後左右に敷き詰めることはできない。よって配列した際に間引かなくても自ずから2Dランダムに近いサンプリングになる。