Terahertz Computer Tomography for Plastics Extrusion (TACTICS)

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ABSTRACT
In this article we propose an approach to reduce the amount of plastic waste during production of plastic profiles. We developed a terahertz computed tomography inline capable setup. For reconstruction a novel imaging model was developed. It takes into account the special properties of terahertz radiation. Furthermore, it allows to use particularities of terahertz measurements, like phase information. Experiments showed that our model is superior to conventional reconstruction techniques, allowing the reconstruction of geometries within an accuracy of the wavelength of terahertz radiation. This system can replace hazardous X-ray or nuclear radiation based sensors with harmless Terahertz radiation.

Keywords: Non Destructive Testing; Terahertz Tomography; Tomographic Imaging; Computed Tomography; Radon Transform; Inverse and Ill-Posed Problems;

1. INTRODUCTION

The plastics industry is a major player in the global economy and has an important role to play in the ecological transition to an energy-efficient and waste-free society. In addition to a higher recycling rate, a better design and more reliable methods for the production of plastic products are crucial to achieving the Sustainable Development Goals. In this work, we particularly focus on the quality control of extruded plastic profiles.

The state of the art quality control is destructive and carried out by hand, resulting in long feedback times for production facilities. Inevitably, this leads to long periods of time during which faulty parts remain undetected in production. They are produced until feedback is received and a large quantity is thrown away in cost of a defect. An inline sensing procedure, applied immediately after the extrusion process, can be an effective way to overcome this problem and therefore reduce waste in the production facilities through real-time feedback and enabled process control.

One possible approach may be X-ray computed tomography (X-ray CT). However, the use of ionizing radiation obviously leads to human health risks. Radiation shielding further increases the cost and size of an actual device. We therefore propose to use non-hazardous terahertz (THz) radiation, offering a safe, cost-effective and now a compact and fast alternative.

Currently, only simple geometries such as tubes can be measured with THz inline sensors [1] and often only single points along a profile are scanned.

Here we try to improve the current state of the art in THz sensing by developing a THz computed tomography (CT) approach for monitoring the extrusion of plastic profiles. For proof-of-principle, a focused THz time domain spectroscopy (THz-TDS) setup in transmission was built to enable basic 2D imaging and CT scan experiments. From such experiments, profiles of real plastic samples were reconstructed.

Compared to the well-known X-ray propagation, THz waves show different effects: a finite THz focal spot size with a diameter in the mm-range, scattering, diffraction and refraction. Therefore a mathematical model was derived which describes the beam propagation through the object more accurately. The classical Radon transform from X-ray-CT was modified to include the THz intensity distribution in the focal spot. This new approach then leads to a more accurate model, considering the finite size of the focal spot. Furthermore, one can derive mathematical expressions, which are needed for the nonlinear reconstruction method.

2. STATE OF THE ART

Typically, material testing of polymers is done manually in a destructive way, resulting in long feedback times. The longer potential production failures remain undetected, the more waste is produced, generated by the manufacturing of defective parts. A non-destructive alternative to overcome this problem is X-ray CT. This technology generates 3D representations of polymer samples. However, at great cost and the expense human safety through the use of ionizing radiation.

An alternative to the potentially risky X-rays is the harmless regime of THz radiation. It provides good properties such as low absorption [2] in polymers, while being safe for humans, making it a suitable candidate for industrial non-destructive testing of polymers and ceramics. Currently, the layer thicknesses of tubed [1] or coatings can be determined industrially. In addition, there are first approaches to perform computed tomography [3] measurements with THz radiation. Compared to X-ray CT, however, several conceptual challenges are still unsolved due to the electromagnetic wave nature of THz radiation.

For reconstruction, it is necessary to model the imaging procedure appropriately, for example including effects such as time-delay, absorption, scattering and refraction by the sample, while keeping the complexity of the imaging model at a reasonable level. In a further step, mathematical algorithms need to be derived to reconstruct a representation of the object.

In X-ray CT, the Radon transform provides a connection between the measured intensity after passing through an object. Mathematically, this leads to a linear problem, which, however, does not contain any of the mentioned THz radiation propagation effects and thus has to be adapted for THz imaging.

In this project, we are pushing the state of the art on the technical frontier by setting up a fast THz-CT device and finding appropriate solutions of the reconstruction problem.

3. BREAKTHROUGH CHARACTER OF THE PROJECT

Our motivation for this project was to reduce plastic waste. The importance of this challenge can be seen in the United Nations Sustainable Development Goals. We believe that a long-term solution to this problem can be achieved by combining political actions and further technical research in various areas.

Our technical approach offers a method to reduce plastic waste during the production process of plastic profiles by improving quality control beyond the latest available technology. Quality control is typically performed in a destructive way, resulting in long feedback times. In case of a production failure, this leads to the production of large amounts of faulty material - before the failure has been identified. Depending on how long the failure remains undetected, considerable amounts of produced plastic material can be lost.

An alternative, non-destructive, in-line testing method is, X-ray CT. However, this method uses ionizing radiation, which poses a potential risk to human operators and essentially leads to bulky and expensive equipment. By applying the well-known principles of X-ray CT to the THz regime, the advantages of working with harmless radiation and the possibility of building compact in-line sensors can be combined. To our knowledge, an in-line THz-CT device has not yet been achieved.

From a scientific point of view, the present project offers a new approach to diffraction-limited 3D-THz imaging. Our implementation allows to directly capture the THz electric field. This is in contrast to X-ray CT, which measures the intensity of X-ray radiation.

A particular breakthrough was achieved by the development of a mathematical imaging model in combination with the corresponding image reconstruction algorithms for THz-CT imaging. This model allows us to work with the maximum amount of information provided by the measurement system.

Even though our research was dedicated to THz-CT imaging, a major strength of the developed concepts is that they are widely applicable like in conventional 2D imaging. This essentially makes it possible to address other interesting applications for THz imaging, such as real time layer-thickness control of paper.

Tab. 1. Comparative table: Different quality control methods

Testing Method	Strength	Weakness
Destructive	cheap, simple	Slow, manually, produces waste, long feedback
X-ray-CT	high resolution, high penetration, established method	Human health risk, nuclear waste, large device, expensive
THz-CT	safe radiation, green technology, compact devices cost-effective	resolution ~100 μm

4. PROJECT RESULTS

For the proof of concept, a laboratory setup based on a THz-TDS setup was designed and built (see Fig. 4). To perform CT measurements the sample was placed on translation and rotation stages. During the measurements it was shifted and rotated through the focussed THz beam.

Due to the physical properties of THz radiation, such as refraction, scattering, diffraction and the finite THz focal spot size, standard X-ray CT reconstruction cannot be applied. A special mathematical model of the imaging was developed X-ray for the accurate reconstruction of the sample cross-section. This model is sophisticated enough to describe the governing principles of THz radiation propagation, but still be compact in order to reconstruct images from it.

In order to incorporate the finite spot size, the model developed here assumes that the beam consists of an ensemble of independent geometrical rays. Their spatial intensity-distribution $w(s)$ is determined by a knife-edge measurement of the THz focal spot. Each individual beam is subject to attenuation and time shifts according to the properties of the sample. Due to the point-like nature of the detector, the measured signal $E_{ij}(t)$ is represented as an integral over all individual geometrical rays.

In a first step we consider wave propagation effects and dispersion to be negligible and find our model for the measured signal as

$$E_{ij}(t) = \int_R w(s-s_i) E^{ref}\left(t - \frac{n-n_0}{\alpha c_0}(Rf)(s,\theta_j)\right) \times exp\left(-\frac{1}{2}(Rf)(s,\theta_j)\right) ds,$$

where the measured signal is considered to be a function of the reference signal $E^{ref}(t)$ and its dependence on the density f of the object. n, n_0 and α are the material constants of the sample. The indices i, j represent the parallel beam position and the projection angle.

A close relationship to the Radon transform can be observed. Here the operator R takes the density of an object f and maps it to its line integrals. It provides a connection between the attenuation of the signal and the object the ray has passed through.

From this model three approximations were derived, two linear problems, where the focussed THz spot is assumed to be infinitely small and a nonlinear problem where the actual shape of the THz spot is considered.

In the first linear reconstruction approach, we calculated the THz signal intensity $\int_R E_{ij}(t)^2 dt$ from our model for an infinitely small THz focal spot leading us back to the classical Radon transform. The image reconstruction using classical filtered back-projection is shown in Fig. 1. The general shape of the object is recognizable, but its edges are overestimated due to scattering. Radiation scattered away from the detector is misinterpreted as strong absorption.

In the second linear reconstruction approach we calculated a quantity representing the time shift of the signal $\int_R tE_{ij}(t)^2 dt / \int_R E_{ij}(t)^2 dt$. Potential scattering effects are suppressed by using the time shift. This approach is unique to THz CT, since time-dependent information is not available in X-ray-CT.

The image in **Fig.** was reconstructed using the iterative Landweber method. The different thickness of the sample walls is clearly visible. The individual widths (full width at half maximum) as determined to be 2.5 mm/2.5 mm/1.5 mm, respectively. This is in good agreement with the dimensions of 2.7 mm/2.7 mm/1.2 mm measured by a calliper.

In the nonlinear case we do not have one single ray, but, as previously stated, an ensemble of independent rays. This ensemble is described by the weight function $w(s)$ and represents the profile of our THz focus. Now neighbouring parts of our data are multiplied with different weights and combined by the single point detector. This approach is still work in progress, but to verify the validity of our imaging model, we have designed a representation of our object, transformed it and reconstructed it again. The results of this reconstruction using artificial data is shown in Fig. 3.

For a more detailed description of the results, a paper is currently being prepared, containing the mathematical derivations and an extensive comparison between different reconstruction approaches [4].

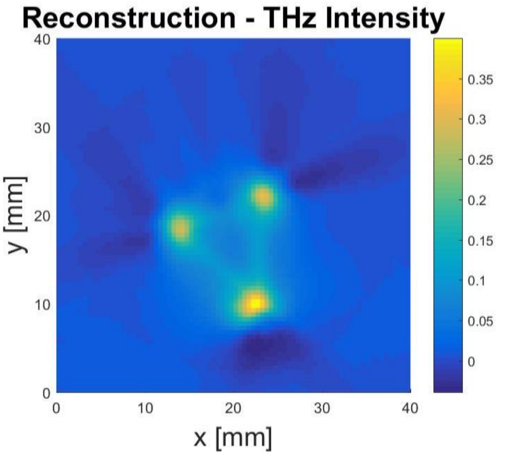

Fig. 1. Image reconstruction using THz intensity data and a filtered back-projection approach.

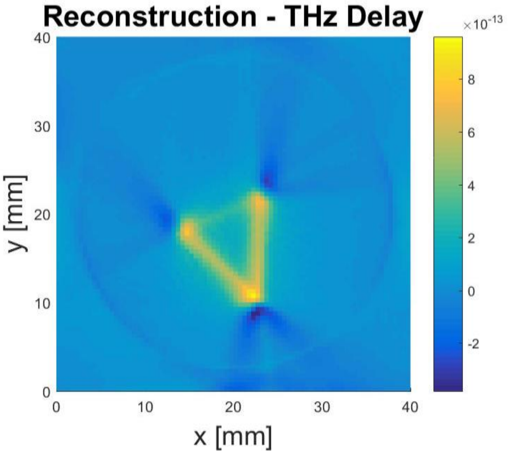

Fig. 2. Image reconstruction using THz time-delay data by a linear Landweber approach.

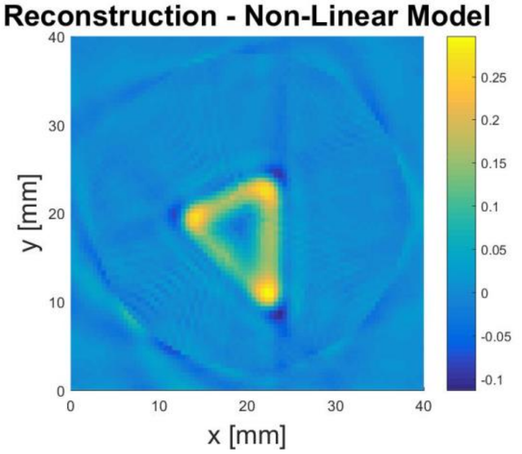

Fig. 3: Image reconstruction from an artificially generated set of data using Landweber iteration.

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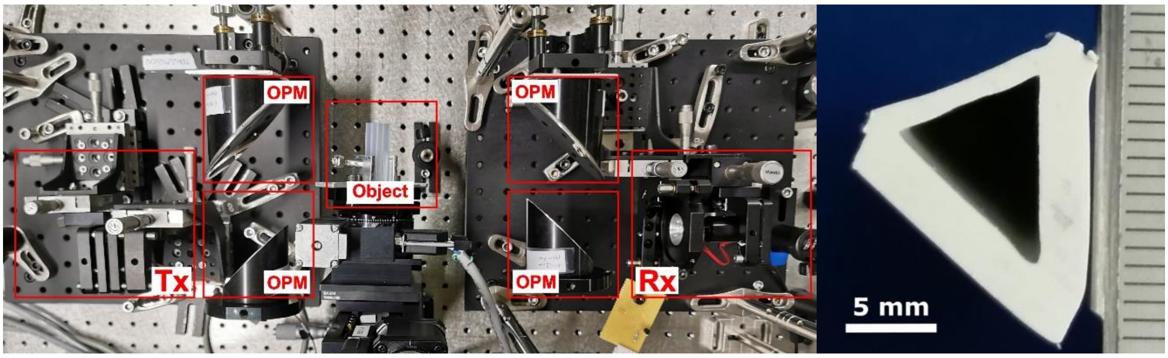

Fig. 4. (left) Image of the THz-TDS setup built in the lab. The THz radiation is guided by off-axis parabolic mirrors (OPM) and the sample is mounted on translation and rotation stages. (right) Image of scanned sample.

5. FUTURE PROJECT VISION

5.1. Technology Scaling

The immediate next steps to further develop our sensor to TRL 5-7 can be subdivided into three categories: hardware-, model- and reconstruction improvements. The hardware improvements will focus on making our laboratory setup faster, transportable and robust for industrial use. In addition, the system must be redesigned so that the antenna and emitter can be rotated instead of the sample. Such a THz-CT system is safe to operate for humans to operate, while at the same time enabling inline monitoring.

Next, our imaging model needs to be advanced to guarantee required accuracy and still be able to reconstruct the profile in real time. As shown above using time delay for reconstruction worked very well. Therefore, we will develop a method, which makes explicit use of it in the nonlinear model. This additional data set will be included in the reconstruction process to obtain a more accurate representation.

If there is only one other material besides air here, further improvements can be achieved by including this a priori knowledge. This can be done by using contour tomography or compressive sensing approaches.

For the next generation of our sensor, more research is required to develop emitters which can produce more powerful and higher bandwidth THz radiation and more sensitive detectors to penetrate larger samples.

5.2. Project Synergies and Outreach

A multi-disciplinary approach (physics, mathematics, mechanical engineering and computer science) is required to realize the TACTICS vision. A first step was created within ATTRACT Phase 1. The projects GRANT, HyperTERA, ROTOR and T-CONVERSE started the discussion to identify synergies at a meeting in Pisa last December, resulting in the organization of a session, entitled "Breakthrough detection and imaging technologies in the THz frequency range", within the 9th International THz-Bio Workshop . Due to the COVID-19 pandemic, the meeting is postponed to 2021.

Furthermore, the TACTICS project partners are research organizations and have a large network of partners from various disciplines. We are connected to the Austrian special research program Tomography across the scales, Austrian industrial research initiative for process analysis and Photonics Austria .

For dissemination we plan the following activities:

- *Online presence* — customer inquiries will be addressed by an informative and up-to-date website.
- *Large-scale industry trade events* — participation in trade shows, like the Hannover Industrie Messe or Photonics West.
- *Scientific dissemination* — publishing articles and participating in conferences.
- *Workshops* — reaching out to potential customers/ investors by organizing dissemination workshops.
- *Success stories* — distribution of more than one success story per year within the consortium networks, including the ATTRACT consortium.

5.3. Technology application and demonstration cases

Our technology has many advantages, such as the harmlessness, the large penetration depth, and the reasonable resolution. All this will enable real-time process monitoring in new areas. In ATTRACT Phase 2 we aim to demonstrate our technology for the following use case:

1. Inline monitoring during plastic extrusion.
2. Detection of small air inclusions in opaque glasses [5],[6].
3. Geometry and defect detection of ceramic based medical implants [7],[8].
4. Paper thickness control [9].

All the above use cases will contribute to a more efficient use of resources and energy. In the case of plastics extrusion it will also help to reduce waste by avoiding the production of faulty parts. An important application of use case 3 is to investigate the quality of load-bearing implants like hip replacements. An additional quality control minimizes the failure and therefore the necessity of a surgery. This will increase the health and life quality of people with hip replacements.

In the case of paper thickness detection we want to replace radioactive gauges currently in use with our harmless sensor, contributing to the health of workers.

Our reconstruction algorithm can be applied in many places, such as using it in conventional 2D-THz imaging and allows the transfer of CT to other wavelength regions.

5.4. Technology commercialization

RECENDT is a research organization trying to advance technologies of non-destructive testing from laboratory setup to industrial application. Here we will follow a two-way strategy:

1. To advance the THZ CT technology further using local (LIT Factory), national (FFG Bridge-1, FFG Early Stage, FFG Basisprogramm, AWS seed and preseed) and European funding programs.
2. Approach industry to identify use~~s~~ cases for our THZ CT based sensor and develop customer specific solutions.

We are currently further advancing our technology within the project ”Photonic sensing for smarter processes”. We plan to submit a dedicated research proposal in spring 2021. Since this project was started by a demand from the plastic extrusion industry, the company Semperit is interested as an early adopter.

5.5. Envisioned risks

Tab. 1. Critical risk of implementation.

Risk	Likelihood	Mitigation
Resolution is too low	Middle	Find new use cases where resolution is enough, Develop THz with higher bandwidth
Measurement time is too slow,	Low	Reduce number of measurements
Price is too high	Middle	Identify use case, where THz-CT is the only solution
Penetration depth is too small	High	Application to profiles with small diameters. Develop sources with more power.

5.6. Liaison with Student Teams and Socio-Economic Study

The TACTICS team strongly support students, exempli gratia ATTRACT Phase 1 was done by one Master and one PhD student. Future support will be done by:

- Inviting students to dissemination workshops.
- Hosting students in Linz to interview the project team.
- Designate a single contact point for interaction with the student team

6. ACKNOWLEDGEMENT

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