CT-based dimensional metrology developments in Brazil: Current status and outlook

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Abstract
Since the 1980s Computed Tomography (CT) has been used in many industrial sectors for non-destructive inspection, including flaw detection, failure analysis, and assembly analysis. Back to the 2000s CT has become a metrology tool for dimensioning and tolerancing analysis as well, in which some topics have gained attention of researchers, such as the traceability of a measurement result and the evaluation of the measurement uncertainty. In Brazil, the first two CT systems for dimensional applications were installed about a decade ago in two research centers. For years these two CT infrastructures for dimensional metrology allowed companies of different segments to benefit from the technique and made it possible for researchers to be involved in the field of CT for dimensional metrology. More recently, those promising initiatives have been drastically reduced for reasons such as the obsolescence of those CT infrastructures, despite the significant research efforts that have been observed in other venues. To reverse this negative outlook associated with the field of CT dimensional metrology in Brazil, this paper outlines an integrative framework for collaborative research and development in the subject, which encourages measures, e.g., to fund basic and applied researches, to train and educate people, and to support industries through measurement services and bespoke solutions.

Keywords: CT-based Dimensional Metrology, Research Infrastructure, Cooperation Framework

1 Introduction

X-ray Computed Tomography (CT) emerged as a technique for dimensional metrology in the 2000s, with the main attribute of enabling the complete characterization of single parts and assemblies, designed with internal geometries and produced, e.g., by additive manufacturing, which cannot be measured by other measurement technologies. The application of CT in the context of dimensional metrology brought with it the need to investigate properties hitherto little explored in previous uses, such as the traceability to the SI unit of length and the uncertainty associated with the result of a measurement. In this regard, the seminal paper by Kruth et al. [1] outlined the various factors that in some way affect a CT-based dimensional measurement, over which the CT metrologist can have some influence, as well as undesired effects that can disturb measurements.

In Brazil, CT was included in the suite of dimensional metrology tools in 2012 with the commissioning of two CT machines by different manufacturers designed for dimensional measurements, one at the Institute of Technological Research (IPT), public research institute linked to the Secretariat for Economic Development of the State of São Paulo, and another at the Federal University of Santa Catarina (UFSC), installed in the metrology infrastructure of CERTI (Reference Centers in Innovative Technologies) Foundation. The introduction of the CT technique into the portfolio of measurement solutions enabled different sectors of the Brazilian industry to take profit from the technology's capabilities, not only for dimensional quality control of single parts and assemblies, but also for material analysis and verification of different types of defects.

As a matter of fact, services used to be the major contributor to the operating rate of the CT facilities, particularly to compose the budget needed to cover the cost of ownership associated with CT and to mitigate the risks of technological obsolescence. The focus on measurement services, on the other hand, required research efforts in topics such as the understanding of the factors that affect the quality of the CT images and analyses, more specifically, the determination of the uncertainty associated with the result of a measurement. These researches were in part developed within bilateral cooperation programs funded by research funding agencies (e.g., DFG – German Research Foundation and Capes – Brazilian Coordination for the Improvement of Higher Education Personnel).

More recently, however, that promising scenario described in the previous paragraphs has been eroded as some critical pieces of the CT machines have reached the end of their lifespan. Being unavailable for use, CT-based measurement services could no longer be offered to the industrial segment and crucial experimental analysis related to, e.g., the topic of uncertainty evaluation, have been discontinued. Thus, people development has been drastically affected, either through training at the operational level or through scientific research at the academic level, even though research initiatives on topics related to CT metrology have occurred on many fronts, most of them in the northern hemisphere, in line with the growth expected for the industrial CT application, as reported by a recent survey [2] and the requirements imposed by Industry 4.0 [3].

To change the conjuncture outlined in the previous paragraph, which clearly applies to Brazil, but which may find some parallel in other developing countries, this paper proposes an integrative framework for collaborative research and development in CT-based dimensional metrology. Within the proposed framework, organizations dedicated to science, technology, and innovation (i.e., research and development centers and universities) are expected to work together, in a spirit of collaboration, with other

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parties involved and interested in developing and strengthening CT as an effective asset of dimensional metrology. The effective operation of the proposed framework should, therefore, would promote measures, e.g., to fund basic and applied researches, to train and educate people, and to support industries through measurement services and bespoke measurement solutions.

Before presenting the framework, a historical background of the initiatives in CT-based dimensional metrology of Brazilian institutions is given in the second chapter and a critical analysis of the current stage is made in the third chapter, which focuses on aspects such as the obsolescence of the CT infrastructure, the difficulty in developing people and preventing brain drain, the lack of international relevance, and the impossibility of small- and middle-sized companies to include CT-based measurements in their quality control loop. The fourth chapter outlines and discusses the cooperation model, which aims to draw up strategic plans for CT metrology facilities, tools, training services, and networks that position Brazil more competitively and promote one of the grounds of Industry 4.0: the continuous improvement in productivity. The conclusions are presented in the fifth chapter.

2 Historical perspective of CT-based dimensional metrology in Brazil

The introduction of CT technology for dimensional metrology in Brazil occurred at the beginning of the last decade from two independent initiatives carried out nearly simultaneously. One of them was associated with a three-year investment program to modernize the infrastructure of the IPT using resources from the Government of the State of São Paulo (more information can be found in IPT's 2010 annual report[1]). The other movement was spearheaded by the Laboratory of Metrology and Automation (LABMETRO) of UFSC and the Center for Metrology and Instrumentation (CMI) of CERTI Foundation using resources from the Metrology Network of PETROBRAS (more information can be found in CERTI's 2012 annual report[2] and PETROBRAS's 2012 technology report[3]). By mid-2012, two CT machines designed for dimensional measurements were com missioned in those science and technology institutions, allowing them to create and undertake new research and development lines and to offer unprecedented measurement services to Brazilian society.

Regarding people development in CT metrology, it is worth mentioning the intensive practice-oriented training in 2010 of two IPT researchers at the headquarters of Werth Messtechnik GmbH in Giessen, Germany. The training bases were laid down in a framework agreement for scientific and technical cooperation in coordinate metrology between the two parties. The training costs were fully covered by the IPT Foundation within the so-called International Development and Training Program (PDCE). Additionally, the Brazilian-German Collaborative Research Initiative on Manufacturing Technology (BRAGECRIM), funded by DFG and Capes, enabled the development of many bilateral research projects, two of them focused on CT metrology: CT-Metro (2009-2013) and IDD-Metro (2014-2018). Both CT-related projects were proposed and developed by CMI/CERTI and LABMETRO/UFSC (Brazil) together with the Laboratory for Machine Tools and Production Engineering (WZL) of RWTH Aachen University (Germany).

The two CT-related research projects associated with the BRAGECRIM program allowed students of the Graduate Program in Mechanical Engineering of UFSC to develop their researches and obtain their master's and/or doctoral degrees in Mechanical Engineering at UFSC (details in section 2.1). More recently, in 2020, the post-doctoral research project of a UFABC researcher at the Manufacturing Metrology Group of KU Leuven made developments in the topic 'measurement uncertainty' possible. The research project was financially supported by the São Paulo Research Foundation (FAPESP) and involved the geometrical characterization of a CT system and the modeling in computational software of dimensional measurement processes (details in section 2.2). Other studies were carried out with internal funding from the respective institutions, which impacted the insertion of some CT-based measurements in the laboratories' scope of accreditation, or supported by the second and third sectors of the economy, some with scientific profile and others with managerial profile (details in section 2.3).

2.1 Outcomes of bilateral research projects

Two master's theses and one doctoral dissertation were defended within the Graduate Program in Mechanical Engineering of UFSC in the years 2012-2013. The documents were written in Portuguese and the main outcomes can be summarized as follows:

- Development and experimental validation of test objects designed to emulate the specificities of measuring tasks performed on industrial CT systems[4].

[1] IPT - Institute for Technological Research of the State of São Paulo - Secretariat of Science, Technology, and Economic Development, 2010 Annual Report. Available at: https://www.ipt.br/download.php?filename=478-Annual_Report_2010.pdf (accessed 5 December 2022)

[2] CERTI - Reference Centers in Innovative Technologies, 2012 Annual Report. Available at: https://www.certi.org.br/en/files/RA-CERTI-2012-EN.pdf (accessed 5 December 2022)

[3] PETROBRAS Technology 2012. Available at: https://petrobras.com.br/lumis/portal/file/fileDownload.jsp?fileId=8A6E079642045DBE0142056664E026E2 (accessed 5 December 2022)

[4] dos Santos, Rafael Pacheco (2012) Development and validation of reference test objects for industrial computed tomography. Master's thesis, Graduate Program in Mechanical Engineering, UFSC (written in Portuguese)

- Experimental evaluation of two strategies to mitigate the uncertainty arising from thermal drifts: reducing the temperature variation and compensating the effect of thermal variation[5].
- Proposition of a structured method to select suitable CT settings for dimensional control considering the measurement accuracy and measurement time[6].

On the other hand, part of the results of these projects were presented in international conferences on computed tomography or published in peer-reviewed scientific journals. Nardelli et al. [4] outlined the experimental investigation of the influence of the extraction operation on CT-based dimensional measurements, in which the occurrence of aliasing could be observed depending on the number of voxels used to define the extracted features. Nardelli et al. [5] described the design and use of modular test parts to quantify different CT-induced measurement errors: scale deviations, edge-offset deviations, random surface deviations, and local deviations. This research line gave rise to an approach to assess the quality of the data extracted with CT systems used to perform dimensional evaluations [6].

In another perspective, Arenhart et al. [7] proposed the use of a so-called multi-wave standard, originally developed at PTB, Germany by Jusko and Lüdicke [8] for the calibration of form measuring instruments, to analyze CT-induced random surface deviations caused by, e.g., scattering and detector noise, relatively large voxel size, and relatively small number of projections. Later, Arenhart et al. [9] presented a multi-wave standard designed for evaluating the frequency response in extracting surfaces with CT systems and its use to evaluate some factors influencing the structural resolution of CT-based measurements. The use of the multi-wave standard was then extended in order to perform a comparative analysis on the use of image-based and surface-based metrics to assess the quality of CT-based dimensional data [10].

The findings of the master's degree project previously mentioned (de Oliveira, 2013), which encompassed the characterization and compensation of geometric errors induced by thermal drift in CT measurements, were presented in the International Symposium on Measurement Technology and Intelligent Instruments [11]. In the specific topic of measurement uncertainty, using the 'modular test parts' previously cited, the effect of influence factors intrinsic to CT-based measurements on the dimensional content of those parts, such as features of size (diameters) and form (roundness) was reported by Baldo et al. [12]. The authors observed a consistent error limit band that could be used to make generic uncertainty statements when considering test parts with similar characteristics.

2.2 Outcomes of bespoke developments

The CT metrology infrastructures previously described were able to provide measurement services for many industrial sectors: automotive, aerospace, electronics, metalworking, to name a few. Part of these services were concerned with the non-destructive analysis of defects in single parts and assemblies made of different materials. As an example of these services, one can mention the integrity analysis of the electron-beam weld joint between the turbine shaft and wheel of a turbocharger system [13]. In fact, the effectiveness of this kind of inspection relies enormously on the characteristics of the CT subsystems (particularly the x-ray source and the x-ray detector) and on the proper definition of the CT control settings by the metrologist.

Other CT-based measurement services involved the verification of dimensional tolerances of industrial parts featuring distinct shapes and materials and the comparison of the CT-based point cloud of a part (actual state) to the CAD model (nominal state) of that part (i.e., the part-to-CAD overlay comparison). In this regard, one can highlight the application of the ISO 15530-3 experimental approach to determine the uncertainty associated with the result of measurements of intrinsic characteristics (features of size) of a part that composes the drive system of a window lift mechanism. Particular attention was given to the design of experiment and to the measurement uncertainty components [14].

The professionals of the two institutions provided as well consultancy services in CT metrology topics. For instance, a general methodology for defining the quotation bases of an industrial CT system suitable for in-line quality control of light metal parts, which make up gasoline-powered handheld outdoor power equipment, was proposed by Baldo et al. [15]. To assist the buyoff activity, elements such as the measurement capability and throughput, machine reliability, data handling and exchange, and up-time performance were considered in the selection procedure. Based on the information provided by the CT manufacturers and on the custom tests, a decision matrix was created for final assessment of different CT systems.

Finally, Baldo et al. [16] experimentally evaluated a point-based compensation approach to correct known systematic effects of CT-based dimensional measurements. In principle, the method allows the user to reduce the measurement uncertainty down to the level of the CT measurement process repeatability. The method primarily relies on the calibration of the dimensional features of reference test part(s) on a measurement technology more accurate than CT, traceable to the SI unit of length, such as a classical

[5] de Oliveira, Fabrício Borges (2013) Investigation and reduction of thermal effects in dimensional measurements using computed tomography. Master's thesis, Graduate Program in Mechanical Engineering, UFSC (written in Portuguese)

[6] Nardelli, Victor Camargo (2012) Improvement of the metrological performance of computed tomography by means of the systematic selection of the setting parameters. Doctoral dissertation, Graduate Program in Mechanical Engineering, UFSC (written in Portuguese)

coordinate measuring machine. Then, measurements of the reference test part(s) on the actual CT system need to be carried out to create the compensation vector, which is later applied to the measurement of regular parts on that CT system.

2.3 Outcomes of other collaborative projects

Baldo et al. [17] described the experimental investigation of the geometric errors of a cone-beam CT system using an image-based measurement method to map them. Special attention was given to the evaluation of the effectiveness of the measurement method itself to detect the geometric errors, by properly designing the experiments and using statistical techniques such as the analysis of means and analysis of ranges, which combine the graphic power of average and range chart with the sensitivity of the analysis of variance. The measurement method was further investigated by the same research team [18] and the utilization of process behavior charts to operate the CT measurement process up to its full potential was presented as well in a separate conference paper [19].

To develop a broader understanding of the effect of different factors on the dimensional content of test parts, the construction of the digital representation of a CT measurement process using a simulation tool and the utilization of the virtual environment to study the relationships between input parameters and dimensional features of a prismatic test part were presented by Baldo et al. [20]. Some of the simulation results confirmed the overall empirical background: (a) the larger the inherent unsharpness, the lower the form error value; (b) the larger the inherent unsharpness, the larger the error for distances and sizes; (c) the higher the noise factor, the larger the form error value. However, questions could be raised on the accuracy of the virtual environment in predicting the systematic components of the measurement error.

3 Critical analysis of managerial practices

The measurement services provided with the CT infrastructure were very important to disseminate the technology in many sectors of the Brazilian economy and to complement the financial resources of the respective CT laboratories. The total cost incurred for making each measurement service was primarily used to set the basic price, which includes consumables such as cathode units and seals, regular maintenance items such as grid and insulator, professionals directly involved in measurements and analyses, and so forth. In order not to make the price prohibitive and to enable different industrial sectors to profit from the technology, replacement costs and major hardware and software upgrades (i.e., investment costs), were just partially included when pricing the measurement services. This strategy was intentionally adopted because some costs were part of the budget of some research projects, such as those related to the BRAGECRIM program, and technological development programs, such as the SIBRATEC (Brazilian System of Technology) program, both supported by federal funding agencies. These programs used to publish calls for project proposals on a regular basis and their maintenance was expected due to the positive results achieved by the initiatives.

Services used to be the major contributor to the operating rate of the CT machines, even in an attempt to cover the high cost of ownership associated with CT and to mitigate the risks of technological obsolescence. However, the unexpected interruption of research and development programs such as those cited in the previous paragraph, resulted in a scarcity of financial resources to maintain the CT infrastructures in prime operating condition and updated as the laboratories began to face the obsolescence of their CT systems. This way, the research activities that were once undertaken, most of them based on physical experiments, were largely discontinued, putting people development in jeopardy, and creating a marked contrast with the researches being currently carried out by international institutions. The fact that the technology has become inaccessible to a broad spectrum of companies established in Brazil, which used to order measurement services, is also noteworthy. Therefore, due to the relatively high acquisition and ownership costs of CT machines, sometimes prohibitive even for large companies, the potential increment in development and quality control results could no longer be observed in many industries.

Ironically, the yet long-lasting lack of resources for research and development initiatives in CT-based dimensional metrology has coincided with the advances in technologies that constitute the smart factories of Industry 4.0. This paradigm shift impacts the whole manufacturing sector, including metrology, which needs to be fast, accurate, reliable, flexible, and holistic in order to promote true data-driven production [3,21]. The Consultative Committee for Length (CCL) Working Group on Strategy (WG-S) made available a document reporting the major challenges and demands for coordinate metrology, including topics associated with CT (CCL Strategy 2018-2028). According with this report, metrological issues still need to be fully understood and resolved, related to the complex physical phenomena that occur during the measurement. In addition, there is no general agreement on proper standards to assure traceability to the SI unit of length and there is no far-reaching uncertainty evaluation method for arbitrary measurement tasks using CT.

4 Proposition of a research cooperation framework

Given the current daunting scenario, but aware of the contributions that have occurred mostly over the past decade, a research cooperation framework is conceived in order to reposition the CT-based dimensional metrology in Brazil and to overcome the technology-related issues in a structured and enduring manner. In this regard, some general principles (section 4.1), lessons learned and reference strategies (section 4.2), and funding reasons (section 4.3) are described prior to presenting and discussing the integrative model (section 4.4).

4.1 General principles

The formulation of the research cooperation framework for CT-based dimensional metrology takes into account some general principles, which are the following:

- The integrative framework is anchored in CT development priorities, dissemination of technology, and exchange of knowledge to generate value.
    - This means that both fundamental and applied researches can be undertaken within the framework, which can result in papers in peer-reviewed journals and/or directly influence services and customers.
- The integrative framework requires the involvement of institutions and/or individuals identified as critical to provide answers to the metrological issues associated with a multi-purpose measurement technique like CT.
    - This means that institutions/individuals doing researches that generate scientific knowledge and institutions delivering measurement services and consultancies can run collaborative projects with mutual benefits.
- The integrative framework relies on collaborative initiatives proposed by institutions and/or individuals that ought to observe well-known project management practices.
    - This means that collaborative projects eligible for financial aid from public/private sources must have clear goals and objectives, well-defined roles and responsibilities, project performance metrics, etc.

4.2 Reference initiatives

The general principles mentioned in the previous section for the research cooperation framework can find some parallel in other collaborative initiatives in Brazil and elsewhere. The Brazilian System of Technology (SIBRATEC) was established by decree no. 6259 from November 20th 2007 as one of the main instruments used by the Brazilian Government to integrate the scientific and technological community. To support the measurement infrastructures, networks of accredited laboratories were created and financed by the Brazilian Financier of Studies and Projects (FINEP). This funding program, however, was limited to a single call for project proposals in 2008. Since then, measurement infrastructures in Brazil have not been supported by initiatives like that just described, despite the proliferation of new technologies for coordinate measurements, such as CT.

The ongoing EU-funded xCTing project is an exemplary research initiative in CT metrology (https://doi.org/10.3030/956172). This research initiative comprises a consortium of nine beneficiaries/participants and six partner organizations working on some CT metrology issues, such as increasing autonomy, robustness, and speed, in order to meet the requirements imposed by smart factories. The overall concept of this collaborative research initiative is very interesting and could be replicated in a more inclusive fashion by adding, e.g., universities, research institutes, and other relevant players from other countries/continents. In fact, the interactions between academia and other stakeholders (e.g., industry and government) can be associated with the well-known triple-helix model of collaborative innovation [22].

4.3 Funding arguments

The research cooperation framework relies on public funding to pay for, at least in part, development and maintenance of CT-based measurement capabilities which are needed to support businesses. This cost-sharing strategy is one of the grounds of the proposed framework. The economic rationale for the existence of a publicly funded research and development in CT-based dimensional metrology is that the private investment needed to generate innovative measurement capability is not sufficient, as observed by the authors and described in the previous chapters. This occurs because the benefits that research and development in CT-based dimensional metrology produce spill over to companies that do not directly contribute to the development of new measurement techniques.

On the other hand, the fact that CT infrastructures generate revenue from measurement services and collaborative research projects indicates that they add value for their customers. The high costs involved with CT laboratories, however, prevent them of being self-financing infrastructures. This means that they would not be developed on the basis of private funds alone, despite the total benefits from the capability outweighing the cost. Therefore, presently, CT-based dimensional metrology can be seen as an infra-technology, i.e., a technology that provides novel capabilities which can be widely applied across a number of sectors to enable further innovation [23-25], which depends on a cost-sharing strategy to ensure that research staff has appropriate measurement capabilities needed to effectively serve society.

4.4 Framework arrangement

Based on the general principles listed in section 4.1, on reference cooperation programs, two of them mentioned in section 4.2, and on the infra-technology premise presented in section 4.3, the research cooperation framework for CT-based dimensional metrology is designed. Figure 1 illustrates the overall cooperation idea in which metrology players in Brazil could be inserted to collaborate more with the state-of-the-art of the CT technology. The framework focuses on the connections between the main metrology players and other interested parties, which would include public funding agencies. These connections are expected to effectively provide solutions to metrological issues found in CT-based dimensional metrology (concerned with, e.g., traceability, uncertainty, and calibration) and make the technology more globally disseminated. The proposed framework allows us to evidence the following outcomes.

- The research cooperation framework provides a supportive approach across the directly-involved entities in CT-based dimensional metrology.
    - Developers of CT solutions (manufacturers), providers of measurement services (enablers), institutions of science, technology, and innovation in CT metrology (R&D organizations), and enthusiasts of CT metrology.
- The research cooperation framework allows the directly-involved entities to set research and development priorities, to identify CT infrastructure needs, and to propose integrative projects.
- The research cooperation framework seeks to integrate the directly-involved entities in order to maximize research and development efforts and to minimize the opportunity costs of leaving capabilities behind.
    - This means that different technical skills, research and development agendas, and infrastructure resources can be combined in order to better address the metrological issues.
- The research cooperation framework is understood as a vehicle for improving CT-based dimensional metrology and providing accurate/reliable information in industrial applications.
- The research cooperation framework allows us to develop and disseminate suitable measurement practices, as well as to spread out important metrology concepts/principles.
- The research cooperation framework aims to create cross-border cooperation relations, thus including geographically-isolated, but not intellectually-isolated, research entities/individuals.
    - This globally research view attenuates the effects of country's economic fluctuations and crashes; therefore, it provides a more predictable environment for research and development.
- The research cooperation framework strengths the country's resilience of the economy and industrialization through suitable knowledge-exchange practices and individual initiatives aligned with recognized challenges and trends.
- The research cooperation framework focuses on fostering growth patterns that improve the knowledge dissemination and take full advantage of professionals/metrologists, technologies, and resources.

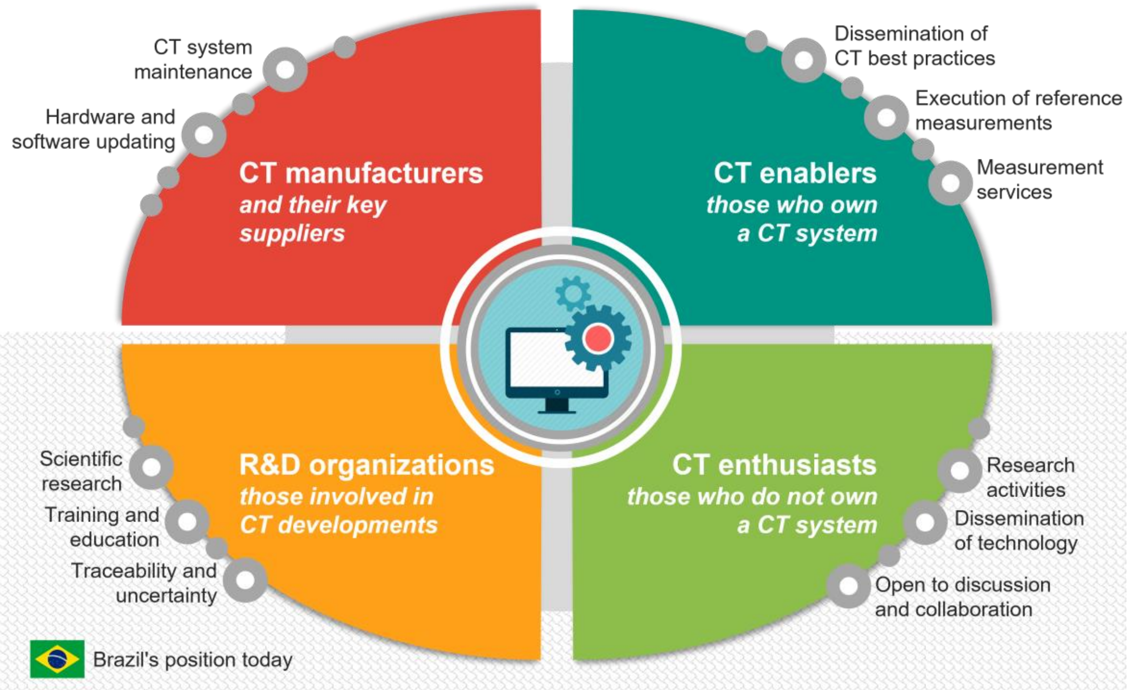

Figure 1: Illustrative scheme of a research cooperation framework for re-emerging CT-based dimensional metrology in Brazil, which includes the main players in dimensional metrology, some of them existing in Brazil as well, and their corresponding expectations.

The integrative framework is concerned with those directly and actively interested in research and development activities in CT-based dimensional metrology. The outcomes of these activities can have a positive impact in the industrial (routine) use of the CT technology. For example, reference measurements executed by some CT metrology infrastructure (CT enablers) can be later used by industry employees to estimate the systematic errors of specific CT measurements. Financially, the CT enabler can charge the industry for this measurement. Other activities, on the other hand, can be supported by public funding agencies, in a project-based format. The way to subsidize, private and/or public, can be based on successful strategies and financing models, as previously described. This is not the main thrust of this paper, which is much more concerned with the research connections, but a scheme of the funding operation for the research cooperation framework is illustrated in Figure 2, considering both public and private funds.

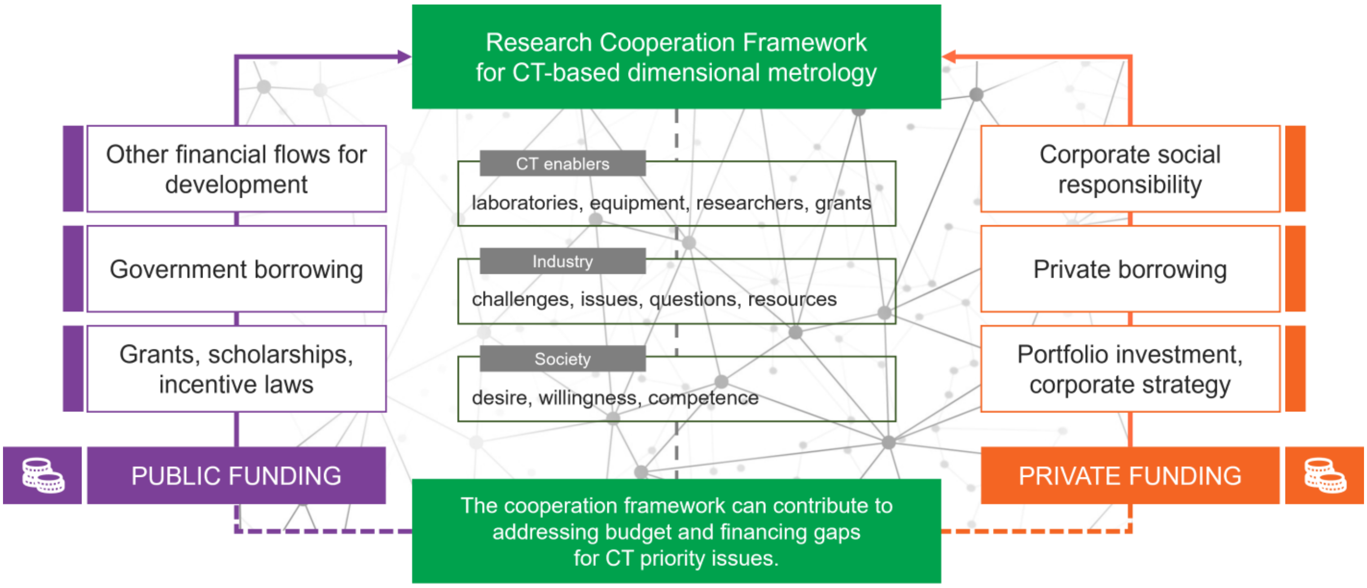

Figure 2: General concept of the public and private funding elements for the research cooperation framework for CT-based dimensional metrology; the main goal is to properly handle the existing financing gaps for metrological CT priority issues.

It is important to note that despite the existence of four main players in the framework, it is possible that the same organization operates in more than one quadrant. For example, there are R&D institutes that also provide measurement services (CT enablers) for industries. These measurement services involve developments and costs that can be covered by industries and, therefore, fund the operation. In this regard, the current position of Brazil in the field of CT-based dimensional metrology is highlighted in Figure 1. Basically, research and development organizations and enthusiasts, who are eager for cooperation, can be identified. For the reasons previously presented in this paper, no measurement services have been offered anymore as the CT infrastructures are out of operation.

5 Concluding remarks and outlook

In this paper, an integrative model for research collaboration in CT-based dimensional metrology was proposed and discussed with the express purpose of reversing the current scenario of that metrology field in Brazil. Shedding light on some of the CT-related metrological issues, the primary goal of the proposed framework is to build networks and to intensify ideas and efforts in favor of enhancing the state-of-the-art of CT technology. In fact, the operation of the research cooperation framework is aimed to result in practices, strategies, and actions that would allow the interest parties to strengthen and disseminate the use of CT as an effective and reliable dimensional metrology technique. For example, the uncertainty determination for task-specific dimensional measurements could be based on different approaches, such as experimental analyses, computer simulations, and even in a hybrid format. Research networks, in this sense, would be very beneficial to develop the full potential of researchers (research groups) from different organizations/countries.

The authors of this paper believe that reasonable solutions to difficult problems, such as the determination of the measurement uncertainty - therefore, the metrological traceability to the SI unit of length - in CT metrology, can be found if, and only if, the metrologists/researchers from different organizations and different backgrounds work together for a particular purpose within collaborative projects. These cooperations would allow involved parties to share their perceptions and experiences, therefore favoring the accumulated knowledge for continuous improvement of CT-related metrological issues. The research cooperation framework, as a vehicle for supporting the CT metrology transformation, aims to provide guidance on reframing practices in CT-based dimensional metrology, make the technology more suitable for the industrial use, produce more reliable (accurate) measurements, and be inclusive, i.e., not leaving no one behind, such as developing countries. Finally, although the framework was proposed considering the experience of the authors with the CT-based dimensional metrology circumstances in Brazil, the framework can be seen as well as an example and inspiration for other countries.

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