Foreword The present paper aims at reviewing the major developments in Digital Volume Correlation (DVC) over the past ten years. It follows the first review on DVC that was published in 2008 by its pioneer [11]. In the latter, the interested reader will find all the general principles associated with what is now called local DVC. They will not be recalled hereafter. In such approaches the region of interest is subdivided into small subvolumes that are independently registered. In addition to its wider use with local approaches, DVC has been extended to global approaches in which the displacement field is defined in a dense way over the region of interest. Kinematic bases using finite element discretizations have been selected. To further add mechanical content, elastic regularization has been introduced. Last, integrated approaches use kinematic fields that are constructed from finite element simulations with chosen constitutive equations. The material parameters (and/or boundary conditions) then become the quantities of interest.

前言本文旨在回顾主要发展数字量相关性 (”) 在过去的十年。它遵循第一个评论” 于 2008 年出版的先锋 [11]。在后者, 感兴趣的读者会发现所有的一般原则与现在叫当地的陷落。他们不会被召回以后。在这种方法中感兴趣的区域分为几个子卷独立注册。除了广泛使用与本地方法,” 已经扩展到全球位移场的方法定义在一个密集的方式对该地区的兴趣。运动基地利用有限元离散被选择。进一步增加机械内容, 并介绍了弹性正规化。最后, 集成方法使用运动学字段与选择由有限元模拟的本构方程。材料参数 (和/或边界条件), 那么成为大量的利益。

These various implementations assume different degrees of integration of mechanical knowl- edge about the analyzed experiment. First and foremost, DVC can be considered as a stand-alone technique, which has seen its field of applications grow over the last ten years. In this case the measured displacement fields and post-processed strain fields are reported. With the introduction of finite element based DVC, the measured displacement field is continuous. It is also a stand- alone technique. However, given the fact that it shares common kinematic bases with numerical simulations, it can be easily combined with the latter. One route is to require local satisfaction of equilibrium via mechanical regularization. Another route is to fully merge DVC analyses and numerical simulations via integrated approaches. Different examples will illustrate how these var- ious integration steps can be tailored and what are the current challenges associated with various approaches.

这些不同的实现承担不同程度的一体化的机械知识, 边分析实验。首先,” 可以被视为一个独立的技术, 其应用领域的增长在过去的十年。在这种情况下, 测量位移场和后续处理应变场。通过引入基于有限元的陷落, 测量位移场是连续的。这也是一个独自站——技术。然而, 考虑到股票普遍与数值模拟运动基地, 它可以很容易地与后者相结合。一种路线是通过机械正规化需要地方满意的平衡。另一个途径是完全合并” 通过综合分析和数值模拟方法。不同的例子将说明这些 var -借据集成步骤可以定制和当前的挑战是什么相关的各种方法。

DVC: Achievements and Challenges 3 Contents 1 Introduction . . . . .

1 Introduction Computed (x-ray) tomography (CT), magnetic resonance imaging (MRI), optical coherence to- mography (OCT), positron emission tomography (PET), single photon emission computed to- mography (SPECT) are five well-known modalities in the medical field. They have revolutionized the way medical diagnosis is performed [102, 138, 167]. The new opportunities offered by these 3D imaging techniques have led to considerable instrumentation developments since the mid 90s, and increased accessibility have made microtomography one tool of choice in material science [142, 200, 208]. It is possible to inspect internally industrial or natural materials [8, 51] using lab tomographs or tomography beamlines at synchrotron radiation facilities. The microstructure of different ma- terials can be visualized and quantified in nondestructive or minimally intrusive manner [208, 144].

1 介绍计算 (x 射线) 断层扫描 (CT)、磁共振成像 (MRI), 光学相干——mography(10 月), 正电子发射断层扫描 (PET)、单光子发射计算——mography (SPECT) 五个著名的医学领域的模式。他们已经彻底改变了医学诊断 (102、138、167) 执行。这些 3 d 成像技术提供的新的机会导致相当大的仪器自 90 年代中期以来, 发展和提高可访问性 microtomography 材料科学选择的工具之一 (142、200、208)。可以检查内部工业或天然材料 (8,51) 使用同步辐射实验室层析 x 射线摄影机或断层 beamlines 设施。的微观结构不同的马——terials 可以可视化和定量无损或最小程度的方式 (208、144)。

For diagnosis, treatment and basic science [102] among other reasons, there is a need for de- veloping intra- and inter-modality registrations [228, 141, 102]. In particular, following temporal motions of bones or tissues calls for registering different images for a better apprehension of qual- itative and quantitative changes. Here again, medical applications have been a major driver for very early works especially from the image processing community (optics and applied mathemat- ics). The same benefit is found in materials science, when the same sample is imaged in the bulk at different levels of load. Localization bands were first revealed within sand samples when x-rayed ex-situ [50].

诊断、治疗和基础科学 [102] 等原因, 需要 de -材料内部和 inter-modality 注册 (228、141、102)。特别是时间运动后骨头或组织要求注册为一个更好的

理解不同的图像定性——itative 和定量的变化。在这里, 医学应用一直是一个主要推动力的非常早期作品特别是图像处理社区 (光学和应用数学- ics)。相同的好处是材料科学中发现, 当相同的样本成像在大部分在不同级别的负载。本地化乐队首次揭示了在砂样品当 x 光检查让其它 [50]。

Specific loading apparatus were subsequently designed to be compatible with the absorption of x-rays to perform in-situ tests. This is one critical element to consider when designing such testing devices [85, 12, 56]. Mechanical experiments coupled with x-ray tomography began with the observations of crack openings in aluminum alloy [85]. Other tests coupled with in-situ tomographic observations were developed over the years [26]. Significant progress was made in the design of new testing setups and more importantly on the understanding of various degradation mechanisms DVC: Achievements and Challenges 5 that could only be revealed thanks to observations in the bulk of materials [56, 26]. Depending on the imaging modality and the studied material, the loading device had to be adapted to the experimental environment [14, 164, 72].

具体加载装置随后被设计为兼容的吸收 x 射线进行现场测试。这是一个关键的元素在设计时要考虑这样的测试设备 (85、12、56)。机械实验加上 x 射线断层扫描始于裂缝开口的 ob -预约了铝合金 [85]。其他测试加上现场层析观测是多年来 [26]。取得重大进展的设计新的测试设置, 更重要的是了解各种退化机制” 的: 成就和挑战 5 只能显示由于观察的大部分材料 [56 岁 26]。根据成像模式和研究材料, 装载设备必须适应实验环境 (14、164、72)。

Having access to ex-situ or in-situ observations during different types of loading histories, the next critical step was the measurement of displacement fields in the bulk of imaged samples.

获得让其它或原位观测在不同类型的加载历史, 下一个关键步骤是位移的测量领域的大部分样品的成像。

The first 3D displacement measurements via so-called Digital Volume Correlation (DVC) were performed on trabecular bone compressed in-situ in a computed microtomographic (CT) scan- ner [12]. A local approach was implemented. Other applications followed in the field of biomechan- ics (e.g., see Refs. [194, 11, 106, 241, 17, 193, 44, 40, 43, 109]). At the beginning of the current decade, DVC was clearly identified as one technique very suited to biomechanical applications [239]. For instance, local variations in microstructure were associated with failure patterns in the verte- bra [220]. The internal strain and failure in prophylactically-augmented vertebrae were studied thanks to DVC analyses [47]. The authors showed that the failure initiated inside the augmented vertebral body, next to the injected cement mass. Noninvasive assessments of the intra-vertebral heterogeneity in density improved the predictions of vertebral strength and stiffness [107].

第一个三维位移测量通过所谓的数字进行骨小梁体积相关 (”) 原位压缩在一个计算 microtomographic(CT) 扫描-尼珥 [12]。当地的一个方法是实现的。领域的其他应用程序遵循 biomechan - ics(例如, 见参考文献。(241 年 106 年 194 年,11 日,17 日,193 年,44 岁,40 岁,43 岁,109])。在当前的十年的开始,” 显然是认定为一种技术非常适合于生物力学应用 [239]。例如, 当地的微观结构变化与失效模式相关的植物香——胸罩 [220]。的内部压力和失败

prophylactically-augmented 椎骨进行了研究 [47] 由于" 的分析。作者表明, 增强椎体内部的失败开始, 在注入水泥质量。无创性评估 intra-vertebral 异质性的密度改善椎体强度和刚度的预测 [107]。

In solid mechanics, different classes of materials were investigated thanks to DVC measure- ments. Very early on, various types of foams were imaged via tomography and their behavior was studied thanks to DVC [207, 11, 197, 181, 59, 15, 64]. The degradation mechanisms of such materials in indentation experiments received some attention [231, 20, 22]. One of the reasons is that tomog- raphy reveals their in-situ temporal development, which can only be assessed post-mortem with other investigations. Such observations were subsequently compared with numerical simulations for (in)validation purposes [201, 21].

在固体力学中, 不同类别的材料研究由于陷落衡量的。从很早开始, 各种类型的泡沫通过断层成像和他们的行为, 研究了由于陷落 (181 年 197 年 207 年,11 日,59 岁,15 岁,64]。这种材料的降解机制在压痕实验中得到一些关注 (231、20、22)。的原因之一是,tomog——raphy 揭示他们的现场时间发展, 只能进行事后评估与其他调查。随后这些观测与数值模拟 () 验证目的 (201 年,21)。

Localized phenomena are situations in which full-field measurements make a (huge) differ- ence (e.g., strain localization [127, 1, 214, 49] and cracks [198, 231, 94]). This is particularly true when kinematic measure- ments can be performed nondestructively in the material bulk. Very het- 6 A. Buljac et al.

本地化现象是藉由此产生的情况下 (巨大的) 不同- ence(例如, 应变局部化 (127,214,49) 和裂缝 [198、231、94])。尤其如此, 当运动测量可以执行无损材料的体积。het - 6。Buljac et al。

erogeneous strain fields were measured by global DVC in a compression test on polypropylene solid foam [197]. When analyzing compressed stone wool, it was shown that the material density was responsible for local hetero- geneities in strains, and that correlations existed between local density and strain [97]. Similar trends were observed in low density wood fiberboard [222]. For cellulose fiber mats correlations between high density gradient zones and maximum eigen strains were reported [112]. More recently it was shown that the volume change in Si-based electrodes increased with the lithiation degree, while the gray levels decreased with respect to the original (i.e., nonlithiated) state [178].

erogeneous 应变场测量全球陷落在聚丙烯固体泡沫压缩试验 [197]。在分析压缩石头羊毛, 结果表明, 材料密度在菌株负责当地的异构性问题, 这地方密度和应变的相关性 [97]。类似的趋势也发生在低密度纤维板木材 [222]。对纤维素纤维垫高的密度梯度区和最大特征之间的相关性菌株被报道 [112]。最近表明, 体积变化在 Si-based 电极与 lithiation 程度增加, 而降低对原始灰度值 (即。[178],nonlithiated) 状态。

Nodular graphite cast iron, which is a model material for DVC analyses, has been extensively studied. Crack initiation was analyzed in very high cycle fatigue experiments with evaluated strain fields [66]. Stress intensity factor profiles were extracted from experimentally measured displace- ment fields [133]. Crack opening displacements were also evaluated in graphite via DVC [160, 163]. A single macrocrack was studied in a double torsion experiment on recrystallized porous silicon carbide by analyzing displacement and correlation residual fields [128]. Delamination in layered composites was quantified with the use of displacement [125] or strain [19] fields. Crack propagation features were analyzed. In particular, the local crack propagation law was extracted from the kinematic measurements [132]. Likewise, crack initiation was observed in cast aluminum alloy with kinematic and residual fields [234]. Short fatigue cracks were analyzed in cast magne- sium alloy with the measured bulk displacement fields [147]. Stress intensity factor profiles were extracted from the analysis of a short fatigue crack in cast iron [119]. Such analyses are very challenging since the graphite nodules interact with short cracks.

结节性石墨铸铁, 模型材料” 的分析, 已进行了广泛的研究。分析了裂纹萌生在高周疲劳实验评估应变场 [66]。应力强度因子信息提取的实验测量, [133]。裂纹张开位移也评估石墨通过陷落 (160、163)。一个宏观裂纹在再结晶双扭实验研究了多孔碳化硅通过分析位移和相关剩余领域 [128]。在分层的复合材料分层量化使用位移 [125] 或 [19] 字段。裂纹扩展特性进行了分析。特别是当地的裂纹扩展法是提取运动学测量 [132]。同样, 观察裂纹萌生与运动学和残余铸造铝合金领域 [234]。分析了短裂纹在演员玛格尼- sium 合金测量体积位移场 [147]。应力强度因子信息提取分析的一个简短的疲劳裂纹在铸铁 [119]。这种分析非常具有挑战性, 因为石墨结节与短裂缝。

Granular materials usually possess sufficient x-ray absorption contrast to enable for DVC analyses [69]. Force chains in Mason sand was evaluated by considering the minor eigen strains evaluated via DVC measurements [103]. The analysis of multiple debond cracks was shown to be possible in a tensile test on a propellant-like material thanks to global DVC by using the DVC: Achievements and Challenges 7 correlation residuals [95]. The same mechanism was found in polymer bonded sugar in uniaxial compression [104]. The gray level residuals were also used to detect matrix/nodule debonding in cast iron [93, 219, 29]. Maximum eigen strain fields enabled multiple microcracking to be quanti- fied in brittle materials [101, 231, 94, 240] and damage in SiC/SiC composites [201]. Other strain descriptors such as the first and second invariants were used to detect cracks [38].

颗粒材料通常具有足够的 x 射线吸收的对比使” 的分析 [69]。力链在梅森沙子被考虑到次要特征评估压力评估通过” 测量 [103]。多个脱胶裂缝的分析被证明是可能的在 propellant-like 材料拉伸试验由于全球” 使用”: 成就和挑战 7 相关残差 [95]。相同的机制被发现在聚合物结合糖单轴压缩 [104]。灰度残差也用于检测矩阵/结节脱胶铸铁 (93、219、29)。最大特征应变场启用多个微裂缝 quanti, 公然反抗在脆性材料 (101、231、94、240) 和损伤 SiC /碳化硅复合材料 [201]。等应变描述符第一和第二不变量被用来检测裂缝 [38]。

The effect of temperature on the material response was analyzed thanks to ex-situ and in-situ tests. Cracking induced by accelerated (i.e., ex-situ) desiccation of a cement paste containing glass beads was quantified via DVC [101]. Similarly, accelerated maturation of Kimmeridge clay was monitored in-situ up to 380°C [63] with 2-min acquisitions of 1800 radiographs. Sintering of copper was monitored in-situ at 1050°C. The motion of particles and shrinkage (i.e., volumetric) strain fields were evaluated [151]. This type of approach corresponds to the first step toward model validation of sintering processes. In-situ thermomechanical tests have started in part thanks to fast acquisitions on synchrotron lines. Fatigue initiation and propagation mechanisms were analyzed in-situ at temperatures up to 250°C in cyclic tensile tests on Al-Si alloy [45]. The duration of each tomographic scan was 45 s. Thanks to fast acquisitions (i.e., 4 s for 720 acquired projections per tomogram) damage mechanisms were observed and quantified in terms of strain fields during in-situ uniaxial compression of a semi-solid Al-Cu alloy at 550°C [32].

分析了温度对材料的影响反应由于让其它和原位测试。引起的开裂 (即加速。让其它) 干燥的水泥浆含有玻璃珠是量化通过" [101]。同样, 加速成熟 Kimmeridge 粘土原位监测到 380°C[63] 2 分钟收购的 1800 片。烧结铜原位监测在 1050°C。粒子的运动和收缩 (即。, 体积应变场进行评估 [151]。这种类型的方法对应于烧结过程的模型验证的第一步。原位热机械的测试已经开始在一定程度上得益于快速收购同步线。疲劳引发和传播机制分析了原位温度高达 250°C 对铝硅合金在循环拉伸测试 [45]。每层析扫描的时间是 45 岁。由于快速收购 (即。,4 s / x 线断层照片)720 年收购了预测损伤机制观察和量化的应变场的现场单轴压缩过程中行业半固态合金在 550°C [32]。

Most of the DVC analyses reported so far were based upon x-ray CT. This technique is suited to elongated (e.g., axisymmetric or cylindrical) samples. However, plate-like samples can also be imaged via computed laminography [87]. When compared to CT [131], it leads to higher levels of measurement uncertainties [156], which are partly due to the missing spatial frequencies and reduced resolution of laminographic scans along the rotation axis [238]. However, it could still be used to analyze the flat-to-slant transition of ductile tearing of aluminum alloys for low stress triaxialities with global DVC [156, 158, 30] and regularized DVC [214, 157].

到目前为止, 大多数陷落的分析报告是基于 x 射线 CT。这种技术适用于细长的 (例如, 轴对称或圆柱) 样本。然而, 弹性板样品也可以成像, 通过辐射分层照相术 [87]。相比 CT[131], 它会导致更高水平的测量不确定性 [156], 这一定程度上是因为缺少空间频率和分辨率降低 laminographic 沿着旋转扫描轴 [238]。然而, 它仍然可以被用来分析韧性撕裂的 flat-to-slant 过渡的铝合金低应力三轴与全球陷落 (156、158、30) 和正规化陷落 (214、157)。

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Registration of medical Magnetic Resonance images has been carried out for a long time for diagnosis and treatment purposes (e.g., see Refs. [228, 209, 141, 102, 199, 195]). Conversely, there are very few results of in-situ mechanical tests imaged via MRI or MRI. Global DVC was applied to the analysis of a compression test on cancellous bone [14]. It was shown that the measurement uncertainties were at most of the same order as for CT and that very early on such materials did not deform uniformly. Global DVC was applied to cardiac magnetic resonance images of a healthy human subject. A finite strain regularization framework was implemented [76].

注册医疗磁共振图像进行了很长一段时间用于诊断和治疗 (例如, 见参考文献。(228,209,141,102,199,195])。相反, 很少有原位力学测试的结果通过核磁共振成像或 MRI。全球" 的应用于压缩试验的分析松质骨 [14]。结果表明, 测量不确定性在大多数相同的顺序等早期的 CT 和材料变形不均匀。全球" 的应用于人类健康的心脏核磁共振图像主题。有限应变正则化框架实施 [76]。

All the previous examples dealt with opaque (to the human eyes) materials. For transparent materials, other methods can be used. For instance, fluorescence confocal microscopy was used to measure 3D displacements of compressed aragose gel containing fluorescent particles. In that case, the warping of each sub-volume was described by six degrees of freedom (i.e., three translations, and three diagonal component of the stretch tensor [71]). Laser-scanning confocal microscopy can also be used to measure the deformation of the same material [105]. So-called cellular surface traction forces were determined by combining the previously mentioned imaging technique and DVC [148]. It was also shown that contractile forces regulate cell divisions [129]. Randomly dis- tributed particles in transparent resins scatter light when illuminated by a planar laser beam [77].

所有前面的例子处理不透明材料 (对人类的眼睛)。透明材料, 可以使用其他方法。例如, 荧光共焦显微镜是用来测量的三维位移压缩 aragose 凝胶含有荧光粒子。在这种情况下, 每个 sub-volume 的扭曲被六自由度 (即。三个翻译, 三对角拉伸张量的分量 [71])。激光扫描共焦显微镜也可以用来测量变形 [105] 相同的材料。所谓细胞表面牵引军队由结合前面提到的成像技术和" [148]。它也表明, 收缩力量调节细胞分裂 [129]。随机说——致敬在透明树脂粒子散射光线下平面激光 [77]。

When the position of the laser beam is changed, a stack of planar slices is obtained and can be registered by DVC. When compared to CT data, similar uncertainty levels were reported. Optical coherence tomography is another 3D imaging technique to image semi-transparent materials. It was shown that full-field OCT setups were well adapted to perform static elastography of tissue samples via regularized DVC [164]. Local DVC was used to monitor an inflation test on porcine cornea [72].

当激光光束的位置变了, 一堆平面片陷落, 可以获得注册。CT 数据相比, 类似的不确定性水平报道。光学相干断层扫描是另一个 3 d 成像技术图像半透明材料。结果表明, 细致的 10 月设置适应执行静态弹性成像的组织样本通过正规化" [164]。当地的陷落是用于监控通货膨胀试验猪角膜 [72]。

This non exhaustive literature review shows that many applications have been made possible thanks to the use of 3D imaging techniques combined with early ex-situ and now more frequently in-situ mechanical tests. DVC is becoming a tool of choice to quantify various deformation and DVC: Achievements and Challenges 9 failure mechanisms. Gradually experimentally measured displacement fields are being compared with 3D numerical simulations for validation and identification purposes. To further illustrate the increased interest in DVC analyses, Figure 1 shows the yearly number of citations counted by the "Web of Science" platform. The one hundred mark was reached in 2010.

这非详尽的文献综述表明, 许多应用程序都能够使用 3 d 成像技术结合早期让其它现在更频繁地原位力学测试。" 正在成为一个选择的工具量化各种变形和陷落: 成就和挑战 9 失败机制。逐渐被比较的实验测量位移场与三维数值模拟进行验证和识别目的。" 的分析进一步说明增加兴趣, 图 1 显示了引用计数的每年 "网络科学" 的平台。在 2010 年达成了一百大关。

Fig. 1 Number of citations when the chosen topic is "Digital Volume Correlation" via Web of Science search on June 23, 2017 Even though many achievements have been reported, a number of cases/materials remain challenging. This papers aims at discussing many of them. However, the first required step is to summarize various 3D imaging techniques and to describe the possible artifacts they may induce in their quantitative use via DVC analyses. The next step is to review issues associated with ex-situ and in-situ mechanical tests. Various DVC approaches have been proposed in the last two decades. They are summarized and illustrated with examples. In order not to duplicate the existing review on local approaches [11], more emphasis is put on global approaches. One key aspect of DVC analyses is their uncertainty quantification, which is partly related to the way 3D images are obtained. Last, some research directions are sketched to address questions and 10 A. Buljac et al.

图 1 的引用时, 选择的主题是 "数字量相关性" 科学通过 Web 搜索 6 月 23 日, 已报告 2017 尽管许多成就, 病例数/材料仍然具有挑战性。本论文旨在讨论很多。然而, 所需的第一步是总结各种 3 d 成像技术, 描述可能的他们在定量使用可能引起工件通过" 的分析。下一步是与让其它相关审查问题和原位力学测试。提出了各种" 的方法在过去的二十年。他们用实例进行了总结和说明。为了不重复现有的审查在当地方法 [11], 更多的重点放在全球的方法。" 分析的一个关键方面是他们的不确定性量化, 这部分相关的 3 d 图像。最后, 一些研究方向勾勒出解决问题和 10。Buljac et al。

limitations of current implementations of DVC algorithms and their subsequent use for modeling and simulation purposes.

陷落的当前实现算法的局限性及其后续使用建模与仿真的目的。

2 Three-dimensional imaging of unloaded and loaded materials 2.1 Three-dimensional imaging of materials The aim of this section is not to give an exhaustive and detailed overview of 3D imaging. The reader will find general sources of information in all of the discussed techniques. Rather the focus is put on the possible consequences of the use of each technique in conjunction with DVC analyses (e.g., artifacts induced by the acquisition process).

2 三维成像的卸载和加载材料 2.1 的三维成像材料本节的目的是给出一个详尽的和 3 d 成像的详细概述。读者会发现一般的信息来源在所有的技术讨论。而重点是放在每个技术的使用可能带来的可怕后果的结合" 的分析 (例如, 收购过程引起的工件)。

2.1.1 Tomography and laminography X-ray computed tomography (or CT) produces 3D images of objects from a set of 2-dimensional x- ray images (i.e., projections). In a CT system, the component to be imaged is placed on a turntable or a rotating axis between the radiation source and the imaging system. While the sample is rotated, the digital detector records a large set of 2D x-ray images for different angular positions.

2.1.1 断层和辐射分层照相术 x 射线计算机断层扫描 (CT) 产生 3 d 图像的对象从一组 (即二维 x -射线图像。预测)。在 CT 系统中, 组件成像是放在一个转盘或辐射源之间的旋转轴和成像系统。样品旋转时, 数字检波器记录大量的 2 d x 射线图像不同的角位置。

The x-ray attenuation (or sometimes phase contrast) map is then computed or reconstructed from these 2D projections. Various algorithms are available to carry out this reconstruction [114]. The x-ray source is either produced in a synchrotron facility (for which the x-ray beam is generally parallel, monochromatic and coherent) or by an x-ray tube (e.g., microfocus sources) for lab tomographs where the beam is cone shaped, polychromatic and incoherent. The typical resolution is of the order of 1 to 10 m per voxel for micro-CT. Therefore x-ray microtomography is sometimes referred to as x-ray microscopy [55, 177].

x 射线衰减 (或有时相差) 从这些 2 d 地图然后计算或重建的预测。各种算法可用于执行这个重建 [114]。产生的 x 射线源是在同步加速器设施 (x 射线的通常是平行的, 单色相干) 或通过 x 光管 (如微焦点来源) 实验室梁的层析 x 射线摄影机锥形状, 多色和不连贯。典型的分辨率是 1 到 10 的 m / ct 机的体素。因此 x 射线 microtomography 有时被称为 x 射线显微镜 [177]。

There are numerous sources of artifacts in computed tomography [48]. Some of them lead to gray level variations (e.g., beam hardening with polychromatic x-ray sources), specific curves DVC: Achievements and Challenges 11 (e.g., streak or ring artifacts) and some are associated with spurious motions (e.g., source motion for lab systems, sample motion, wobbling) that degrade the reconstruction qualities. Not all of them are impacting DVC analyses. However, careful analyses should be performed to evaluate measurement uncertainties before reporting any result (see Section 4).

有许多来源的工件在计算机断层扫描 [48]。其中一些导致灰度变化 (例如, 射束硬化与多色 x 射线源), 具体的曲线”: 成就和挑战 11(例如, 条纹或环构件) 和一些与假动作 (如源运动实验室系统, 样品运动, 摆动), 降低重建质量。并不是所有的影响” 的分析。然而, 仔细分析应该执行评估测量不确定性在报告任何结果 (见第 4 节)。

In tomography, the rotation axis is perpendicular to the x-ray beam. Consequently, most of the imaged samples have stick-like shapes so that the total x-ray attenuation does not vary too much between different angular positions. If the rotation axis is no longer parallel to the detector plane, then thin sheets can be imaged. This type of imaging configuration is designated as laminography [87], which is used for non destructive evaluations (NDEs) in the micro-electronics industry [81], but micrometer resolution is restricted (up to now) to synchrotron facilities thanks to the use of parallel beams.

在断层扫描, 旋转轴垂直于 x 射线光束。因此, 大多数的成像样品有设置形状, 这样总 x 射线衰减不同角位置之间相差太多。如果旋转轴不再是探测器平面平行, 然后薄片可以成像。这种类型的成像配置指定为辐射分层照相术 [87], 用于微电子行业的非破坏性评估 (濒死经历)[81], 但微米分辨率限制 (到目前为止) 同步加速器设备由于使用平行光束。

All the artifacts listed above for computed tomography may occur in computed laminography as well. Further, it is noteworthy that the sampling of the 3D Fourier domain of the region of interest is incomplete in laminography [88], which leads to additional imaging artifacts [238].

上面列出的所有工件的计算机断层扫描可能发生在辐射分层照相术。此外, 值得注意的是 3 d 的傅里叶域中的抽样地区的兴趣是不完整的辐射分层照相术 [88],[238] 导致额外成像工件。

These artifacts may degrade the displacement and strain resolutions when DVC is applied [156].

这些工件可以降低位移和应变分辨率陷落时 [156]。

In Section 4.1, displacement and strain uncertainties are studied for three different materials that are imaged via laminography. Figure 2 shows sections of the three reconstructed volumes. For the two aluminum alloys, the volume fraction of features (i.e., pores and secondary inclusions) to be used in DVC analyses is less than 0.8

在 4.1 节, 位移和应变的不确定性研究了三种不同的材料, 通过辐射分层照相术成像。图 2 显示了部分重建的三卷。两个铝合金的体积分数的特性 (即。、毛孔和二级夹杂物) 用于” 的分析 AA2139 坡度小于 0.8

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(a) AA2139 (b) AA2198 (c) GJS-400 Fig. 2 Mid-thickness section in 3D reconstructed volumes of two different aluminum alloys and one cast iron sample. The picture definition is 2040 × 2040 pixels for aluminum alloys and 1600 × 1600 for cast iron. The physical length of one voxel is 0.7 m for aluminum alloys and 1.1 m for cast iron. The ring artifacts from static features on the projection radiographs are visible (especially for sub-figures (a) and (b)) Nanotomography is nowadays accessible in synchrotron facilities and even lab tomographs thanks to various focussing devices of x-ray beams [237]. Resolutions as low as 20 nm can be achieved in synchrotron facilities [144]. This type of resolution requires very stable systems and very accurate actuation to allow for meaningful reconstructions. Nanolaminography was also shown to be feasible very recently at the European Synchrotron Radiation Facility [90].

(a) AA2139 (b) AA2198 (c) 数次- 400 图 2 Mid-thickness 部分 3 d 重建的两个不同的铝合金和铸铁样品。的定义是 2040×2040 像素照片铝合金和铸铁 1600×1600。体素的实际长度是 0.7 m 铝合金和 1.1 m 铸铁。投影射线照片上的环形工件从静态特性是可见的 (特别是 sub-figures (a) 和 (b)) Nanotomography 在实验室同步加速器设施甚至现在访问层析 x 射线摄影机由于各种 x 射线聚焦装置 [237]。分辨率低至 20 nm 可以实现同步加速器设施 [144]。这种类型的解决方案需要非常稳定的系统和非常准确的驱动, 允许有意义的重建。Nanolaminography 也被证明是可行的最近在欧洲同步加速器辐射设施 [90]。

Although tomography, because of its medical inheritance is mainly associated with the use of x-rays as the radiation source, the procedure itself is above all a technique of reconstruction of data acquired by the radiation-matter interaction where scattering is weak. It can therefore be adapted to many types of radiations as diverse as neutrons [224, 225], muons, electrons or gamma radiations [24, 173, 172, 174], visible optics, THz electromagnetic radiations, magnetic fields or ultrasound.

虽然断层扫描, 因为医学的继承主要与使用的 x 射线作为辐射源, 重建的过程本身是最重要的一个技术 radiation-matter 获得的数据交互的散射很弱的地方。它因此可以适应多种辐射等中子 (224、225), 介子, 电子或　辐射 (173、172、174), 可见光学太赫兹电磁辐射、磁场和超声波。

DVC: Achievements and Challenges 13 2.1.2 Magnetic Resonance Imaging MRI is a noninvasive imaging technique that produces three dimensional images without the use of damaging radiation (e.g., x-rays). It is often used for disease detection, diagnosis, and treatment monitoring [138]. Its principle consists of exciting and detecting the change in direction of the spins of magnetic atom nuclei, and in particular protons that are very convenient for imaging water in living tissues. Powerful magnets are utilized. They produce strong magnetic fields that force protons to align with them. When a radiofrequency current is then pulsed, the protons are stimulated and spin out of equilibrium, thereby "straining" them against the pull induced by the magnetic field. When the radiofrequency field is turned off, the sensors detect the energy released as the protons realign with the magnetic field. The time it takes for the protons to realign and the amount of released energy change depending on the environment and the chemical nature of the molecules.

": 成就和挑战 13 2.1.2 磁共振成像 MRI 是一种非侵入性成像技术, 生成三维图像不使用有害的辐射 (如 x 射线)。它通常用于疾病检测、诊断和治疗监测 [138]。原理由激动人心和检测的变化方向旋转磁性原子的原子核, 非常方便, 特别是质子成像水生活组织。利用强大的磁铁。他们产生强磁场, 强迫质子对齐。当射频电流脉冲, 质子是刺激和失去平衡, 从而引发的"紧张"他们对拉磁场。射频场关闭时, 传感器检测到释放的能量的质子与磁场调整。质子的时间重新调整和释放能量的总量变化取决于环境和分子的化学性质。

Spatial encoding of the MRI signal is accomplished through the use of gradients in magnetic fields that cause atom spins in different locations to precess at slightly different rates. Phase tagging enables for another spatial encoding, thereby providing echo planar images (i.e., one slice). As the protons undergo relaxation, the change in the local magnetic fields creates currents in the receive coils. These currents are detected as a change in voltage. The signal is then sampled, digitized, and finally stored for processing. It is broken down and spatially located to produce images.

空间编码的核磁共振信号是通过使用梯度磁场, 导致不同位置原子自旋进动率略有不同。阶段为另一个标签使空间编码, 从而提供 (即回波平面图像。一片)。质子接受放松, 改变当地接收线圈的磁场产生电流。这些检测到电流电压的变化。信号采样, 数字化, 最后存储进行处理。分解和空间生产图片。

Pixel sizes range in clinical MRI from mm to sub-mm. Voxel dimensions are given by the pixel size and the thickness of the slice (i.e., measured along the magnetic field gradient). Slice thicknesses in clinical MRI vary from a maximum　5 mm, which is achieved using multislice imaging, to sub-mm with 3D scanning techniques. When using micro-MRI equipments, the voxel size can be decreased to typically 100 m [14] but require extremely intense magnetic fields. The acquisition process associated with MRI is generally much longer than with (x-ray) tomography.

像素尺寸范围从毫米到 sub-mm 在临床磁共振成像。立体像素尺寸给出像素大小和切片的厚度 (即。, 沿着磁场梯度测量)。在临床 MRI 片厚度不同最大 5 毫米, 这是通过使用多层成像,sub-mm 与 3 d 扫描技术。当使用 micro-MRI 设备, 可以减少体素的大小通常是 100 m[14] 但需要极其强烈的磁场。收购过程与 MRI 通常是更长的时间比 x 射线断层扫描。

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This is even longer when micro-MRI is performed (e.g., 9 h for 512 × 256 × 256-voxel images with an isotropic voxel size of 78 m, see Figure 3(a)). The trabecular network of cancellous bone revealed by micro-MRI was shown to be suitable for correlation purposes.

这是更长当 micro-MRI 执行 (例如,9 h 512×256×256 -立体像素图像的各向同性体素的大小 78 m, 参见图 3 (a))。松质骨小梁网的揭示了 micro-MRI 被证明适用于相关的目的。

(a) (b) Fig. 3 Compressive test monitored via micro-MRI [14]. (a) Frontal section of the reference configuration in which the sample and the loading device are shown. (b) Loading device for in-situ experiments In any 3D imaging technique there are artifacts related to its operating principle [117]. One additional challenge in the medical field, which is not restricted to MRI, is associated with patient motion during the acquisition process. Registration techniques were developed in particular to tackle such issues [102].

图 3 (a) (b) 抗压测试监控通过 micro-MRI [14]。(一) 额部分的参考配置示例和装载设备。(b) 原位实验加载装置在任何 3 d 成像技术有工件相关工作原理 [117]。在医学领域一个额外的挑战, 并不局限于核磁共振成像, 在收购过程中与患者运动相关。注册技术开发特别是应对这样的问题 [102]。

2.1.3 Optical Coherence Tomography Optical coherence tomography (or OCT) is a noninvasive imaging technique of optically semi transparent (e.g., biological) materials at micrometer resolutions, i.e., similar to that of optical microscopy. One of the most remarkable applications concerns ophthalmology. OCT is based on interferometry in so-called weakly coherent (i.e., polychromatic or white) light. There are different variants of OCT, all of them typically use Michelson interferometers [182]. Full-field OCT utilizes DVC: Achievements and Challenges 15 a Michelson interferometer with microscope lenses placed in both arms [13, 54]. The length of the reference arm determines the inspected sample depth with equal optical length, and the amplitude of the coherent signal in both arms at a given location indicates the level of (single) backscattering.

2.1.3 光学相干断层扫描光学相干断层扫描 (OCT) 是一种非侵入性成像技术的光学半透明 (例如, 生物) 材料在微米的分辨率, 即。与光学显微镜相似。最引人注目的一个眼科应用问题。10 月是基于所谓的弱相干干涉法 (即。多色或白色) 光。10 月有不同的变体, 它们通常使用迈克尔逊干涉仪 [182]。细致的 10 月利用”: 成就和挑战 15 迈克耳孙干涉仪与显微镜镜头放在双臂

[13 日,54]。参考臂的长度决定了检查样本以同样的光学长度、深度和相干信号的振幅双臂在一个给定的位置显示 (单一) 反向散射的程度。

To extract the amplitude of the interference signal, interferometric images are acquired by means of a digital camera, and phase-shifted by the oscillation of the reference mirror. By computation, an image of the coherence volume is then obtained in real time (i.e., at a typical rate of a few Hz). The illumination system uses a halogen lamp. Because of the very wide spectrum of the light source, interferences occur only for very small differential path length between both arms, thus limiting the thickness of the slice with a coherent backscattering, i.e., the depth resolution.

提取干扰信号的振幅, 干涉图像获得通过数码相机、镜子和相移的振荡参考。通过计算, 一个形象的一致性体积然后实时 (即获得。在一个典型的几赫兹)。使用卤素灯照明系统。因为非常广泛的光源, 干扰发生只有很小的微分双臂之间路径长度, 从而限制与相干后向散射片的厚度, 即。, 深度分辨率。

Typically, micrometer resolution can be achieved both in plane and perpendicular to it. Increasing the path length of the reference arm provides deeper and deeper images of the medium. Stacking those images produces a 3D volume of the (scattering) microstructure.

通常, 测微计的分辨率可以达到在平面和垂直于它。增加了参考臂的路径长度提供了越来越深的图像媒介。叠加这些图像产生 3 d 体积 (散射) 的微观结构。

By construction, this technique is restricted to semi-transparent solids with low attenuation.

通过建设, 这种技术仅限于半透明固体较低的衰减。

The ability to image the inner structure for scattering media makes OCT very appealing for biological tissues. Figure 4 shows two such examples. In both cases, a 2D slice is shown with the observation face located at the top. The first example, Figure 4(a) is a porcine eye cornea, which constitutes a good model system for human eyes. For such a transparent medium, the technique is very well suited and the scattering is very weak (i.e., inner structures are clearly revealed).

图像的能力的内部结构散射媒体使生物组织 10 月非常具有吸引力。图 4 显示了两个这样的例子。在这两种情况下, 一个 2 d 切片显示与观察脸位于顶部。第一个例子, 图 4 (a) 是一个猪眼睛角膜, 构成一个良好的模型系统对人类的眼睛。对于这样一个透明的介质, 技术非常适合和散射很弱 (即。显然, 内部结构显示)。

The second example (human breast tissue) is more delicate to image because of attenuation and much more intense scattering. Inner micronodules (with about no scattering) are clearly seen.

第二个例子 (人类乳腺组织) 更微妙的图像由于衰减和更强烈的散射。内部 micro-nodules(大约没有散射) 清楚地看到。

Yet, their shape is not enough to determine their nature. Elastography may help diagnose their possible carcinogenic character. One way to have access to such information is from imaging the same tissue under slightly different mechanical loadings. DVC is a technique of choice to provide the relative strains within the medium, and hence the sought elastic contrast [164].

然而, 其形状决定他们自然是不够的。弹性成像有助于诊断其可能致癌的性格。获得这些信息的一个方法是成像相同的组织下稍微不同的机械载荷。" 技术的选择提供介质内的相对紧张, 因此寻求弹性对比 [164]。

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(a) (b) Fig. 4 Section view through full-field OCT for two biological samples. The top of these images is the observation side. The width of these images is about 1 mm. (a) Porcine eye cornea revealing a lamellar collagen microstruc- ture; (b) Human breast tissue where micro-nodules are visible. Both examples are taken from Ref. [164] In terms of 3D imaging characteristics, OCT has some specificities. First, standard optics may require refraction corrections to be applied for curved objects [72]. This is important for a genuine rendering of the microstructure. Second, images are naturally noisy because of the low level of the coherent scattering signal as compared to the total light intensity, and because of the fast scanning through the depth (imposed for biological samples to avoid motion, viscous creep, or the mere time evolution of the living tissues). Further, because of multiple scattering or light absorption, images tend to display an artifactual gradient in the depth direction (i.e., deeper is darker). The same effect is also responsible for a "shadowing" effect whereby a scatterer will be more or less visible depending on the medium along the optical path (this can be guessed to be responsible for the faint vertical columnar structure in Figure 4(b)). Similarly, noise also increases with depth.

图 4 (a) (b) 截面视图通过细致的 10 月两个生物样品。这些图片是观察的一面。这些图片的宽度大约是 1 毫米。(a) 猪眼睛角膜露出一层状胶原 microstruc——真正的;(b) 人类乳腺组织 micro-nodules 是可见的。例子都是取自 Ref。[164] 3 d 成像特点而言,10 月有特异性。首先, 标准光学可能需要申请折射修正曲线对象 [72]。这是一个真正重要的微观结构的呈现。第二, 自然图像噪声由于低水平的相干散射信号相比总光强, 因为快速扫描通过深度 (出于生物样本, 以避免运动, 粘性蠕变, 或生活的纯粹的时间演化组织)。此外, 因为多次散射或光吸收, 图片往往显示在深度方向 (即 artifactual 梯度。, 更深层次的是暗)。同样的效果也负责"遮蔽"效应, 将或多或少的散射体可见根据介质沿光路 (这可以猜到负责微弱垂直柱状结构在图 4 (b))。同样, 噪音也会增加与深度。

This effect can be accounted for in registration techniques (as discussed below in Section 3.1.2).

这种效应可以在注册技术占 3.1.2 节 (下面讨论)。

2.1.4 Other 3D imaging techniques DVC was also applied to 3D images acquired with other modalities. Its feasibility was shown for volumes obtained by optical slicing (or scanning) tomography [77, 78], optical rotating scanning tomography(ORST) [155], terahertz tomography [84], confocal microscopy [148], laser-scanning confocal microscopy (LSCM) [194], and ultrasonic imaging [24].

2.1.4 其他 3 d 成像技术" 也应用于 3 d 图像与其他形式获得的。其可行

性是卷通过光学切片显示 (或扫描) 断层扫描 (77、78), 旋转扫描光学断层扫描 (失去)[155], 太赫兹断层 [84], 共焦显微镜 [148], 激光扫描共聚焦显微镜 (LSCM)[194], 和超声成像 [24]。

DVC: Achievements and Challenges 17 2.2 Ex-situ and in-situ experiments The majority of in-situ experiments cited so far in this paper have been performed with x-ray imaging devices (i.e., either in synchrotron facilities or lab tomographs even including medical scanners). Therefore, the two following sub-sections will deal with x-ray imaging. Some of the discussed features may also apply to in-situ experiments using other imaging modalities (e.g., MRI [14]). However, they will not be reviewed hereafter. Conversely, MRI will prevent the use of magnetic materials in the design of the loading frame, as opposed to x-ray imaging, provided it does not intersect the beam. Figure 3(b) shows the mini-compression stage that was built from glass fiber reinforced PEEK (polyetheretherketone) to be MRI-compatible.

": 成就和挑战 17 2.2 让其它和现场实验的大部分现场实验引用到目前为止, 本文已经与 x 射线成像设备 (即执行。在同步加速器设施或实验室层析 x 射线摄影机甚至包括医学扫描仪)。因此, 之后的两个小节将处理 x 射线成像。讨论的一些功能可能也适用于原位实验使用其他成像技术 (例如,MRI [14])。然而, 他们不会检查以后。相反,MRI 可以防止使用磁性材料在加载框架的设计, 而不是 x 射线成像, 它不相交梁提供。图 3 (b) 显示了 mini-compression 阶段, 是由玻璃纤维增强 PEEK MRI-compatible (polyetheretherketone)。

2.2.1 Ex-situ imaging Ex-situ imaging is the easiest and most natural way of analyzing mechanical tests. It requires imaging to be performed at different loading steps. However, if some mechanical load is applied it has to be removed and it may change some of the studied phenomena (e.g., cracks may close when damage is investigated). Conversely, permanent changes, such as plasticity or densification, do not significantly change upon unloading the sample. For some materials (e.g., sand), the fact that the specimen was unloaded to be x-rayed ex-situ did not change the sought information (e.g., density maps [41]) provided it is held in a constant hydrostatic confinement. Tomodensitometric measurements allowed Desrues et al. [50] to study the complex pattern of localization bands in the bulk of sand samples as early as in 1996.

2.2.1 让其它成像让其它成像是最简单、最自然的方式分析机械测试。它需要执行成像在不同加载步骤。但是, 如果一些机械载荷应用它必须被移除, 它可能会改变一些研究现象 (例如, 裂缝可能会关闭时损坏了)。相反, 永久的改变, 如可塑性或致密化, 不显著改变在卸货的示例。对于一些材料 (如沙子), 标本被卸载的 x 光检查让其它没有改变寻求信息 (例如, 密度地图 [41]) 提供恒定水压软禁。Tomodensitometric 测量允许 Desrues et al。[50] 研究复杂模式的本地化乐队的大部分砂样品早在 1996 年。

In some other cases, the load is not necessarily of mechanical origin. For instance, cracking induced by accelerated desiccation of concrete-like material could be studied via ex-situ imaging even though the climatic chamber was located next to the beamline. In such cases, it is worth remembering that large rotations may occur because of repositioning issues [232] and consequently 18 A. Buljac et al.

在其他一些情况下, 负载不一定是机械原点。例如, 加速干燥引起的开裂 concrete-like 材料可以通过让其它成像研究尽管气候室位于 beamline 旁边。在这种情况下, 值得记住的是, 大旋转可能发生因为重新定位问题 [232], 因此 18。Buljac et al。

consistent strain descriptors may be considered even though the strain levels themselves remain low [101]. This observation also applies to in-situ tests [14].

一致的应变描述符可以考虑即使应变水平仍然很低 [101]。这一观点同样适用于原位测试 [14]。

The following example is devoted to the analysis of accelerated desiccation [101]. The model material was made of 35 vol.

下面的例子是用于加速干燥的分析 [101]。35 vol.

The resulting radiographs, whose definition is 2048 × 2048 pixels, were used to reconstruct, via an in-house filtered back-projection algorithm [61], 3D images whose final voxel size is 10.2 m.

由此产生的射线照片, 其定义是 2048×2048 像素, 用于重建, 通过内部过滤投影算法 [61],3 d 图像的最终 m 立体像素大小是 10.2。

DVC analyses were conducted with 4-noded tetrahedra (i.e., T4-DVC [93]). The measurement mesh was adapted to the cylindrical geometry of the sample. The external radius of the region of interest is equal to 305 voxels, and the height is equal to 260 voxels (i.e., the analyzed volume contains 76 million voxels). The advantage of such elements is that the actual geometry can be faithfully meshed with 19,494 T4 elements (Figure 5). The characteristic element size, which is defined as the cubic root of the average number of voxels per element, is equal to 16 voxels. The spatial displacement resolution, which is defined as the cubic root of the mean number of voxels considered for the nodal displacement measurement, is equal to 27 voxels.

" 进行了分析与 4-noded 四面体 (即。,T4-DVC [93])。测量网格适应样本的圆柱几何。感兴趣的外部区域的半径等于 305 体素, 和高度等于 260 像素点 (即。, 分析了卷包含 7600 万像素点)。这些元素的优点是, 与 19494 年实际的几何可以忠实地网状 T4 元素 (图 5)。特征元素的大小, 这是定义为体素的平均数量的立方根每个元素, 等于 16 个像素点。的空间位移分辨率定义为平均数的立方根的体素被认为是节点位移测量, 等于 27 体素。

DVC: Achievements and Challenges 19 Fig. 5 Cylindrical region of interest and corresponding mesh of T4 elements.

": 成就和挑战 19 图 5 圆柱感兴趣的区域和相应的 T4 元素的网格。

A Matlab implementation was used to run the following analyses. Optimized C++ kernels [121] computed all the data needed to perform DVC. Binary MEX files were then generated and called in the Matlab environment. The DVC computation was run on a workstation with an 8-core Intel Xeon E5-2650v2 (2.6 GHz and 32 Go of memory). It took less than 2 minutes for the DVC code to converge (i.e., the norm of displacement corrections is then 10−4 voxel). Figure 6(a) shows a 3D rendering of gray level residuals. The latter ones correspond to the gray level difference between the volume in the reference configuration and the volume of the deformed configuration, which was corrected by the measured displacement field. The high gray levels corresponded to the various cracks induced by accelerated desiccation. These residuals are very useful when checking the consistency of a DVC analysis. In the present case, the registration was successful except at the exact location of the cracks because displacement continuity was assumed. The only information left in the thresholded residuals was the cracks (Figure 6(b)). It was concluded that two damage mechanisms operate, namely, inclusion/matrix debonding and matrix cracking.

Matlab 实现用于运行以下分析。优化的 C + + 内核 [121] 计算所需的所有数据执行陷落。二进制墨西哥人文件被生成并在 Matlab 环境中。” 的计算是运行在一个工作站和一个 8 核 Intel Xeon e5 - 2650 v2 (2.6 GHz 和 32 的内存)。花了不到 2 分钟的收敛 (即” 的代码。, 位移修正的标准是 10−4 体素)。图 6 (a) 显示了一个 3 d 渲染的灰度残差。后者的对应的灰度差别量的参考配置和体积变形的配置, 这是纠正测量位移场。灰色的高水平与各种加速干燥引起的裂缝。这些残差非常有用当检查的一致性” 的分析。在目前的情况下, 注册成功除了在裂缝的确切位置, 因为位移连续性假设。剩下的唯一信息的阈值残差是裂缝 (图 6 (b))。得出两种破坏机制运作, 即包含/矩阵剥离和基体开裂。

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(a) (b) Fig. 6 (a) 3D rendering of the gray level residuals. (b) Thresholded residuals highlighting the two damage mechanisms of the cementitious matrix reinforced by glass beads 2.2.2 In-situ tests In the vast majority of cited works, in-situ experiments were conducted. In that case, the sample is imaged when the load is applied. This required for the design of specific testing machines.

图 6 (a) (b) (a) 的 3 d 渲染灰度残差。(b) 阈值残差强调胶结矩阵的两种破坏机制强化了 2.2.2 玻璃珠在绝大多数的原位测试引用作品, 进行了现场实验。在这种情况下, 样品加载时成像应用。这需要设计特定的测试机器。

One key aspect is related to the fact that both tomography and laminography use a set of pro- jections equally spaced, thus all angular positions should be accessible without any part of the testing machine obscuring the x-ray beam. This has led to the use of external tubes as frames of the testing machine [26]. In that case the whole testing machine is mounted on the turntable.

相关的一个关键方面是事实, 断层和辐射分层照相术都使用一组支持注射的等距的, 因此所有的角位置应该访问没有任何部分试验机掩盖了 x 射线。这导致了使用外部管作为试验机的帧 [26]。在这种情况下整个试验机安装在转盘上。

Figure 7(a) shows one of the first in-situ testing machines that was used on beamline ID19 at the European Synchrotron Radiation Facility (ESRF) in Grenoble (France). It was used to study different damage mechanisms in the bulk of an Al/SiC composite [27].

图 7(一个) 显示的第一现场测试机器是用于 beamline ID19 欧洲同步辐

射设备 (ESRF) 在格勒诺布尔 (法国)。这是用于研究不同损伤机制的大部分铝/碳化硅复合 [27]。

More recently, commercial systems have been designed in which the testing machine allows the loaded sample to be rotated under load without using the turntable of the tomograph. One natural solution is to have two rotational actuators that allow torsion to be applied and to per- form tomographic acquisitions, in addition to a longitudinal actuator (Figure 7(b)). Again, one DVC: Achievements and Challenges 21 limitation is related to the minimum distance between the testing machine and the (divergent) x-ray source. Resolutions as low as 6 m can be achieved in LMT' s tomograph.

最近, 商业系统试验机的设计允许旋转载荷加载示例不使用层析 x 射线摄影机的转盘。一个自然的解决方案是有两个旋转执行器允许扭转应用和每层析-形式收购, 除了纵向传动装置 (图 7 (b))。再一次, 一个": 成就和挑战 21 限制与试验机和之间的最小距离 (发散) 的 x 射线源。分辨率低 6 m 可以实现以前的层析 x 射线摄影机。

(a) (b) Fig. 7 Example of testing machines for in-situ tests. (a) Tension/ compression testing machine on a synchrotron beamline [27]. (b) Tension/ torsion/compression testing machine for a lab tomograph One way of validating such new testing machines is to check whether 3D reconstructions can be performed at full load capacity. Figure 8 shows a 3D rendering of an indentation test on two half-cylinders 35 mm in diameter made of granite when loaded at 20 kN. During the 360° rotation, the force had fluctuations less than 5

图 7 (a) (b) 测试机器现场测试的例子。(一) 张力/压缩试验机在同步加速器 beamline [27]。(b) 张力/扭力/压缩试验机等实验室层析 x 射线摄影机一种验证新的测试机器是检查是否可以进行 3 d 重建在全负荷能力。图 8 显示了一个 3 d 渲染的压痕试验在两个 half-cylinders 35 毫米直径的花岗岩加载时 20 kN。在 360° 旋转, 力波动小于 5

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Fig. 8 3D rendering of indentation test on granite samples Very recently, nanotomography was used to image mechanical tests in lab tomographs or synchrotron facilities. In particular, ex-situ [161] and in-situ [177] indentation tests were analyzed.

图 8 3 d 渲染的压痕试验花岗岩样品最近,nanotomography 用于图像层析 x 射线摄影机或同步加速器设施机械测试实验室。特别是, 让其它 [161] 和现场 [177] 压痕测试进行了分析。

For the last case, one key challenge was associated with the design of a nanomechanical test stage that could be integrated into x-ray nanotomographs.

在过去的情况下, 一个关键的挑战是与纳米机械的设计, 可以集成到 x 射线 nanotomographs 测试阶段。

As previously discussed, even though x-ray tomography is the most utilized 3D imaging pro- cedure, it is also possible to image sheet-like samples via laminography. Consequently, the loading device becomes larger in comparison with tomography (Figure 7(a)). Figure 9(a) shows a testing machine that is fitted on the turntable to perform synchrotron laminography at the European Synchrotron Radiation Facility (ESRF) in Grenoble, France. The distance of the sample center point and the detector is 130 mm, which is compatible with micrometer resolutions thanks to the availability of parallel x-ray beams. In order to perform nanolaminography lightweight testing machines are needed (i.e., the whole experimental setup weighs less than 50 g). It is was shown that good quality reconstructions were obtained for an in-situ tearing test when the physical size of one voxel was equal to 100 nm. The subsequent feasibility of DVC analyses was also proven.

正如前面所讨论的那样, 尽管 x 射线断层扫描是最利用 3 d 成像 pro -出场, 也可能通过辐射分层照相术片状样品图像。因此, 装载设备变大与断层相比 (图 7 (a))。图 9(一个) 显示一个试验机安装在转盘上执行同步加速器辐射分层照相术欧洲同步辐射设备 (ESRF) 在格勒诺布尔, 法国。样本中心点的距离和探测器 130 毫米, 这是兼容千分尺决议由于平行 x 射线的可用性。为了执行 nanolaminography(即需要轻量级测试机器。, 整个实验装置的重量少于 50 克)。结果表明, 高质量的重建时获得了一个现场撕裂测试体素的物理尺寸等于 100 海里。陷落的后续可行性分析也证明。

This study was crucial to understand the development of plasticity and damage in an aluminum alloy [28].

本研究是理解的关键开发铝合金的塑性和损伤 [28]。

DVC: Achievements and Challenges 23 Fig. 9 Example of testing machine for in-situ tests in synchrotron laminography on beamline ID15 of ESRF.

": 成就和挑战 23 无花果。9 例原位测试的测试机在同步加速器辐射分层照相术 beamline ID15 ESRF。

The zoomed section shows the testing stage. The central part of the sample is shown on the screen With the development of in-situ tests, one challenge is related to the fact that most of the 3D imaging techniques mentioned above require acquisition times that are not compatible with uninterrupted experiments. At various stages of the test, the sample can still be loaded, provided it is motionless with respect to the turntable during the whole scanning duration. Such limitations are gradually pushed back via two complementary solutions to achieve time-resolved (or 4D) tomography [33, 65, 143, 178, 213]: –On third generation synchrotron, the x-ray beams are very energetic and may even be "pink" (i.e., with a finite band of wavelength to further intensify the beam, and thus tomography may not require very long exposure times). Consequently, the use of high speed digital cameras offers the possibility to perform full scans at frequencies as high as 20 Hz. To achieve such levels, the sample and its loading frame have to be spun continuously at high rotation speed, thereby possibly degrading the reconstruction quality when standard algorithms are used [143].

放大部分显示了测试阶段。样品的中心部分显示在屏幕上的发展原位测试, 相关的一个挑战是大多数的上面提到的 3 d 成像技术需要采集时间不兼容不间断实验。在测试的不同阶段, 仍然可以被加载, 提供的样品是不动的转盘在整个扫描时间。这样的局限性逐渐推迟通过两个互补的解决方案来实现时间分辨 (或 4 d) 断层扫描 (33、65、143、178、213):——第三代同步加

速器,x 射线非常精力充沛, 甚至可能是“粉红”(即。, 有限的波长来进一步加强梁, 因此断层可能不需要很长的曝光时间)。因此, 使用高速数码相机提供了可能性进行全扫描频率高达 20 Hz。为了达到这种水平, 将样例及其加载框架不断在高转速, 从而可能有辱人格的重建质量当使用标准算法 [143]。

–Soft routes [213] can also be devised by combining DVC analyses and image reconstruction pro- cedures. Under these conditions, the reference scan is performed when the sample is unloaded (or very modestly preloaded), and then radiographs are acquired on the fly without any inter- 24 A. Buljac et al.

——软路由 [213] 也可以设计相结合” 的分析和图像重建 pro -出场。在这些条件下, 参考扫描样品时执行卸载 (或非常谦虚地加载), 然后射线照片上获得飞行, 没有任何国际米兰- 24。Buljac et al。

ruption of the test [110]. In such situations, Projection-based DVC (P-DVC) is utilized [124].

出现测试 [110]。在这种情况下,Projection-based 陷落 (P-DVC) 是利用 [124]。

The spirit of this technique will be presented in Section 5.6.

这种技术的精神将在 5.6 节。

–Both previous cases may be combined to enable the tests to be run even faster without degrading the overall quality of the measured displacements and the reconstructed volumes.

——前两例可能结合, 使测试运行更快没有测量位移的总体质量退化和重建的卷。

3 From local to integrated DVC To measure bulk displacement fields, there are two classes of registration techniques, namely, feature (or particle) tracking (which produces sparse sets of correspondences) and correlation procedures (which produce dense sets of correspondences). In the following, feature tracking (e.g., see Refs. [217, 116, 216, 62, 146]) will not be reviewed. The discussion will focus on different variants of DVC in which mechanical information is gradually included.

3 从本地集成” 测量体积位移字段, 有两类注册技术, 即功能 (或粒子) 跟踪 (产生稀疏集通讯) 和相关程序 (产生密集的组通讯)。在以下功能跟踪 (例如, 见参考文献。(217、116、216、62、146]) 将不会被审查。将集中讨论不同变体的陷落机械信息逐渐包括在内。

In experimental fluid mechanics, a sister technique is referred to as tomographic particle image velocimetry (or tomo-PIV) when dealing with the measurement of 3D velocity fields via correla- tion techniques [57, 203]. In the medical field (and applied mathematics), such technique is called “image registration” and appeared earlier [228, 141, 102] than in experimental mechanics [12, 207].

在实验流体力学, 妹妹技术被称为层析粒子图像测速技术显现的 (或 tomo-PIV) 在处理三维速度场的测量通过 correla, 技术 [203]。在医学领域 (应用数学), 这种技术称为“图像配准”, 出现早期 (228、141、102) 比在实验力学 [207]。

One reason of this delay may come from the needed resolution for the technique to be useful, which varies with the field of application. In medical imaging an uncertainty of about one voxel is generally considered as acceptable, whereas in mechanical testing, at least some 10−1 voxel-size uncertainty on displacements (or better) is needed to estimate meaningfully commonly encoun- tered strains. This difference in ambition for medical applications, materials science or mechanics of materials may thus have required a technique that had matured within the domain of medical imaging confronted with other issues than accuracy. However, it is also noteworthy that cross- references are scarce, so that it is also plausible that these techniques emerged independently and progressed with their own specificities as called for by applications.

这个延迟的原因之一可能来自于需要解决的技术很有用, 这随应用领域。在医学成像一个不确定性的体素通常被认为是可以接受的, 而在机械测试, 至少有一些 10−1 voxel-size 不确定性位移 (或更好的) 需要估计有意义一般 encoun——事故菌株。这种差异在野心对于医疗应用程序, 因此, 材料科学和材料力学可能需要技术, 成熟的医学成像领域内的面对其他问题比精度。然而, 同样值得注意的是: 交叉引用稀缺, 所以它也是合理的, 这些技术出现了独立和发展自己的特异性所要求的应用程序。

DVC: Achievements and Challenges 25 It is also interesting to note that the same distinction has been made in both fields between so- called local and global approaches [228, 197]. Local approaches to DVC [12, 207] consist of dividing the region of interest into small volumes (hereafter referred to as subvolumes). The registration is performed independently on each subvolume. Conversely, in global approaches [228, 197] the registration is performed over the whole region of interest (ROI).

": 成就和挑战 25 也有趣的注意, 相同的区别已经在这两个领域之间的所谓局部和全局方法 (228、197)。本地方法"[207] 包含感兴趣的区域划分成小卷 (以下称为子卷)。执行注册独立在每个子卷。相反, 在全球执行方法 (228、197) 登记在整个地区的利益 (ROI)。

3.1 Overall presentation of DVC The two 3D images to be registered are denoted as f (x) (assumed here to be the "reference" image) and g(x) (the "deformed" image), where f and g are scalar gray levels at each voxel location x. Fundamentally, DVC rests on the basic assumption that upon a mere change in the position of voxels, defined by a displacement field u(x), the two images can be brought to perfect coincidence such that g(x + u(x)) = f (x) (1) Although this equation appears as trivial, a number of common issues can be mentioned that motivated different variants in the past: 1. Images are strictly defined only at integer voxel positions. However, in practice u may assume arbitrary values, and hence it is essential (and this becomes really critical when subvoxel resolutions are aimed for) to provide an estimate of the gray level at an arbitrary position.

3.1 " 的总体介绍注册的两个 3 d 图像被指示为 f (x)(这里假定的"参考"的形象) 和 g (x)("变形" 的形象),f 和 g 标量灰色水平在每个体素位置 x。从根本上说," 基于基本假设在仅改变像素点的位置, 由位移场 u (x), 定义两个图像可以带来完美的巧合,g (x + u (x)) = f (x) 方程 (1) 虽然微不足道, 很多常见问题可以提到动机不同变体在过去:1。图像是严格定义只有在整数体素位置。然而, 在实践中你会认为任意值, 因此它是至关重要的 (这就变得

非常重要, 当 subvoxel 决议目的是) 提供一个估计的灰度在任意位置。

2. Images are naturally discrete, not only from the voxel structure, but also from the encoding of gray levels. This argument is not very stringent for computed tomography where gray levels are computed, and hence the gray level discretization of the starting images (radiographs) is largely erased. However, in other cases, or when the contrast is poor, a modest gray level dynamic range may reveal limiting.

2. 自然图像是离散的, 不仅从立体像素结构, 而且也从灰色的编码水平。这个观点不是很严格的计算机断层扫描, 灰色的水平计算, 因此开始图像的灰度离散化 (片) 在很大程度上是抹去。然而, 在其他情况下, 或者当对比度差, 适度的灰度动态范围可能揭示限制。

3. Images are noisy. Even when no motion is expected between two images of the same scene acquired consecutively and with the same device, i.e., u(x) = 0, f and g are different. Their 26 A. Buljac et al.

3. 图像是吵了。预计, 即使在没有运动两个同一场景的图像获得连续相同的设备, 即。u (x) = 0, f 和 g 是不同的。他们的 26 个。Buljac et al。

difference (x) g(x)−f (x) is at best (i.e., excluding the case of spurious changes of intensity or motion) the sum of the noise affecting g (often assumed to be statistically similar to that of f) and −f .

不同 (x) g (x)−f (x) 是在最好的情况下 (即。, 排除虚假的情况下强度的变化或运动) 的和噪声影响 g(通常认为是统计上类似于 f) 和 −f。

These three items imply that Equation (1) even with the exact displacement is not strictly satisfied. In fact interpolation and discretization errors are both expected to be of zero mean, and hence they can be included in what is called (effective) noise. Thus, rather than trying to exploit the above identity voxel-wise, it is important to assess how good (or bad!) the registration is.

这三个物品暗示方程 (1) 即使准确的位移并不严格满足。事实上插值和离散化错误都是零均值的预期, 因此它们可以被包含在所谓的 (有效的) 噪音。因此, 而不是试图利用上述身份 voxel-wise, 重要的是要评估好 (或糟糕!) 登记。

In fact the natural answer is the following: assuming that the exact answer for u is known, how credible is it to measure locally a gray level f on one voxel, and to estimate (via interpolation) geu at the same position, after displacement correction geu (x) = g(x + u(x)) (2) This is assessed with a suited similarity measure S(f, geu). For any displacement field u, one may construct a corrected image geu , and thus a cost function (see Section 3.1.2) TDVC [u] = S(f, geu) (3) The solution of DVC is given by the displacement field, i.e., the argument that minimizes the above cost function. This can be seen as defining a tolerance to the deviation between the above estimates. f and geu are allowed to differ by a gray level difference that is compatible with what is known from the noise statistical characteristics. It is also noteworthy that when noise has a specific spatial correlation this similarity measure is intrinsically nonlocal. This is also the reason why after a DVC analysis, it is very important to examine carefully the so-called residual field (x) = geu (x) − f (x) , (4) because even if overall characteristics such as the global variance may be compatible with noise, faint correlations can be easily visualized and detected to signal a violation of the DVC hypotheses DVC: Achievements and Challenges 27 (to be interpreted as being acceptable or requiring an enhanced model). In order to ease notations in the following, the subscript to ge will be omitted.

实际上自然回答如下: 假设 u 的确切答案, 有多可靠测量局部灰度 f 体素, 并评估 (通过插值)geu 在同一位置, 位移校正后 geu (x) = g (x + u (x)) (2) 这是一个合适的相似性度量评估与年代 (f, geu)。对于任何位移场 u, 可以构造一个 geu 修正图像, 因此成本函数 (见第 3.1.2)TDVC [u] = S (f, geu) (3) 的解" 是由位移场, 即。, 上面的论点最小化代价函数。这可以被看作是定义一个公差之间的偏差估计之上。f 和 geu 允许不同的灰度差异兼容已知的噪声统计特性。它也值得注意, 当噪声都有一个特定的空间相关性这种相似性度量本质上是外地的。这也是陷落后的原因分析、仔细检查是非常重要的所谓的剩余磁场 (x) = geu (x)−f (x),(4) 因为即使总体特征, 如全球噪声方差可能兼容, 微弱的相关性可以轻松可视化和检测信号违反了" 假设" 的: 成就和挑战 27(被视为被接受或需要一个增强模型)。为了缓解以下符号, 通用电气将省略的下标。

Considering that Equation (1) is now endowed with some tolerance, the determination of the displacement field u(x) is an ill-posed problem. This constitutes the major difficulty of DVC. In order to make the problem well-posed, constraints are to be added to the displacement field, u.

考虑到方程 (1) 是现在被赋予了一些宽容, 位移场的决心 u (x) 是一个不适定问题。这构成了" 的主要困难。为了使问题适定、约束添加到位移场,u。

Namely, rather than leaving the displacement vectors free to vary arbitrarily from one voxel to its neighbors, displacements may be sought in a restricted space, U, and it is only within this space that the image similarity is to be optimized. Specifying some of these spaces will naturally lead us to distinguish local and global approaches. Restriction to a subspace of displacement field can be interpreted as a (strong) regularization, and tuning the dimensionality of this subspace will allow the conditioning of the problem to be adjusted, and in turn the robustness of the displacement field measurement with respect to noise.

即, 而不是离开位移向量可以任意从一个立体像素到邻国不同, 位移可能寻求在受限空间中,U, 只有在这个空间的图像相似性是优化。指定一些空间自然会让我们区分本地和全球的方法。限制的一个子空间位移场可以被视为一种 (强) 正规化, 和调优这个子空间的维数将允许调整问题的调节, 进而位移场测量的可靠性对噪音。

Another route for making the problem well-posed, is to opt for a weak regularization. This approach consists of introducing two displacement spaces U1 U2 , such that the displacement field is allowed to explore the space with a higher dimensionality, U2 , although the more restricted space U1 is expected to be more likely. To express this choice, another functional for the trial displacement field TReg [u] is introduced, which is a penalty given to the candidate u when it does not belong to the preferred subspace. This penalty is usually chosen as a function of the distance between u and its projection Π1 [u] onto U1 TReg [u] = (ku − Π1 [u]k) (5) Tikhonov regularization [215] is such a weak regularization. For DVC, it will be shown that some specific forms of regularization are very well suited, thereby allowing for a smooth continuation of DVC to mechanical identification of a constitutive behavior.

另一个使问题适定的路线, 是选择弱正则化。这种方法由两个位移引入空间 U1 U2, 这样允许位移场探索更高维度的空间,U2, 尽管更多的限制空间 U1 预计将更有可能。表达这个选择, 另一个功能试验位移场 TReg (u) 介绍, 这是一个点球给候选人 u 当它不属于首选的子空间。这个处罚通常选择的函数 u 及其投影之间的距离 Π1 (u) 到 U1 TReg [u] = (ku−Π1 (u) k) (5) Tikhonov 正则化 [215] 是这样一个弱正则化。", 它将显示一些特定形式的正规化非常适合, 从而允许" 顺利延续的力学本构行为的识别。

It is important to note that such a regularization may be considered from different standpoints.

需要注意的是, 这样一个正规化可以考虑不同的观点。

If some information about the mechanical behavior is known, it is natural to use it in the above 28 A. Buljac et al.

如果一些力学行为的信息是已知的, 是很自然的使用它在上面的 28 个。Buljac et al。

term, and a large weight is adequate. However, when the constitutive law is unknown, the above regularization may be seen as selecting the equivalent of "shape functions." Hence the subspace U1 is to be compared with that obtained from, say, a finite element discretization. This may be convenient, even if it is not meant to be realistic at the scale of elements. In the following, it will be shown that U1 may be the kernel of a differential operator, meaning that locally the shape function obeys a specific differential equation. Interestingly, depending on how much the regularization is trusted, from a neutral shape function generator up to a reliable mechanical description, one may continuously tune the weight of the above functional.

术语, 和一个大重量是足够的。然而, 当本构定律是未知的, 上面的正则化可能被视为选择"形状函数的等效。"因此, 子空间 U1 获得价格相比, 说, 有限元离散化。这可能是方便的, 即使它并不意味着现实元素的规模。在下面, 它将表明,U1 可能微分算子的内核, 即局部形状函数遵循一个特定的微分方程。有趣的是, 这取决于有多少正规化是可信的, 从一个中立的形状函数发生器到一个可靠的力学描述, 可以不断调整上述功能的重量。

Last, it is natural to wonder about the possibility of being misled by the "nice-looking" aspects of the obtained solution, by the use of regularization. For this reason, the following presentation will emphasize the use of gray level residual fields that measure very accurately (i.e., voxelwise) the relevance of the proposed solution. Hence if a regularization property is forced illegitimately on the displacement field, then the residual field will very clearly show that the proposed solution is not suitable. One cannot overemphasize the usefulness of such residuals.

最后, 它很自然地会想到的可能性被误导的"好看的"方面获得解决方案, 通过使用正则化。出于这个原因, 以下报告将强调使用灰度残留字段, 测量准确 (即。建议的解决方案,voxelwise) 相关性。因此如果一个正则化属性是强制非法位移场, 然后剩余字段将非常清楚地表明, 该解决方案是不合适

的。一个人不能过分强调这样的残差的有效性。

3.1.1 Gray level interpolation The question of gray-level interpolation is not specific to 3D images, and for Digital Image Cor- relation, with 2D images, this question has been very thoroughly studied [212]. Because pixels and voxels can be seen as integrating a fine scale information over an elementary square or cube, it is natural to consider the gray level as resulting from a convolution of an intrinsic fine scale texture by an elementary d-dimensional rectangular window function w(x) (valued one if the ab- solute value of all coordinates are less than 1/2, and 0 otherwise). Such a function enhances the regularity of the original signal.

3.1.1 灰度插值灰度插值的问题不是针对 3 d 图像, 数字图像共同关系, 与 2 d 图像, 这个问题一直很彻底研究了 [212]。因为像素和像素点可以被看作是精细的集成信息在一个小学广场或多维数据集, 它是自然考虑灰度的卷积内在所产生的小尺度结构的基本采用矩形窗函数 w (x)(价值如果 ab -溶质的价值坐标都小于 1/2, 否则和 0)。这样一个函数提高了原始信号的规律性。

For instance, starting from discrete spikes (i.e., Dirac comb) centered at voxel centers, this convolution provides a piecewise (i.e., voxelwise) constant function. Starting from a voxelwise DVC: Achievements and Challenges 29 constant function, its convolution would be a continuous one, piecewise linear along lines parallel to axes. More generally, if the original fine scale texture is C n (derivatives up to order n exist and are continuous), its convolution by w(x) is C n+1 . Exploitation of this line of thought has led to the powerful concept of spline functions, that provide an elegant way of generating an interpolation function with a prescribed position at integer coordinates, with a tunable smoothness [205]. Cubic splines are very popular, because of their good trade-off between smoothness (resulting interpolation is C 2) and compact support leading to efficient implementations. The limit of an infinite order spline interpolation is an interesting and appealing object as it produces a C ∞ interpolation function. It can be shown theoretically that this coincides with the convolution with a cardinal sine function, and hence it would match precisely what is implicitly performed with a Fourier transform (where translation is obtained by simple phase shift on the Fourier transform [36]).

例如, 从离散 (即峰值。狄拉克梳) 在体元中心集中, 这提供了一种分段卷积 (即。voxelwise) 常数函数。从一个 voxelwise 陷落: 成就和挑战 29 常数函数, 其卷积将连续, 分段线性沿着线平行于轴。更一般地, 如果原始小尺度纹理是 C n (n 阶偏导数存在, 是连续的), 其卷积 w (x) 是 C n + 1。开发这一想法导致了样条函数的强大的概念, 提供了一种优雅的方式生成一个插值函数在整数与规定的位置坐标, 可调平滑 [205]。立方样条函数是非常受欢迎的, 因为他们之间的权衡好光滑 (结果 interpo -副调制是 C 2) 和紧凑的支持导致有效的实现。无限阶样条插值的极限是一个有趣的和有吸引力的对象产生一个 C∞ 插值函数。理论上可以证明, 这正好与红衣主教正弦函数的卷积, 因此它将匹配恰恰是隐式地执行与傅里叶变换 (翻译是通过简单的相移傅里叶变换 [36])。

It is unfortunately difficult to go much further from the theoretical side, as the starting point is the fine scale reality that is unknown. From experience, a piecewise linear interpolation (which is a first order spline interpolation), is cheap and easy but does not lead to a high fidelity. Cubic (and even quintic) splines have been observed to be a better approximation (leading to smaller interpolation errors and uncertainties) [212, 186].

不幸的是很难从理论方面走得更远, 出发点是小尺度的现实是未知的。从经验中, 分段线性插值 (一阶样条插值), 是廉价和容易但不导致高保真。立方 (甚至五次) 样条函数已经观察到的是一个更好的近似 (导致较小的插值误差和不确定性)(212、186)。

It may be observed that before achieving perfect registration, using a poorer but faster inter- polation procedure may provide an easily accessible acceleration at no implementation cost. Once a reasonable registration has been achieved, then very few additional iterations using the best available interpolation procedure will provide the desired final hundredths of voxel corrections.

可能观察到之前实现完美的登记, 使用一个贫穷但更快的国际米兰——polation 过程可能提供一个方便的加速度没有实施成本。一次注册取得合理, 然后使用最佳可用很少的额外的迭代插值程序将提供所需的体素的最后数修正。

3.1.2 Similarity measures It was earlier mentioned that different similarity measures have been proposed to assess regis- tration. That is for each voxel, x, the reference gray level f (x) and that of the deformed image corrected by a trial displacement field ge(x) are to be compared. As earlier stated, their difference 30 A. Buljac et al.

3.1.2 相似措施早些时候提到的, 不同的相似性措施提出了评估里吉斯-tration。每个体素,x, 参考灰度 f (x) 和变形图像的纠正试验位移场通用电气 (x) 相比。正如之前所说, 他们的区别 30。Buljac et al。

is at least (that is when the trial displacement field is the exact solution) equal to the sum of the noise affecting each image. Thus the similarity measure implicitly involves a noise model.

至少是 (即当试验位移场的精确解) 等于影响每个图像噪声之和。隐式地包含噪声模型的相似性度量方法。

The most common model is white Gaussian noise, which states that the probability distribution function for the noise is 2 1 p( ) = √ exp − 2 (6) 2 2 where is the standard deviation. Generally, a displacement field is not to be judged based on a single voxel prediction, but rather over a zone of interest, Z. The “whiteness” of noise means that it is uncorrelated from one voxel to any other one. As a result, the probability of observing a residual field (x) = ge(x) − f (x) is Y P [ ] = p((x)) x Z ! (7) 1 X exp − 2 (x)2 2 x Z Assuming that the noise variance is identical for all voxels, maximizing the likelihood P [ ] for the residual field, is equivalent to minimizing its cologarithm, and hence, a natural similarity measure appears X SSSD [ ] = (x)2 (8) x Z where it is recalled that (x) = g(x + u(x)) − f (x). This first measure is the sum of squared differences that is postulated as an appropriate similarity measure [197, 171]. This observation calls for some comments: –First, there is no reason to postulate an expression for S. It has to result from the properties of noise. In the case of uniform, Gaussian and white noise, the most appropriate measure is the sum of squared differences.

最常见的模式是高斯白噪声, 即噪声的概率分布函数 2 1 p( )=√exp−2(6) 2 2 的标准差。通常, 位移场不是基于单一立体像素预测来判断, 而是一个感兴趣的区域,z 噪音意味着它的“白”是不相关的另一个从一个立体像素。因此, 观察剩余场的概率 (x) = 通用电气 (x)−f (x) = Y P[ ]= P((x)) x Z !(7)1 X exp−2 (X) 2 2 X Z 假设噪声方差是相同的所有体素, 最大化残余的 P( ) 可能性领域, 相当于其余对数减少, 因此, 出现自然相似性测量 X SSSD( )= (X) 2 (8) X Z 的地方回忆说, (X) = g (X + u (X))−f (X)。这第一个措施是平方的总和差异作为一个适当的假定相似性度量 (197、171)。这个观察呼吁一些评论: 首先, 没有理由假定一个表达式对美国造成噪声的特性。在统一的情况下, 高斯白噪声, 最合适的测量是平方的总和差异。

–All the above qualifiers (uniform, white, Gaussian) are essential. Any violation of the above would call for a modified measure.

——所有上述限定符 (制服, 白色, 高斯) 是至关重要的。任何违反上述要求修改措施。

DVC: Achievements and Challenges 31 –Let us consider full-field OCT as a practical case. The 3D image consists of a stack of 2D images that correspond to the scatterers assumed to be dilute in a semi-transparent medium. Thus for each slice at a constant depth, a uniform white Gaussian model is a fair approximation (which can easily be checked). However, as depth increases the noise amplitude increases.

31 ”: 成就和挑战——让我们考虑细致的 10 月作为一个实际案例。三维图像由一堆 2 d 图像相对应的散射被认为是半透明介质稀释。以恒定的深度, 因此每一块均匀的白色高斯模型是一个公平的近似 (这可以很容易地检查)。然而, 随着深度的增加噪声振幅增加。

This is partly due to the ambient scattering produced by the medium, which limits the signal amplitude (however, the same bias affects both the reference and the deformed image, and hence its correction is not essential as long as the displacement does not involve very large depth z variations). The depth z also affects the noise amplitude that is expected to grow with it. However, it is quite easy to measure the noise variance as a function of depth, 2 (z). From the later, a modified criterion results X (x)2 SOCT [ ] = (9) (z)2 x Z where the fact that the residual involves two images should have led to doubling the variance, but because a constant multiplicative factor in S plays no role, it has been discarded from the above expression.

这部分是由于产生的环境散射介质, 这限制了信号幅度 (然而, 同样的偏见影响参考和畸形的形象, 因此其校正并不重要只要位移不涉及很大的深度 z 变化)。z 也影响深度的噪声幅度预计将增长。然而, 很容易测量噪声方差的函数深度, 2 (z)。从后, 修改后的标准结果 X (X) 2 SOCT( )=(9) (z) 2 X z 的残余涉及两个图像应该导致一倍方差, 但是因为一个常数乘法因素中没有地位, 它已经被丢弃的从上面的表达式。

–Often, as is the case for optics, the noise variance is a function of the gray level intensity itself. The brighter a voxel, the higher its absolute noise level, and as the noise amplitude grows sub-linearly with the intensity, its relative noise level decreases with the intensity. This p is true for any

Poisson (or shot) noise where (f) = f . However, as the number of "counts" increases, the distribution can be well accounted for by a Gaussian distribution. Moreover, a white noise assumption can still be valid, and hence only uniformity is to be questioned. In such cases, it is straightforward to extend the previous analysis to obtain X (x)2 SPoisson [ ] = (10) f (x) x Z As above the constant factor of 1/(4 2) has been omitted. In such cases, as noted in Ref. [211], taking the Anscombe transform of the original gray levels [145] or more simply, taking the 32 A. Buljac et al.

——通常, 光学, 噪声方差是一个函数的灰度强度本身。光明的体素, 绝对的噪音水平越高, 并随着噪声振幅的增长 sub-linearly 强度, 其相对强度噪音水平降低。这个 p 是适用于任何泊松噪声 (或照片), (f) = f。然而, 随着"计数" 的数量增加, 分布可由高斯分布。此外, 一个白噪声的假设仍然可以有效的, 因此只有均匀性受到质疑。在这种情况下, 它是简单的扩展前面分析获得 X (X) 2 SPoisson( )= (10) f (X) X Z 如上的常数因子 1 /(4 2) 被省略了。在这种情况下, 正如 Ref。[211], 采取的安斯科姆变换原始灰色水平 [145] 或更简单,32 个。Buljac et al。

square root of gray levels, fˆ = f , restores a constant variance noise affecting fˆ. Hence it p √ p suffices to register g onto f , using SSSD , as an appropriate similarity measure X p p 2 SAnscombe [ ] = g(x + u(x)) − f (x) (11) x Z Note however that this transformation relies on the fact that a zero gray level (f = 0) means that the light intensity is 0, and hence an offset in gray levels, which is commonly used without questioning its relevance, is not allowed without taking it into account in the above expression.

根灰色的水平,ˆ= f, 恢复一个常数影响 fˆ 噪声方差。因此 p√ 就可以注册 g 到 f, 使用 SSSD, 合适的相似性度量 X p p 2 SAnscombe( )= g (X + u (X))−f (X) 然而,X Z(11) 指出, 这种转变依赖于一个零灰度 (f = 0) 意味着光强度为 0, 因此一个偏移量在灰色的水平, 这是毫无疑问地常用其相关性, 是不允许的, 没有考虑到它在上面的表达式。

–If the noise is uniform and Gaussian but not white, one should measure its covariance Cov(y) = h (x + y) (x)ix (12) where the dependence only on y results from the assumed statistical stationarity. The inverse covariance is a metric kernel A(y), defining the so-called Mahalanobis distance [140]. It is conveniently computed from its Fourier transform that is equal to the inverse of the Fourier transform of Cov(y). If F designates the Fourier transform and F−1 its inverse, then 1 A(x) = F−1 (13) F(Cov(x)) From this metric, the (Mahalanobis) similarity measure writes X X SMahalanobis [ ] = (y)A(y − x) (x) (14) x Z y Z When the covariance is purely local (i.e., at the voxel level), it is to be noted that this formula coincides exactly with SSSD . As for the Anscombe transform, there exists a filter H, such that the mere quadratic difference of fˆ = H ? f and ĝ(x) = [H ? g](x + u(x)) coincides with SMahalanobis [ ]. In Fourier space, this filter is the square root of F(H) = F(A)1/2 .

——如果噪音是统一和高斯而不是白色的, 一个人应该衡量其协方差 x (y) = h (x + y) (x) 第九 (12), 只依赖于 y 假定的结果统计平稳性。逆协方差度量内核 (y), 定义所谓的距离 [140]。它很方便地计算它的傅里叶变换等于 x 的傅里叶变换的逆 (y)。如果指定的傅里叶变换和 F−1 它的逆矩阵,

然后 1 F (x) =−1 (13) F (x (x)) 从这个指标,(Mahalanobis) 相似性测量 x SMahalanobis 写道 [ ]= (y) (y−x) (x) (14) x Z y Z 当协方差是当地 (即纯粹。立体像素级), 是与 SSSD 指出, 这个公式完全一致。至于安斯科姆变换, 存在一个过滤器 H, 这样仅仅二次不同 f^= H ?f 和 ĝ(x) = [H ?g] (x + u (x)) 正值 SMahalanobis( )。在傅里叶空间中, 这个过滤器是根号 (H) = F (A) 1/2。

–Finally, let us consider the case when the noise is uniform, white, but not Gaussian. In this case, it is characterized by a nontrivial probability density function (p.d.f.), p( ). Following the above derivation, it is observed that the absence of correlation implies that probabilities DVC: Achievements and Challenges 33 can be multiplied, and hence their logarithm summed, thereby providing a similarity measure that is still proportional to the log-likelihood, or up to a change of sign to comply with the above Gaussian case, the similarity measure to be minimized reads X SnG [ ] = − log(p((x))) (15) x Z A simple and useful application of the above result consists of having the superposition of two Gaussian noises. In particular, one can be a low probability one but with a broad variance, akin to “salt and pepper noise” . In such cases, the − log( ) function is no longer a mere parabola, but for large arguments it may open up to a cone (if one wants to preserve convexity, a very useful property here) or flatten out to a constant asymptote.

——最后, 让我们考虑这样一种情况, 当噪音是制服, 白色, 但不是高斯。在这种情况下, 它的特点是一个非凡的概率密度函数 (p.d.f), p( )。上面的推导后, 发现没有相关意味着概率": 成就和挑战 33 可以成倍增加, 因此他们对数总结, 从而提供一个相似措施, 仍是对数似成比例, 或改变的标志符合上述高斯情况下, 最小化读取 X 的相似性度量方法合成天然气 ( )=− 日志 (p((X))) (15) X Z 上面的一个简单而有用的应用程序由两个高斯噪声的叠加的结果。特别是, 一个人可以是一个低概率但广泛的方差, 类似于“椒盐噪声”。在这种情况下,− 日志 ( ) 函数不再只是抛物线, 但对于大型参数可能打开一个锥 (如果一个人想要保留凸性, 一个非常有用的属性) 或平一个常数渐近线。

Let us emphasize that the above expressions are all derived from measurable properties from the noise, and no free parameters are to be tuned.

让我们强调, 上述表达式都是来源于从噪音, 可测量的属性, 没有自由参数调优。

Yet, the list of popular similarity measures is far from being exhausted. For instance, cross- correlation is frequently chosen since the early developments of DVC [12, 212]. Let us first note that if the zone of interest is large, and if the displacement is uniform over the zone, the (normalized) cross-correlation function of f and g coincides, up to a translation, with the auto-correlation function of the reference zone of interest, but reaches its maximum at a position that is equal to the displacement between the two zones. Moreover, the cross-correlation function is easily h i obtained in Fourier space as F−1 F[f]F[g] . Thus, it offers the possibility of exploring all potential displacements simultaneously and this for a modest cost using fast Fourier transforms [42]. Finally, using a subvoxel interpolation of the cross-correlation, very precise localization of the maximum can be achieved, which is implicitly based on a C ∞ interpolation of both images. Those properties made the success of Particle Image Velocimetry (PIV) in the early days [2] during which robust and fast methods that could be implemented easily were sought, and this technique was a well suited answer to these needs.

然而, 受欢迎的相似性措施的列表是远非精疲力竭。例如, 跨关联经常选择初以来的发展" 的 [212]。让我们先注意, 如果感兴趣的区域很大, 如果位移均匀区,f 和 g(规范化) 互相关函数的一致, 翻译, 与自相关函数的引用区域感兴趣的, 但是达到最大值, 等于两个区域之间的位移。此外, 我获得的互相关函数很容易 h 傅里叶空间 −1 F [F] [g]。因此, 它提供了探索所有潜在的可能位移同时这温和的成本使用快速傅里叶变换 [42]。最后, 利用互相关的 subvoxel 插值, 最大可以达到非常精确的定位, 这是隐式地基于 C∞ 插值的图像。这些属性使成功的粒子图像测速技术 (PIV) 在早期 [2] 在健壮的和快速的方法可以方便地实现, 这技术是适合解决这些需求。

34 A. Buljac et al.

34(A)。Buljac et al。

However, it is to be stressed that raw fast Fourier transform algorithms assume spatial peri- odicity of the functions to be transformed. Thus if the two zones for f and g do not coincide, the cross-correlation function (be it computed with FFT or not) takes into account non overlapping edges and hence is not a satisfactory measure. This can be corrected by progressively clipping the zone in the deformed image to the predetermined displacement, but the iterative scheme reduces drastically the attractiveness of this similarity criterion. This correction consists of computing the cross-correlation between f and ge rather than f and g X SCC [ ] = g (x) − he (e g i)(f (x) − hf i) x Z X = (1/2) g (x) − f (x))2 (e (16) x Z X −(1/2) g 2 i − 2he [he g ihf i + hf 2 i] x Z The last term in the sum does not vary with the displacement iff the statistical sampling of the gray values allows he g 2 i and he g i not to vary much when the zone of interest is moved. In this case, the cross-correlation function coincides with the quadratic difference.

然而, 它是强调原始快速傅里叶变换算法假设空间邻近 odicity 功能的改变。因此, 如果 f 和 g 的两个区域不一致, 互相关函数 (它与 FFT 计算) 考虑非重叠的边缘, 因此不是一个令人满意的措施。这可以通过逐步修正剪切带的变形图像预先确定的位移, 但迭代计划大幅减少的吸引力这相似准则。这个校正由之间的互相关计算 f f 和 g 和通用而不是 X 鳞状细胞癌 ( )= g (X)− 他 (e g i) (f (X)− 高频 i) X Z X = (1/2) g (X)−f (X)) 2 (e (16) Z X−(1/2) g 2−2 他 [他 g ihf 我 + 高频 2]X Z 的最后一个学期不随位移之和 iff 灰色的统计抽样值允许他克 2 我和他克我不改变当感兴趣的区域移动。在这种情况下, 互相关函数正值二次不同。

Second, and more importantly, there is no way to deal efficiently with a displacement field that is not a pure and uniform translation. Even a rigid rotation cannot be represented simply in Fourier space. Additionally, the computation load for estimating ge is much greater than computing the above quadratic difference and its gradients.

第二, 更重要的是, 没有办法有效地处理一个位移场, 并不是一个纯粹的和统一的翻译。甚至一个刚性旋转不能只是在傅里叶空间表示。此外, 计算

负荷估算 ge 远远大于计算上述二次差异及其梯度。

It is often mentioned that the cross-correlation criterion to be maximized is independent of a possible affine transformation of gray level that would affect g but not f . This is true, however, it is odd to express such a demand at this stage. What is meant here is that the starting point, Equation (1), is not satisfied and should rather be written as g(x + u(x)) = (1 + a)f (x) + b (17) where the brightness b and contrast a corrections have been written so that the previous case coincides with a = b = 0. It is noteworthy that if no information is available on a and b, it DVC: Achievements and Challenges 35 may be seen as saying that a and b are part of the noise, but they have some specificities. For instance if they have known spatial correlations (say long wavelengths only), the above similarity measure SMahalanobis , will lead to cancel brightness and contrast modulations over large distances by a moving average filter (i.e., removing the effect of a and b fields), and this will be done automatically without having to formulate the appropriate filter "manually." The limit case of having a spatially constant a and b is obtained by taking care of the appropriate limit (the direct covariance function becomes somewhat undefined).

通常提到的互相关准则最大化是独立的一个可能的仿射变换的灰度影响 g 而不是 f。这是真的, 不过, 奇怪的是表达这样一个需求在这个阶段。是什么意思是起点, 方程 (1), 是不满意, 而应该写成 g (x + u (x)) = (1 + 1) f (x) b + b(17) 亮度和对比度修正一直写, 这样前面的情况正好与 a = b = 0。值得注意的是如果没有信息可以在 a 和 b, 它的陷落: 成就和挑战 35 可能被视为说 a 和 b 是噪音的一部分, 但他们有特异性。例如如果他们知道空间相关性 (长波长) 说, 上述相似性度量 SMahalanobis, 将导致取消亮度和对比度调节大距离移动平均滤波器 (即。, 消除 a 和 b 字段) 的影响, 这将自动完成, 而无需手动制定适当的过滤器"。" 的极限情况获得的空间常数 a 和 b 是照顾适当的限制 (直接协方差函数变得有些未定义)。

Alternatively, it is possible to consider a and b in a similar fashion as u, as unknown parameters to be determined to register at best the two images. This can be formulated easily as a natural extension of the optimization of the similarity measure, leading to the joint determination of the gray level transformation and of the displacement simultaneously [100]. One may also consider a sequential determination, searching first for a and b at fixed displacement, and then for u using the predetermined gray level corrections for ge, and iterating these two steps up to convergence.

另外,a 和 b 可以考虑以类似的方式为 u, 作为未知参数确定登记在最好的两个图像。这很容易制定的自然延伸相似度的优化措施, 导致联合测定的灰度变换和位移同时 [100]。也可以考虑一个连续的决心, 首先寻找 a 和 b 在固定位移, 然后为你使用预定的灰度修正通用电气和迭代收敛这两个步骤。

With this formulation, it is straightforward to notice that a and b are given by a mere linear regression, which consists of matching the mean value and the standard deviation of f and ge, which is precisely what is obtained treating a and b as noise. However, let us insist on the fact that once again, after having written Equation (17) properly, and chosen to treat a and b either as noise or as unknowns, the appropriate similarity measure is naturally generated and leads to the solution. Without much surprise, the same solution emerges whatever the choice is made for the status of a and b.

用这个配方, 容易注意给出的 a 和 b 是一个纯粹的线性回归, 包括匹配的平均值和标准差 f 和通用电气, 这正是获得治疗 a 和 b 是噪音。然而, 让我们坚持这一事实再一次, 后写方程 (17),a 和 b, 选择治疗作为噪声或作为未知数, 合适的相似性度量是自然生成, 导致解决方案。没有太多惊喜, 同样的解决方案出现不管选择是为 a 和 b 的状态。

Let us also note that Equation (17) may mean that the same parameters a and b hold for the entire image. This is not at all equivalent to treating the problem with a partition into zones, for each of whom a and b are determined anew. The latter problem introduces much more unknowns than the former, and hence the uncertainty attached to the determination of the displacement (and gray level corrections) is much higher (especially for small subvolume or element sizes, see 36 A. Buljac et al.

我们还要注意, 方程 (17)a 和 b 可能意味着相同的参数对整个图像。这不是相当于把一个分区的问题区域, 其中每个 a 和 b 是重新确定。后者问题介绍了未知远远超过前者, 因此不确定性与位移的确定 (和灰度修正) 要高得多 (尤其是小尺度子卷或元素, 看到 36。Buljac et al。

Section 4). It may be desirable to introduce some flexibility in the gray level corrections, but in this case again, the best way to proceed is to introduce a parameterization of the way a and b may vary in space.

第四节)。它可能是可取的介绍一些灵活性的灰度修正, 但在这种情况下, 最好的办法是引入一个参数化的方式进行 a 和 b 在太空中可能会有所不同。

In cases where two images may be related by more complex contrast corrections, other statis- tical measures have been introduced. The so-called mutual information [209, 199], I(f, ge), checks for the existence of a well defined value of ge knowing f without having to specify explicitly the relation between the two. More precisely, the mutual information is defined as X P (f, ge) I(f, ge) = P (f, ge) log (18) P (f)P (e g) f,e g where P (f, g) is the joint distribution function. If f and ge were unrelated then their joint distri- bution would be equal to the product P (f)P (e g), and their mutual information would be 0. The mutual information measures the "entropy reduction" brought by the knowledge of one of the two gray levels, say f , when considering the other one. It is more transparent when noting that the argument of the log function is nothing but the ratio of the conditional probability distribution, g |f) = P (f, ge)/P (f) and the probability of ge, P (e P (e g) without the knowledge of f . Interestingly, when the joint distribution of f and ge (assuming displacement corrections have converged) is Gaussian, it has been shown that the mutual information reduces to a function of the normalized covariance, log(1 − Cov2) [118]. Thus when one quantity would be Gaussian and related to the other one by an affine relationship, the mutual information criterion reduces to maximizing the covariance or the cross-correlation.

在两幅图像的情况下可能会被更复杂的相关对比修正, 其他统计学的——提卡措施介绍了。所谓的互信息 (209、199), 我 (f, 通用电气), 检查一

个良好定义的值存在的通用电气知道 f 无需指定明确两者之间的关系。更准确地说, 互信息定义为 X P (f, ge) 我 (f, 通用电气)= P (f, ge) 日志 (18)P P e g f (f), e g P (f, g) 是联合分布函数。如果 f 和通用电气无关他们的联合 distri bution 等于产品 P (f) P e (g), 和他们共同的信息将是 0。互信息措施带来的 "熵减少的两个灰色的知识水平, 说 f, 在考虑另一个。更透明的注意的是, 对数函数的参数只是条件概率分布的比例,g | f) = P (f, ge) / P (f) 和通用电气 (ge) 的概率,P (e P f e (g) 的知识。有趣的是, 当 f 和通用电气的联合分布 (高斯假设位移修正聚集), 它已经表明, 归一化互信息函数减少的协方差, 日志 (1−Cov2) [118]。因此当一个数量将高斯和另一个相关的仿射关系, 互信息准则降低最大化协方差或互相关。

The freedom of being able to deal with an arbitrarily complex (i.e., nonlinear) relationship has however a large cost related to sampling issues. In order to faithfully infer a joint distribution function, a large sample size is needed and thus a local approach is inappropriate because of the small number of voxels involved. In addition, a purely local approach would allow the nonlinear relationship relating f and ge to differ from one zone to another, thereby further relaxing the registration constraints. Another difficulty is that gray levels are subjected to noise, and hence DVC: Achievements and Challenges 37 they should rather be defined as an interval of width (or rather a probability distribution function (pdf) having a standard deviation). This is essential to compare two gray levels that are supposed to be identical. One may wonder where this key parameter appears, since this is usually not made explicit. In fact the statistical entropy measure involves a probability distribution that is defined numerically with a particular binning, that should have a width . The strong dependence of the entropy on this binning (or discretization) is very seldom discussed. This is a fragility of this criterion, together with the fact that locally all spatial correlation is lost (voxels may be shuffled spatially without consequence on the resulting entropy).

的自由能够处理任意复杂的 (即。、非线性) 关系不过大成本相关抽样问题。为了忠实地推断出一个联合分布函数, 需要大样本大小, 因此一个本地的方法是不合适的, 因为小数量的像素点。此外, 一个纯粹的本地方法允许 f 和通用电气有关的非线性关系从一个区域到另一个不同, 从而进一步放松登记约束。另一个困难是, 灰色的水平受到噪音, 因此": 成就和挑战 37 他们应该被定义为一个区间的宽度 (或者说一个概率分布函数 (pdf) 标准差)。这是必要的比较两个灰色的水平应该是相同的。可能想知道这一个关键参数, 因为这通常是不明确。事实上统计熵定义的测量涉及到概率分布数值与特定装箱, 应该有 的宽度。熵的强烈的依赖在这面元 (或离散化) 是很少讨论。这是这一标准的脆弱性, 加上本地所有空间相关性丢失 (压可能打乱空间没有后果产生的熵)。

A second weakness is the lack of "distance" or progressiveness in the joint distribution function.

第二个弱点是缺乏"距离"或共产党员先进性的联合分布函数。

When ge differs from most other gray levels in voxels having the same f value, the difference ge − hg(f)i does not come into play, and hence no difference is made between a small or a large violation of a potential g(f) relationship. This in turn implies a lack of convexity of the similarity measure, and the numerical difficulties resulting thereof, that is lack of uniqueness, and the solution possibly depends on the type of minimization algorithm (and on possible convergence parameters when required). Finally, it is to be stressed that cases where an arbitrary complex relationship between f and ge are not very frequent to say the least. When it is needed to take into account such complex correspondence, one may simply parameterize this relationship (e.g., stating that g(f) be a polynomial or any other nonlinear functional form) and identify the required parameters with the least variability that is needed (e.g., not estimating a different polynomial for each zone when a local approach is used).

当通用电气不同于大多数其他灰色水平压拥有相同的 f 值, 通用电气的区别 −hg (f) 我不发挥作用, 因此没有区别之间是由小型或大型违反了一个潜在的 g (f) 的关系。这反过来意味着缺乏相似性度量的凸性, 并由此数值困难, 缺乏独特性, 最小化算法的解决方案可能取决于类型 (和可能的收敛参数时需要)。最后, 要强调之间复杂关系的情况下任意 f 和通用电气至少可以说不是很频繁。时需要考虑这些复杂的对应关系, 这种关系可能只是一个参数化 (例如, 说明 g (f) 是一个多项式或任何其他非线性函数形式) 和识别所需的参数变化最少的需要 (例如, 不估计为每个区当地不同的多项式的方法是使用)。

3.1.3 Inter-modality registration Among the few cases when such nonlinear correspondence may be useful, is when a different modality (and hence a different contrast) is used for f and g and still one would like to register the two images. One such example was studied in details [225], where x-ray and neutron tomographic 38 A. Buljac et al.

3.1.3 Inter-modality 登记等少数情况下非线性通信可能是有用的, 当一个不同形态 (因此不同的对比) 用于 f 和 g 和仍然想注册两个图像。详细研究了这样一个例子 [225],x 射线和中子 38 层析。Buljac et al。

images of the same sandstone sample were captured, and a common referential was sought to fully benefit from both modalities and their resulting contrast. The presence of elements that display different contrasts with only one modality forbids the use of parametric relationships, yet it is possible to design a learning scheme that is a simple extension of standard DVC, and that leads to registration and simultaneously allows the different phases to be naturally segmented.

图片相同的砂岩样品被抓获, 一个常见的引用是试图充分受益于两个模式及其产生的对比。元素显示不同的对比的存在只有一个通道禁止使用参数的关系, 还可以设计一个学习计划, 是一个简单的扩展标准", 同时导致注册和允许不同阶段自然分割。

Plain x-ray tomography as such delivers a scalar field (i.e., x-ray absorption) that is relative to a specific energy for monochromatic sources as is usually the case in synchrotron beamlines, or to an energy spectrum for lab CT scanners. This provides a very rich information in terms of 3D spatial resolution. Yet, in some cases, it is difficult to discriminate between different phases.

普通 x 射线断层扫描等提供了一个标量场 (即。x 射线吸收), 是相对于

一个特定的能量为单色源通常是在同步加速器 beamlines, 或实验室 CT 扫描仪的能谱。这提供了一个非常富有的 3 d 空间分辨率信息。然而, 在某些情况下, 很难区分不同阶段。

Thus, very early on, the idea of combining different modalities has emerged. The main motivation came from the field of medical imaging where the patient motion has always been a difficult obstacle to overpass. Thus a secondary modality that could detect the phase of breathing or cardiac rhythm allows radiographs to be acquired in situations close to steadiness in spite of uninterrupted motions [228]. Such a case however involves a rather poor usage of the secondary acquisition device.

因此, 从很早开始, 结合不同模式的概念出现了。的主要动力来自于病人的医学成像领域的天桥的运动一直是一个困难的障碍。因此第二形态, 可以检测阶段的呼吸或心脏节律允许射线照片被收购的情况下接近稳定尽管不间断运动 [228]。然而这种情况下涉及到一个相当贫穷的使用二次采集设备。

However, still in the field of medical imaging, it was realized that two 3D-imaging modalities could be combined to get a richer information, as the physical origin of contrast in the two modalities could differ [141]. In order to achieve full benefit from these modalities, it is essential to be able to express them in the same reference frame. This automatically calls for image registration as a powerful tool to put the two images in coincidence. However, for the very purpose of using different contrasts, not to mention different resolutions or different acquisition times that could induce slight distortions between the two modalities, it is difficult to define what a good matching is. Reference [102] provides a review of early registration techniques that were used on the turn of the century.

然而, 仍然在医学成像领域, 它是意识到两个 3 维成像方法可以获得更丰富的信息相结合, 对比两个模式的物理起源不同 [141]。为了达到充分受益于这些方法, 至关重要的是能够表达它们在同一参考系。这个自动调用图像配准的一个强大的工具, 要把这两个图片巧合。然而, 对于使用不同的对比的目的, 更不用说不同分辨率或不同采集时间, 可能引起轻微扭曲之间的两个模式, 很难定义什么是良好的匹配。参考 [102] 提供了一个审查的早期注册技术在世纪之交的时候使用。

DVC: Achievements and Challenges 39 In the field of materials science, dealing with different modalities has the potential of revealing chemical contrast. For instance dual source x-ray tomography with a simultaneous acquisition of the two perpendicular beams set at two different energies provide two 3D images with different contrasts [67, 113, 180]. Yet, in that case, the two volumes are expected not to be very different, and registration may not be extremely challenging. The association of x-ray and neutrons but bring out much more salient differences [6].

": 成就和挑战 39 在材料科学领域, 处理不同的模式有可能揭示化学对比。例如双 x 射线源断层扫描的同时采集两个垂直的光束在两种不同的能量提供两个 3 d 图像不同的对比 (67、113、180)。然而, 在这种情况下, 预计两卷不是很不同, 和登记不得极具挑战性。协会的 x 射线和中子, 但更突出的差异 [6]。

Specific features or markers that have a well defined signature in both modalities were first a privileged way to find a common reference frame. This technique however refers to marker track- ing rather than DVC. It is fair to note that when a simple mapping is sought (i.e., translation, rotation and scale factor) and when there is no need for very accurate registration, this marker tracking technique offers a simple solution. However, the definition and selection of the appropri- ate markers are essentially manual and hence registration requires a significant and incompressible time. Additionally, this technique cannot be considered as optimal in terms of an abstract consideration of the usage of information that is present in the images as only a small fraction of the image is used.

特定功能或标记有一个定义良好的签名在这两个模式首次特权的方式找到一个共同的参考框架。然而这种技术是指标记跟踪- - -荷兰国际集团 (ing) 而不是陷落。公平地注意, 当一个简单的映射是寻求 (即。, 平移、旋转和比例因子), 当不需要非常准确的登记, 这个标记跟踪技术提供了一个简单的解决方案。然而,appropri——吃的定义和选择标记本质上是手工登记, 因此需要一个重要的和不可压缩时间。此外, 这种技术不能被认为是最优的一个抽象的共同电灼疗法使用的信息出现在图像的图片只是一小部分。

It is worth noting that DVC (or DIC for 2D images) strictly speaking cannot be used as the conservation of brightness, which lies at the very heart of the method, does not hold. Hence a much more general similarity measure is to be used (see Section 3.1.2). If no more than two phases are considered an affine transform of gray levels is sufficient, and hence a standard DVC algorithm allowing brightness and contrast changes, enables a proper registration to be achieved. Care should be taken to perform the gross gray level correction early enough to be consistent with a correction scheme based on small perturbations. In more general cases, however, correspondence between the two images has to phrased in more general terms. Even a nonlinear relationship between the gray levels of the two modalities may be inadequate, as the same gray level of one modality may be expressed as different gray values in the other modality.

值得注意的是,”(或 DIC 2 d 图像) 严格来说不能用作保护亮度, 位于心脏的方法, 不持有。因此使用一个更一般的相似性度量 (见第 3.1.2)。如果不超过两个阶段被认为是一个灰色的仿射变换的水平就足够了, 因此一个标准” 的算法允许亮度和对比度变化, 允许适当的登记。应该小心执行总灰度修正早期足以符合基于小扰动校正方案。在更一般的情况下, 然而, 两幅图像之间的通信必须措辞更一般的条件。甚至灰色的水平之间的非线性关系的两个模式可能不足, 是相同的灰度形态可以表示为不同的灰值形态。

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It is for these registrations that a similarity measure based on mutual information is suited [236, 139]. Mutual information is one choice out of many comparable measures based on joint his- tograms, called f-information or f-divergence [226]. As earlier mentioned, the joint histogram does not take into account the spatial correlation in the images and depends on the chosen binning of the histogram.

正是因为这些注册, 基于互信息的相似度度量适合 (236、139)。互信息

是一个选择的许多类似措施基于联合他——tograms 称为 f-information 或 f-divergence [226]。正如之前提到的, 联合直方图没有考虑图像的空间相关性, 取决于所选的装箱的直方图。

Introducing a similarity measure that is a function of the pair of gray levels on the registered images, Φ(f (x), ge(x))2 , rather than the mere quadratic difference as used earlier, allows one to come up with a generalized formulation of DVC. A Bayesian framework provides an interpretation of the joint distribution and in agreement with the noise interpretation of the quadratic differ- ence that was presented earlier, the Φ2 function can be chosen as the cologarithm of the joint histogram. In Ref. [225], it was shown that the analytical formulation of the Newton's descent minimization algorithm assumes a form that is a natural extension of the incremental correction, see Equation (24). Moreover, if Φ2 is adjusted from a previous determination of the registration, such an approach can be seen as a learning scheme of the suited potential to be minimized.

引入相似度度量是一个函数的一双灰色的水平在注册图像,Φ(f (x), 通用电气 (x)) 2, 而不是单纯的二次区别正如之前使用的, 允许一个人想出一个广义陷落的配方。联合分布的贝叶斯框架提供了一种解释与噪声和协议的解释二次稍早出现- ence 不同,Φ2 函数可以选择的余对数联合直方图。Ref。[225], 表明牛顿下降最小化算法的分析制定假设的形式是一个增量修正的自然延伸, 见方程 (24)。此外, 如果 Φ2 调整从先前确定的登记, 这种方法可以被看作是一个学习方案, 适合可能最小化。

Such an approach was shown to be successful for x-neutron tomography registration that was performed for a Bentheim sandstone with a rather similar resolution [225]. Figure 10 shows two complementary composite checkerboard images made of squares extracted from one modality or the other after registration. It is seen that some morphologic features (crack or boundary) are visible in both modalities and show an excellent continuity. Conversely, other features such as the large white inclusion show a large attenuation with neutron imaging but appears as almost invisible with the x-ray modality.

这种方法被证明是成功的 x-neutron 断层 Bentheim 砂岩进行了登记, 一个类似的决议 [225]。图 10 显示了两个互补的复合棋盘图像的方块提取从一个形态或其他注册后。看到一些形态学特征 (裂纹或边界) 是可见的形式和展示一个优秀的连续性。相反, 其他特性, 比如大型白色包含显示一个大与中子成像衰减, 但似乎与 x 射线形态几乎看不见。

DVC: Achievements and Challenges 41 (a) (b) Fig. 10 Complementary mosaic images showing alternating square patches cut out of the two tomographic modalities (x-ray or neutrons) after registration. It is observed that some features (boundary, crack) show an excellent continuity, whereas other features exhibit a very different contrast.

": 成就和挑战 41 (a) (b) 图 10 互补马赛克图像显示交替广场补丁的后两层析模式 (x 射线或中子) 登记。观察到一些特性 (边界、裂缝) 展示一个优秀的连续性, 而其他特性表现出截然不同的对比。

3.2 Kinematic basis Let us now discuss the choice of the kinematic basis. As mentioned earlier, the choice of the space U the displacement field belongs to is the key to provide a regularization and to make the problem well-posed. Therefore a well suited choice will help convergence to a satisfactory measurement result and above all it will yield small uncertainty levels [23, 196, 191, 149, 150]. Conversely, if not well chosen, it may limit the possible performance of the algorithm and thus the quality and reliability of the obtained measurement. In a few words: it is crucial to use the least number of parameters to describe the displacement fields, but as this number is reduced the risk of excluding the actual displacement from the trial space increases, and hence it may induce a model error [23, 94]. Thus it is essential to judge the quality of the obtained displacement from the residual field to check whether manifestations of unanticipated phenomena would not be visible.

3.2 运动的基础上让我们现在讨论运动基础的选择。正如前面提到的, 你的空间位移场的选择属于是提供一个正规化的关键, 使适定的问题。因此适合选择将帮助收敛到一个满意的测量结果, 最重要的是它将产生小的不确定性水平 (196,191,149,150]。相反, 如果没有很好的选择, 它可能会限制可能的算法的性能, 从而获得测量的质量和可靠性。用几句话: 这是至关重要的用最少的参数来描述位移字段, 但这个数字是减少风险的排除试验空间的实际位移增加, 因此它可能诱发模型误差 [94]。因此判断至关重要的质量获得了剩余的位移场　检查意外现象的表现是否会不可见。

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Another factor may be taken into account, namely, computation time. The manipulation of a large quantity of data naturally leads to heavy computational load. Hence a natural idea is to partition the images into small subvolumes and register them independently. When subvolumes are small, it is not needed to incorporate many parameters to account for the local kinematics, and hence one may be faced with a large number of very small sized problems, each of which being possibly addressed in parallel (see Section 5.2). This is the spirit of the so-called “local” approaches.

另一个因素可能是考虑, 即计算时间。大量的数据的操纵自然导致沉重的计算负载。因此一个自然的想法是将图像划分为小的子卷和独立注册。当子卷很小, 它不需要将许多占当地的运动学参数, 因此一个可能会面对大量的非常小的问题, 每一个都是可能解决并行 (见 5.2 节)。这是所谓的“本地”的精神的方法。

3.2.1 Local DVC As of today, local approaches to DVC are more often used than global approaches (see all the examples discussed in the introduction). There are several reasons, one of them being that they were developed ten years earlier than global approaches. Local DVC was first implemented in which the mean 3D translations per considered subvolume were evaluated [12]. The local rotations were subsequently added in the set of measured degrees of freedom per subvolume [207]. The method was applied for the analysis of a compression test on aluminum foam (i.e., representative of the behavior of trabecular bone). An extension of the previous technique is to apply it to measure the rigid body motions of grains of complex shape. It has been referred to as discrete DVC [86, 3] and has been utilized to study strain localization in sand for which the local grain rotations play a major role. The first order warping of subvolumes was proposed by Bornert et al. [18] and Verhulp et al. [230]. Higher order interpolations were implemented later on [70, 130, 186]. All these improvements aim at better capturing the local kinematics arising in mechanical tests.

3.2.1 当地" 的今天, 当地的" 的方法比全球更常用的方法 (见介绍所有讨论的例子)。有几个原因, 其中之一是, 他们比全球十年前开发方法。当地陷落首次实现的意思是 3 d 翻译每考虑子卷进行评估 [12]。当地的旋转随后被添加到组测量自由度/子卷 [207]。方法应用对泡沫铝压缩试验的分析 (即。, 代表骨小梁的行为)。之前的扩展技术是应用于测量谷物的刚体运动的复杂形状。被称为离散陷落 (86 3), 利用应变局部化研究沙当地的粮食轮换中发挥重要作用。提出了子卷的一阶弯曲 Bornert 等。[18] 和 Verhulp et al。[230]。高阶篡改以后实施 (70、130、186)。所有这些改进旨在更好地捕捉当地产生机械运动学测试。

However, even if more and more parameters are used to perform the registration of subvolumes, often only the displacement vector of the center is kept, and a final post-processing is carried out that consists of computing an interpolated (and smoothed) displacement field based on the discrete DVC: Achievements and Challenges 43 measurements at each subvolumes center. This last operation is performed without reference to the analyzed images and thus is not considered here as part of the DVC computation. However, one should note that this is a critical step for computing, say, strain fields.

然而, 即使越来越多的参数是用来执行子卷的登记, 通常只有中心的位移矢量, 最后进行后处理, 包括计算一个插值 (平滑) 位移场基于离散陷落: 成就和挑战 43 测量在每个子卷中心。执行最后一个操作没有引用分析图像, 因此这里不考虑的一部分" 的计算。然而, 我们应注意, 这是一个关键步骤计算、应变场。

The interested reader will find many details on this technique in the first review paper on DVC [11]. Similarly, some examples can be found in the same paper on its early use. The intro- duction of the present paper also lists more recent applications. In order to have a fully dense displacement evaluation (i.e., for any position within the ROI), global approaches were introduced.

感兴趣的读者会发现很多细节在第一篇综述该技术" 的 [11]。同样, 在同一篇论文中可以找到一些例子在初期使用。本文的介绍——导也列出了最近的应用程序。为了拥有一个完全致密位移评价 (即。ROI) 中的任何位置, 介绍了全球的方法。

The registration is therefore using all the voxels belonging to the ROI at once.

因此注册使用所有体素属于 ROI。

3.2.2 Global DVC Global approaches to DVC were developed more recently. In that case, the kinematic degrees of freedom are spatially coupled, and hence there is no way to compute parts of the problem independently except if parallel algorithms based on domain decomposition methods are imple- mented [176]. The latter ones have yet to be extended to global DVC.

A single and hence “global” solution has to be determined at once. This may appear as leading to very heavy computations.

3.2.2 全球” 全球” 是最近开发的方法。在这种情况下, 运动自由度空间耦合, 因此没有办法独立计算的那部分问题除非基于域分解方法及其并行算法——表示“状态” [176]。后者的尚未扩大到全球的陷落。一个单一的, 因此“全球”解决方案待定。这可能表现为导致很重计算。

However, a number of algorithmic features may be used to preprocess some computations used several times. It then appears that the computation of ge with the current determination of the displacement field is the most time intensive part of the computation, and hence computing time is (today!) not a relevant argument for choosing one approach or another one.

然而, 很多算法的特性可用于预处理一些计算使用几次。然后它看来, 通用电气与当前的计算位移场的确定是最密集的部分时间计算, 因此计算时间 (今天!) 不是一个相关参数选择一种方式或另一个。

The first implementation of a global approach consisted of discretizing the region of interest with 8-noded cube (C8) elements for which trilinear shape functions are chosen [197]. It is now referred to as C8-DVC. It is to be noted that there is not a big difference between local and global descriptions of the kinematics. The same type of intrinsic complexity may be incorporated within one C8-element and one local cubic zone of the same shape and size [122]. However, within a global setting, the displacement field is continuous at any location within the ROI (without resorting 44 A. Buljac et al.

全球第一个实现方法包括离散化感兴趣的区域与 8-noded 立方体 (C8) 元素的三线的形状函数选择 [197]。现在被称为 C8-DVC。是指出, 本地和全球没有一个很大的区别的运动学描述。相同类型的内在复杂性可能包含一个 C8-element 和一个当地的立方区内相同的形状和大小 [122]。然而, 在全球设置, 任意位置的位移场是连续在 ROI(不通过 44。Buljac et al。

to a post-processing step), and the field used for the determination is trusted for each voxel, rather than keeping only the central displacement and discarding all other computed parameters.

后处理步骤), 字段用于每个体素的决心是可信的, 而非只保留中央位移和丢弃所有其他计算参数。

Moreover, the global feature of the approach leads to the fact that neighboring elements help each other. If one element lacks contrast but its surrounding ones are contrasted then global DVC may still converge and succeed in determining the displacement field [156, 30, 157, 28]. Most applications of global DVC were based upon finite element discretizations of the ROI. This is not mandatory. For instance, spectral approaches have been implemented even more recently and, up to now, have been only applied to synthetic cases [159].

此外, 全球的方法会导致相邻元素的互相帮助。如果一个元素缺乏对比, 但周边的对比然后全球” 的可能仍收敛, 成功地确定位移场 (157 年 156 年,30 日,28)。全球” 的大多数应用程序是基于有限元离散的 ROI。这不是强制性的。例如, 谱方法实现了更最近, 到目前为止, 只有应用于合成 [159]。

Most of the global DVC results have been obtained by using C8 elements

[197], which is a natural choice to make structured meshes compatible with the underlying voxels. More recently, T4 elements have also been used [93]. One of their advantages lies in the fact that more complex geometries can be faithfully meshed (see Figure 5). In both cases bilinear or linear shape functions have been considered. Higher order displacement interpolations may be considered. However, it will require the size of the elements to be increased in order to keep the uncertainty levels under control. Since DVC analyses are an inverse problem, the general guideline is the smaller the number of unknowns with respect to the available number of voxels, the lower the measurement uncertainty (this observation is true for local and global DVC). However, if the number is too small, interpolation errors may occur. The gray level residuals are the key quantity to make sure the choices have been adequate.

大多数全球" 的结果已经通过使用 C8 元素 [197], 这是一个自然选择结构化网格与底层压兼容。最近,T4 元素也被使用了 [93]。他们的一个优势在于, 更复杂的几何图形可以忠实地网状 (参见图 5)。在这两种情况下双线性或线性形状函数被认为是。可以考虑高阶位移篡改。然而, 它需要元素的大小增加为了控制水平的不确定性。自" 的分析是一个反问题, 一般的指导方针是未知数数量越小对可用的像素点的数量, 降低测量的不确定性 (这个观察是对本地和全球" 的。然而, 如果数量太小, 插值可能发生错误。残差灰色水平是关键量, 以确保选择已经足够了。

When studying cracks, the continuity property is no longer satisfied across the cracked surface.

研究裂缝时, 连续性财产不再是满足在裂缝的表面。

As earlier mentioned, this violation will often be quite visible in the residual fields [192, 133, 198, 94]. This is a very nice property as it allows one to clearly see a crack that may sometimes be difficult to detect otherwise. Segmentation may then be quite easy. Moreover, it has been proposed to use an enriched kinematics, following X-FEM approaches (as in 2D-DIC [188]), through an eXtended C8-DVC (or XC8-DVC) [192, 185].

正如之前提到的, 这违反往往会是完全可见的残留字段 (192、133、198、94)。这是一个很好的属性, 它允许一个清楚地看到一个裂缝, 否则有时可能很难检测。分割可能会很容易。此外, 它提出了使用一个丰富运动学, 后 X-FEM 方法 (如 2 d-dic[188]), 通过一个扩展 C8-DVC(或 XC8-DVC) (192、185)。

DVC: Achievements and Challenges 45 To illustrate such situations, let us consider a four-point flexural test on plasterboard. This material is composed of a plaster foam core cast between two paper linings. It now is the most widely used interior finish in construction. In addition to the fire resistance to be checked, a lightweight plate must meet mechanical requirements, the most severe of which is resistance to flexure, a crucial mechanical property for transport, handling and installation of the plate. The studied sample was prepared from industrial plasterboard and cut to a size of 200 $\times$ 13 $\times$ 15 mm3 .

": 成就和挑战 45 来说明这种情况下, 让我们考虑石膏板的四点弯曲试验。这种材料是由石膏泡沫核心投两个纸衬里。现在是使用最广泛的室内装

修施工。除了防火检查, 一个轻量级的板必须满足机械要求, 其中最严重的是抗弯强度, 关键力学性能运输、装卸和安装板的。研究样本准备从工业石膏板和削减到 200×13×15 mm3 的大小。

The outer span was 150 mm, and the inner span 40 mm. The supports were machined PMMA cylinders 16 mm in diameter. The setup used in this study is shown in Figure 11(a). It enables two specimens to be tested at the same time. The central part of the device is clear from any obstruction in order to allow for x-ray transmission. Loading was applied manually by turning the two wing screws.

外部跨度是 150 毫米, 内跨越 40 毫米。支持是加工 PMMA 圆柱体直径 16 毫米。在这项研究中使用的设置如图 11 所示 (一个)。它使两个标本同时进行测试。设备的核心部分是明确从任何阻塞以允许 x 射线传播。加载应用手动通过将两个翼螺丝。

(a) (b) (c) Fig. 11 (a) In-situ flexural testing device. The sample was imaged in the initial state (i.e., without loading, b) and at several loading levels (the final deformed configuration is shown in c). 1 voxel 50 m The experiment was carried out on LMT' s tomograph (NSI X50+) with the following acquisi- tion parameters: the beam tension is 90 kV and the electron current 200 A, the physical size of one voxel is 25 m. 900 radiographs were acquired in a 360°-rotation for each scan. The total du- 46 A. Buljac et al.

(a) (b) (c) 图 11 (a) 原位挠曲测试设备。样品在初始状态 (即成像。没有加载,b) 和几家加载水平 (最终变形配置 c 所示)。1 体素 50 米 以前的实验进行了层析 x 射线摄影机 (NSI×50 +) 使用以下 acquisi, 参数: 梁张力是 90 kV 和 200 A 电子电流, 体素的物理尺寸是 25 m。900 片是在 360° 旋转为每个扫描。总 du - 46。Buljac et al。

ration of an acquisition is 60 min. The sample was imaged at initial state and then at three levels of loading. Figure 11(b-c) shows the analyzed volumes by DVC. The ROI after voxel aggregation has a size of 792 × 192 × 192 voxels. The physical voxel size then becomes 50 m. No crack is visible on the section of the volume in the deformed configuration.

配给的收购是 60 分钟。样本成像在初始状态, 然后加载的三个层次。图 11 (c) 显示分析卷陷落。体素聚合后的 ROI 的大小为 792×192×192 像素点。物理就变成了 50 m 立体像素大小。不可见的裂纹部分的体积变形的配置。

The size of the C8 elements was chosen to be equal to 12 voxels. The DVC results are shown in Figure 12. The root mean square correlation residual for the analyzed scan is equal to 2.65

C8 元素被选中的大小等于 12 像素点。" 的结果如图 12 所示。分析扫描的均方根相关剩余等于参考扫描的动态范围的 2.65

(a) (b) (c) Fig. 12 DVC results in 4-point flexure. 3D renderings of thresholded gray level residual (a), longitudinal displacement (b) expressed in voxels (1 voxel 50 m), and maximum eigen strain fields (c) DVC: Achievements and Challenges 47 Let us insist on the fact that the tomographic observations alone would not allow the mecha- nism of failure of plasterboard to be deduced from such tests. The contribution of DVC is crucial in order to finely analyze them.

(a) (b) (c) 在四点弯曲图 12 ” 的结果。3 d 渲染的阈值灰度残 (a), 纵向 位移 (b) 表达的体素 (1 体素 50 米), 和最大本征应变场 (c) ”: 成就和挑战 47 让我们坚持的层析观测本身不允许失败的机甲, 多年的石膏板推断从这样的测试。陷落的贡献为了精细分析是至关重要的。

3.3 Numerical implementation In order to detail the numerical implementation, the sum of squared differences similarity criterion is chosen as it is the most generic one (i.e., relevant for Gaussian and white noise). Thus X TDVC [u] = (g(x + u(x)) − f (x))2 (19) x As previously discussed, a space of displacement field U is selected, and introducing a kinematic basis with a set of vector fields i (x), is chosen so that the displacement is expressed as X u(x) = ui i (x) (20) i Let us note that such a writing holds for both local and global methods. Local would simply mean that some functions i and j have a non overlapping support when i 6= j. With those notations, DVC consists of measuring all amplitudes ui that may be gathered into a (long) column vector of unknowns denoted u.

3.3 数值实现为了详细数值实现, 平方的总和差异相似准则是选为最通用的一个 (即。, 相关的高斯白噪声)。因此 X TDVC (u) = (g (X + u (X))−f (X)) 2 (19) X 正如前面讨论的, 选择空间位移场 u, 并引入运动学基础上的向量场 i (X) 选择的位移表示为 X u (X) = ui i (X)(20) 我让我们注意到这样一个编写适用于本地和全球的方法。当地只会意味着一些函数 i 和 j 非重叠的支持当我与那些符号,6 = j。” 包括测量所有振幅 ui 可能聚集成一个 (长) 未知数的列向量表示你。

The minimization of TDVC is performed using Newton’s descent scheme. The problem being nonlinear, it is solved iteratively, by computing incremental corrections u to the current es- timate at step n, u(n) , so that u(n+1) = u(n) + u. The correction is computed from the osculating quadratic form that approximates TDVC . The following linear system is thus to be solved [M] u = b (21) 48 A. Buljac et al.

的最小化 TDVC 使用牛顿下降方案执行。非线性问题, 它解决了迭代, 通过计算增量修正 u 当前 es - timate n 步, 你 (n), 你 (n + 1) = 你 (n) + u。密切的修正计算二次形式 TDVC 近似。因此要解决以下线性系统 [M] u = b (21) 48。Buljac et al。

where the matrix [M] is the Hessian of TDVC , which can be computed once for all at conver- gence [197, 170], i.e., replacing geu by f X Mij = (f (x) · i (x))(f (x) · j (x)) (22) x and the right hand side vector is computed (and this is critical) without approximation X bi = (f (x) · i (x))(e gu (x) − f (x)) (23) x The pseudo-inverse of Ni (x) = (f (x) · i (x)) is recognized, so that [M] = [N]> [N], b = [N]> , and one may also write u = [M]−1 b = [N]† (24) where the notation [N]† ([N]> [N])−1 [N]> stands for the so-called Moore-Penrose pseudo- inverse matrix [154, 179].

矩阵 [M] 在哪里 TDVC 的麻绳, 可以计算一次所有转换- gence(197、170), 即由 f, 取代 geu X Mij = (f (X) · i (X)) (f (X) · j (X)) (22) X 和右边向量计算 (这是关键) 没有近似 X bi = (f (X) · i (X)) (e gu (X)−f (X)) (23) X 的伪逆倪 (X) = (f (X) · i (X)) 是公认的, 所以 [M] = [N] > [N] b = [N] > , 和一个也写 u = [M]−1 b = [N]† (24) 表示法 [N]† ([N] > [N])−1 [N] > 代表所谓 Moore-Penrose 伪逆矩阵 (154、179)。

There is a huge diversity of issues associated with nonlinearities. For DVC, they are not too limiting. The approximation of the objective functional by its osculating paraboloid (i.e., using the Hessian at convergence) is generally an excellent choice. Yet there are two pitfalls to avoid.

有一个巨大的多样性与非线性相关问题。", 他们不太限制。目标函数的近似其密切抛物面 (即。在收敛, 用麻绳) 通常是一个很好的选择。然而, 有两个要避免的陷阱。

The first one is the existence of poorly conditioned modes when too many kinematic degrees of freedom are proposed as compared to the available information. Typically, when very small subvolumes, or very small elements are considered, the ratio of the to-be-measured parameters to the given information becomes too large, eigen-modes of the [M] matrix appear with very small eigen values. Here the solution is to be less ambitious for the spatial resolution, and/or to provide additional prior knowledge [123, 122]. This is the spirit of regularization that will be detailed further down.

第一个是条件很差的存在模式时提出了太多的运动自由度比可用的信息。通常, 当非常小的子卷, 或非常小的元素被认为是, 的比值来衡量参数给定的信息变得太大,eigen-modes [M] 矩阵的出现非常小的特征值。这里的解决方案是不那么雄心勃勃的空间分辨率, 和/或提供额外的先验知识 (123、122)。这是正规化的精神, 将详细的进一步下降。

The second pitfall is that the above osculating harmonic potential is a good approximation only within a range of variation of the displacement that can be compared to the correlation length of the image texture. This means that when u is close to the actual solution, say because DVC: Achievements and Challenges 49 it has been well initialized, it will easily converge to the correct solution. In contrast, for very poor initial guesses, i.e., very remote from the actual one, the above Newton’s algorithm may not converge.

第二个缺陷是, 上述密切谐波可能是一个很好的近似只有在变化范围内的位移, 这可以与相关图像纹理的长度。这意味着, 当你接近实际的解决方案, 因为" 说: 成就和挑战 49 已经初始化, 它很容易收敛到正确的解决方案。相比之下, 非常贫穷的初始猜测, 即。非常远离实际的一个, 上面的牛顿算法可能不收敛。

The previous observation applies to both local and global approaches. Finding suitable starting points for the final optimization step is critical, and all usable codes spend considerable effort on this. One of the easiest ways to circumvent this problem is to devise multiscale approaches [197, 97, 60, 45]. If the (reference and deformed) images are low-pass filtered prior to registration, local minima are erased with the wavelength of the filter around the solution. This naturally provides a much more robust approach. However, because images are low-passed filtered, the registration is not very precise. Understanding that this filtering is only a temporary operation provided to get an approximate solution to start with, then the solution is to built up a pyramid of progressively more and more filtered images, which can conveniently be down-sampled to reduce the computation load, and start registration from the top of the pyramid, and use the resulting displacement field as an initialization of the lower level, down to the original image in which no filtering is being used [98, 245, 16, 187, 80].

以前的观察适用于本地和全球的方法。找到合适的起点最后优化步骤是至关重要的, 和所有可用的代码花费相当大的精力。绕过这个问题的最简单的方法之一是设计多尺度方法 (197、97、60 岁,45 岁)。如果 (参考和变形) 图像是低通滤波在登记之前, 局部最小值与滤波器的波长在抹去的解决方案。这个自然提供了一个更健壮的方法。然而, 由于图像是低分通过过滤、登记不是很精确。理解这种过滤是只有一个临时操作提供了一个近似解, 然后逐步的解决方案是建立一个金字塔过滤图像越来越多, 方便可以 down-sampled 减少计算负荷, 并开始登记从金字塔的顶端, 并使用产生的位移场作为初始化的低水平, 到原始图像中没有使用过滤 (98,245,187,80]。

As detailed below, regularization will provide an additional functional TReg to be added to TDVC . The numerical strategy to solve the regularized problem will be essentially the same as above. A new Hessian and second member will be computed and added to the above [M] and b, so as to estimate the displacement field. The regularized Hessian is aimed at obtaining a better conditioning, and thereby decreasing the uncertainty, as will be shown in the next section.

如下详细, 正则化将提供额外的功能 TReg TDVC 添加。数值策略来解决上面的正则化问题将是基本相同的。一个新的黑森和第二成员将计算和添加到上面的 [M] b, 以估计位移场。正规化黑森的目的是为了获得一个更好的条件, 从而减少不确定性, 将在下一节中所示。

3.4 Identification and Validation In the above discussions, the kinematic bases were chosen mostly based on numerical convenience.

3.4 识别和验证在上面的讨论中, 运动基地选择主要基于数值方便。

However, little consideration was paid to the relevance of a particular basis. To do so, it is necessary to incorporate some additional information coming from the mechanical behavior of the sample.

然而, 很少考虑支付给一个特定的相关性。为此, 有必要把一些额外的信息来自样品的力学行为。

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Thus prior to discussing more elaborate regularization strategies, a short review of the usage of DVC-measured displacement fields in the context of mechanical identification is proposed.

因此讨论更详细的正则化策略之前, 一个简短的回顾 DVC-measured 位移的使用领域提出了机械的上下文中识别。

Comparisons between DVC measurements and FE calculations have been first attempted for cancellous bone to validate the strain predictions of the numerical model [242]. A good agreement was observed in the loading direction, yet less accuracy was achieved in the transverse directions.

比较" 的测量和有限元计算第一次尝试了松质骨来验证数值模型的应变预测 [242]。良好的协议是在加载方向, 然而不准确性是在横向方向上实现。

It may be hypothesized that parameters affecting the accuracy may include lateral boundary con- ditions. It was confirmed for a scaffold implant under uniaxial compression for which the measured boundary conditions were applied to each boundary of the region of interest. Good agreements between the results from the DVC measurements and the FE simulations were obtained in the primary loading direction as well as in the lateral directions [137].

可能是假设参数影响的准确性可能包括横向的边界条件。这是确认支架植入在单轴压缩下的测量边界条件应用于每个边界地区的利益。良好之间的协议的结果" 的测量和有限元模拟得到主加载方向以及横向方向 [137]。

It is worth noting that experimental boundary conditions are very important inasmuch as one cannot guarantee that a mechanical test be always perfect (in particular for in-situ test- ing where the rigidity of testing devices is often a limitation, see Section 2). This is especially true in biomechanics where the specimen shape is not chosen but given [106]. For instance, the failure mechanisms may change when intervertebral disks are present or not. Further, when exper- imentally measured boundary conditions are utilized in FE simulations, the displacement errors between DVC-measured fields and computed fields via FE simulations were the lowest [108]. This trend was also recently confirmed in the study of cancellous bone [37] and the analysis of vertebral failure patterns [108]. Further, micromotions captured by DVC were shown to be consistent with FE simulations of implants [210]. Damage in bone-cement interfaces was assessed via DVC and consistently compared with FE simulations [221].

值得注意的是, 实验边界条件非常重要, 因为不能保证一个机械的测试总是完美 (尤其是原位测试- - -荷兰国际集团 (ing) 的刚度测试装置通常是一个限制, 见第二节)。尤其是在生物力学试样形状不是选择而是 [106]。例如, 失败机制可能会改变椎间磁盘存在与否。此外, 当擅长——对测量边界条件用于有限元模拟,DVC-measured 字段之间的位移误差和计算领域通过有限元模拟 [108] 是最低的。这一趋势也在松质骨的研究最近证实 [37] 和 [108] 椎失败的分析模式。此外, 微动被" 被证明是符合有限元模拟的植入 [210]。损伤骨水泥界面评估通过陷落和始终与有限元模拟 [221]。

Validation frameworks based on 3D (and 4D) imaging have been proposed [160, 29, 37]. One key aspect is related to the management of boundary conditions [78, 185, 206], as discussed above for biomechanical studies. If measured boundary conditions are used, it is possible to evaluate gray level residuals from simulated displacement fields and estimate the absolute quality of numerical DVC: Achievements and Challenges 51 models [29]. Otherwise, only relative qualities are obtained when measured displacements are com- pared with computed fields. With such approaches, ductile damage predictions could be probed for different experimental configurations with cast iron and partial validations were achieved with microscale FE simulations [29, 206].

验证框架基于 3 d (4 d) 提出了成像 [37]160 年,29 日。一个关键方面是相关的管理边界条件 (78、185、206), 正如上面所讨论的生物力学研究。如果使用测量的边界条件, 可以评估灰度从模拟位移场和残差估计的绝对质量数值": 成就和挑战 51 模型 [29]。否则, 只有相对的品质得到了 com 测量位移时, 缩减计算字段。用这样的方法, 韧性损伤预测可以探测不同的实验配置与铸铁和部分验证了微尺度有限元模拟 (206)。

Extended FE simulations were validated against experimentally measured displacement fields via extended DVC by comparing measured and predicted profiles of stress intensity factors [185, 189]. Crack opening displacements measured via DVC were compared to predictions by FE analyses for a test with a chevron notched sample made of polygranular graphite to validate a cohesive zone model [160]. Similar analyses were reported for a woven ceramic matrix composite [202].

扩展有限元模拟与实验验证测量位移场通过扩展" 通过比较测量和预测的应力强度因子 (185、189)。裂纹张开位移测量通过" 的比较通过有限元分析来预测——ses 测试与雪佛龙切口 polygranular 石墨制成的样品来验证一个内聚区模型 [160]。类似的分析报告为编织陶瓷基复合材料 [202]。

Phase field simulations were validated against experiments through the comparison of crack pat- terns in lightweight concrete and plaster [166].

相场模拟与实验验证通过裂纹的比较各种轻质混凝土、石膏 [166]。

Very few parameter calibrations have been reported so far when dealing with DVC measure- ments and FE simulations. Among them, the virtual fields method was used to calibrate elastic parameters for cornea [73], trabecular bone [79] and 3D particulate composite [184]. Finite ele- ment model updating was used to calibrate plastic parameters when Al-SiC composite and cast magnesium alloy were indented in-situ [162]. Such parameters were also calibrated for nodular graphite cast iron when cyclically loaded in uniaxial tension [93]. The criterion describing the transition from pristine to compacted (i.e., crushed) states was determined by analyzing in-situ indentation tests on plaster foam [21].

很少参数校准迄今已报告在处理的力量" 的测量和有限元模拟。其中, 虚拟字段的方法被用来校准弹性参数角膜 [73],[79] 小梁骨和三维颗粒复合材料 [184]。有限避署, 模型更新塑料被用来校准参数当 Al-SiC 复合铸造镁合金和缩进现场 [162]。球墨铸铁等参数也校准在单轴循环加载紧张 [93]。描述从原始过渡到压实的标准 (即。、碎) 国家决心通过分析现场压痕测试石膏泡沫 [21]。

3.5 Regularized DVC In registration techniques applied to medical imaging, regularization techniques have been con- sidered very early on. They all derive from Tikhonov-like propositions [215] to account for various constraints by adding a penalty term to the DVC cost function [199, 102, 195, 115]. In experimental mechanics such type of approaches were introduced more recently [123, 122, 214] extending elastic 52 A. Buljac et al.

3.5 正规化陷落在注册技术应用于医学影像, 正则化技术已经完全认为早期。他们都来自 Tikhonov-like 命题 [215] 占各种约束通过添加一个惩罚项" 的成本函数 (199、102、195、115)。在实验力学等类型的方法介绍了最近 (123、122、214) 扩展弹性 52。Buljac et al。

regularization initially introduced in 2D-DIC [190, 218]. The regularization strategy allows the DVC problem to be made well-posed even when discretized onto a very fine mesh. It was shown that the ultimate limit of a regular cubic mesh with elements reduced to a single voxel could be handled with such a strategy [123]. However, in that case, the number of unknowns becomes very large, and the regularization kernel involves a more complex problem to solve, and hence regularized DVC becomes much more demanding in terms of computation time and memory management. To overcome this difficulty, a dedicated GPU implementation has been set up that can handle several million degrees of freedom problems within an acceptable time (less than 10 minutes) [122]. When analyzing localized phenomena (e.g., strain localization and cracks), special care should be exercised to properly capture high local strain gradients [214] or displacement discontinuities [94, 119]. It will be illustrated in Section 3.5.4.

中引入正则化最初 2 d-dic (190、218)。正则化策略允许" 的问题是适定的即使离散到细网格。结果表明, 常规的立方网的极限元素减少到一个立体像素可以处理这种策略 [123]。然而, 在这种情况下, 未知的数量非常大, 和正则化内核是一个更复杂的问题来解决, 因此正规化陷落变得更加苛刻的计算时间和内存管理。为了克服这个困难, 成立了一个专门的 GPU 实现, 可以处理几百万自由度问题在一个可接受的时间内 (少于 10 分钟)[122]。在分析局部现象 (例如, 应变局部化和裂缝), 特别应注意适当捕捉当地高应变梯度 [214] 或位移不连续 (94、119)。这将是 3.5.4 所示部分。

3.5.1 Regularization functional When designing the penalty term, two questions have to be addressed: What should the penalty be based on in order not to bias the measurement? How should its weight be set? The very early suggestions by Tikhonov and Arsenin [215] were to add to the DVC functional a term such as kuk2 = |u(x)|2 . This choice is here not appropriate as it tends to drag P x displacements toward u = 0, especially in zones where the image texture is poor. Introducing the |L(u)|2 , where L(u) =
u instead of P norm of a differential operator such as TReg [u] = x the raw displacement, would be a better choice as uniform translations would not be affected as they belong to the kernel of the gradient operator. However, rigid body rotations have a nonzero gradient and hence they would be dampened out by such regularization. Requiring that all rigid body motions belong to the kernel of L(u), selects automatically linear functions of strain. Hence | L(u)|2 coincides with the potential energy density of a linearly elastic solid. Such a form may be DVC: Achievements and Challenges 53 suited when observing a solid that is not subjected to a mechanical loading, but for mechanical tests, such a regularization would drive the solution toward a rest state.

3.5.1 正则化功能在设计的惩罚项, 必须解决两个问题: 惩罚应该基于什么为了不偏见的测量? 它的重量应如何设置? 早期建议 Tikhonov 和 Arsenin[215] 被添加到" 的功能术语如 kuk2 u (x) = | | 2。这个选择是不合适的, 因为它往往会拖向 u = 0 px 位移, 尤其是在图像纹理差的区域。介绍 L (u) | | 2, L (u) = u P 规范而不是微分算子如 TReg (u) = x 原始位移, 将是一个更好的选择尽可能统一的翻译不会影响他们属于内核的梯度算子。然而, 刚体转动有非零梯度, 因此他们会抑制这样的正规化。要求所有的刚体运动属于 L 的内核 (u), 选择自动应变的线性函数。因此 L (u) | 2 | 伴随着潜在的能量密度的线性弹性固体。这种形式可能是": 成就和挑战 53 适合当观察固体不承受机械负荷, 但对于机械测试, 这种正则化驱动解决方案向休息的状态。

Following along these lines leads to a second order differential operator for L, which can be compared to the divergence of the stress field for a linear elastic solid. When a finite element description is used for the displacement field, i.e., supported by a mesh, one may rely on the numerical model of elasticity to relate the L operator to the finite element stiffness matrix [K].

后沿着这些思路导致 L 的二阶微分算子, 可相比的散度为一个线性弹性固体应力场。当一个有限元描述用于位移场, 即。, 由一个网, 一个可能依赖于数学模型的弹性与 L 运营商有限元刚度矩阵 [K]。

In the absence of body forces, this matrix applied to the vector of nodal displacement provides a vector of unbalanced forces at nodes f = [K]u. Choosing as penalty the quadratic norm of the vector f (restricted to internal nodes) gives precisely what is needed as a Tikhonov regularization functional, the kernel of which contains all displacement fields that are solution to a linear elastic problem [123, 122]. This means that a zone where the texture is poor or simply missing, would be interpolated as the solution to an elastic problem matching the displacement at the boundaries where it is known. This is in line with the "regularization" property of this additional functional, which is to alleviate ill-conditioning by adding prior knowledge on the displacement field.

没有身体的力量, 这个矩阵应用到节点位移提供一个向量的向量节点不平衡力的 f = [K] 你。选择惩罚二次范数的向量 f(限于内部节点) 给恰恰需要 Tikhonov 正则化功能, 包含所有的内核解一个线性弹性位移字段问题 (123、122)。这意味着区域纹理是穷人或只是失踪, 将插值作为一个弹性问题的解决方案匹配边界的位移是已知的。这是符合"正规化"属性的附加功能, 减轻病态的位移场加入先验知识。

It is to be observed that linear elasticity involves several parameters that can be tailored to a situation at play [123, 122, 214, 94]. If the actual behavior of the sample is elastic, one would like to use a regularization kernel as close as possible to the actual constitutive law. However, sometimes, one may want to depart from the real behavior. For instance, for developed plastic flows, one may neglect elastic strains, and hence the elastic kernel to be used for regularization should mimic plastic strain. For instance, plastic strains are generally isochoric, and hence one may choose an incompressible elastic law to prevent any volume change [214]. More generally, the tangent behavior is a good candidate for identifying the proper elastic law to be used. When approaching a perfectly plastic plateau, there exists a strain direction where the elastic stiffness 54 A. Buljac et al.

是观察到的线性弹性所涉及到的一些参数, 可以根据情况在起作用 (123、122、214、94)。如果样品的实际行为是有弹性的, 一个想要使用一个正则化内核尽可能接近实际的本构定律。然而, 有时候, 一个可能想离开真实的行为。发达塑料流动, 例如, 人们可能会忽略弹性应变, 因此弹性内核用于正则化应该模拟塑性应变。例如, 塑料压力通常是等体积的, 因此你可以选择一个不可压缩弹性法律来防止任何体积变化 [214]。更一般的, 切的行为是一个很好的候选人确定适当的弹性要使用法律。接近完美的塑料高原时, 存在一个弹性应变方向刚度 54。Buljac et al。

vanishes. This calls for an anisotropic elastic kernel that would leave free the easy strain direction but would penalize shear in a different direction.

就消失了。这要求一个内核将自由简单的各向异性弹性应变方向但会惩

罚剪切方向不同。

3.5.2 Regularization weight The second question to be answered deals with the weight to be given to the regularization kernel.

3.5.2 正规化重量第二个问题需要回答处理重量给正规化内核。

Different heuristics have been proposed in the literature [58]. However, it is difficult to assess how relevant they would be for the present purposes. Here it is proposed to follow a different route that gives a simple interpretation to this weight.

提出了不同的启发式在文献 [58]。然而, 很难评估有关他们将目前的目的。这里拟遵循不同的路线, 让一个简单的解释这个重量。

For any trial displacement field, u, the similarity measure of DVC provides a cost function, TDVC [u]. In the immediate vicinity of the optimal solution, u∗ , one may Taylor expand the functional TDVC [u∗ + u] for a small perturbation, u, as TDVC [u∗ + u] = S(f, fe u) = S(f, f + f · u) (25) = S0 + S2 [u] + O[u4] where S0 is a constant (which can be neglected in the minimization), and S2 is a quadratic form in u whose kernel is the Hessian of TDVC , denoted as [M] in Equation (22). The linear term in u is absent as a result of S being minimum. It is to be noted that in the above equation, the second argument of S has been changed to f because geu∗ f . S2 is thus the osculating har- monic approximation of the nonlinear DVC functional. Using the notation u for the discretized displacement field represented as a column vector of nodal displacements, S2 reads S2 [u] = u> [M]u (26) Similarly, the regularization functional using linear elasticity is a quadratic form of the dis- placement field. Within a finite element discretization where [K] is the elastic stiffness matrix, one can write TReg [u] = u> [K]> [D][K]u (27) DVC: Achievements and Challenges 55 where [D] is a diagonal matrix valued 1 for internal nodes (where the balance equation holds) and 0 on boundary nodes (where a displacement or nonzero load is prescribed).

对于任何试验位移场,u, ” 提供了一个成本函数的相似性度量,TDVC (u)。在最优解的附近,u∗, 泰勒可以扩大功能 TDVC [u∗+ u] 小扰动, u, 作为 TDVC [u∗+ u] = (f, fe u) = 年代 (f, f + f · u) (25) = S0 + S2(u) + O[u4], S0 是一个常数 (可以忽略最小化), 和 S2 是一个二次型的 u 内核的黑森 TDVC, 表示在方程 (22)[M]。的线性项 u 缺席由于年代最低。要注意, 在上面的方程中, 第二个参数 S 已经改变了 f 因为 geu∗ f。S2 因此密切哈尔-莫尼近似非线性” 的功能。使用的符号你离散位移场表示为一个列向量的节点位移,S2 读取 S2[你]= 你 > [M] 你 (26) 同样, 正则化功能使用线性弹性是一种二次的 dis -位置字段。在有限元离散化 [K] 弹性刚度矩阵, 可以写 TReg[你]= 你 > [K] > [D] [K] 你 (27)”: 成就和挑战 55 [D] 是一个对角矩阵的内部节点 (平衡方程持有) 和 0 边界节点上 (位移或者非零负载规定)。

Let us now consider as a trial displacement field a plane wave, v (x) = e1 exp(ie2 · x/) with a wavevector along e2 , a unitary vector, with displacements parallel to e1 (chosen perpendicular to e2 so that the strain is pure shear), and 2 the wavelength. When the wavelength is varied, on average the quadratic form S2 remains constant. Conversely, TReg [v] is proportional to the inverse fourth power of . This exponent 4 defines the "spectral sensitivity" of the regularization term, as compared to 0 for the DVC problem. This comes from the fact that [K] is the discrete form of a second order differential operator acting on the displacement field. This difference in sensitivity requiring an intrinsic length is now exploited to write a full cost function as (TDVC [u] − S0) 4 TReg [u] TTot [u] = + 4 (28) S2 [v] TReg [v] Let us note that the weight of the regularization part is set by a free parameter, , whose meaning becomes transparent. The relative magnitude of the two terms in the above sum depends on the length scale over which the displacement field varies. When this scale is larger than the DVC functional dominates over the regularization part, and conversely, shorter length scales are controlled by the regularization part. Thus the above expression has a minimizer that is a low-pass filtered DVC displacement field, and tuning allows one to adjust the cut-off frequency.

现在让我们考虑作为平面波审判位移场,v (x) = e1 exp (ie2 · x /)wavevector e2, 统一的向量, 与平行位移 e1(选择垂直于 e2, 这样纯剪应变), 和 2 波长。当波长不同, 平均二次形式 S2 保持不变。相反,TReg (v) 成正比的四次方 。这个指数 4 定义了"光谱灵敏度"的正则化项, 比 0 " 的问题。这来自这样一个事实:[K] 是一个二阶微分算子的离散形式作用于位移场。这种差异在灵敏度要求一种内在的长度是现在利用写一个完整的成本函数 (TDVC[你] −S0) 4 TReg[你]TTot[你]= + 4 (28)S2 [v] TReg [v] 让我们注意, 正规化的重量是由自由参数, 的意义变得透明。的相对大小两项在上面的金额取决于位移场的长度尺度不同。当这种规模大于 陷落正规化部分功能占主导地位, 反之, 较短的长度尺度由正则化的部分控制。因此上述表达式有一个最小值, 是一种低通滤波" 的位移场, 和调优 允许调整截止频率。

In order to better appreciate the usefulness of this formulation, it is worth making the following remarks: –Any discretization involves a cut-off length scale, namely, the subvolumes size in local DVC, or the element size in unregularized global DVC, but in those approaches the small-scale shape functions are not designed to be mechanically realistic but rather convenient, either for parallel computation or for benefitting from all meshing tools available. In contrast, the above regularization uses a much more realistic small-scale displacement interpolation; 56 A. Buljac et al.

为了更好的欣赏这个配方的有效性, 值得做以下备注:——任何涉及截止长度尺度的离散化, 即子卷的大小在当地陷落, 或元素大小 unregularized 全球" 的, 但这些方法的小规模的形状函数并不是设计为机械现实而是方便, 对并行计算或受益于啮合所有工具可用。相比之下, 上面的正则化使用一个更现实的小规模位移插值;56 个。Buljac et al。

–Provided the regularization length is larger than the element size, the influence of the mesh (and its fineness) is reduced to a minimum; –Changing the regularization length is trivially performed without having to re-mesh. It is noteworthy that for slender objects or regions of interest, one may introduce a regularization length that is larger than the smallest size of the sample/ROI. Such a property is not available using a regularization based on the window size or element size in the mesh; –It has been shown that using the ultimate regular mesh composed of $1 \times 1 \times 1$ voxel cubes could be handled with such a regularization, with a weight that could be decreased down to very few (i.e., 3.3) voxels [123]; –Edges (which are not free boundaries) are not regularized by the above construction. They cannot be considered as balanced nodes because the outer region exerts unknown forces / torques on the studied domain. It is however possible to construct linear operators acting on the boundary nodal displacements that behave in the same way (invariant under a rigid body motion, and are the discrete version of a second order differential operator [123, 214]). This regularization introduces a similar tunable smoothness as the bulk regularization, although the mechanical justification is more fragile. However, it remains exactly within the spirit of a mathematical regularization for ill-conditioned problems; –The tunable length scale is convenient to capture a first rough approximation of the displace- ment field (i.e., using a large regularization length scale), and progressively relaxing to a small value. As shown in 2D analyses [218], even in the limit of a vanishing , such an initializa- tion procedure may provide better solutions than that obtained with the same discretization but without regularization [29].

——提供了正则化长度大于元素大小、网格 (及其细度) 的影响减少到最低限度;——改变正则化长度非常无需 re-mesh 执行。值得注意的是细长的物体或区域的兴趣, 你可以介绍一个正规化的长度大于最小大小的样本/ROI。这样的属性不可用使用正则化基于网格窗口大小或元素大小;——它已被证明, 使用终极规律 1×1×1 组成的网状体元数据集可以处理这样一个正规化, 重量, 可以减少 (即很少。3.3) 体素 [123];——边 (不自由边界) 不是由上面的正规化建设。他们不能被视为平衡节点因为未知的力/力矩施加的外部区域的研究领域。然而有可能构造线性算子作用于边界节点位移, 以相同的方式 (不变的刚体运动, 和是一个二阶微分算子的离散版本 (123、214))。这个正则化引入了类似的可调平滑散装正规化, 虽然机械理由更加脆弱。然而, 它仍然是完全在数学正规化的精神坏脾气的问题;——可调长度尺度是方便捕捉第一次取代的近似值, 字段 (即。, 使用一个大正规化长度尺度), 逐步放松 小值。所示的 2 d 分析 [218], 即使在消失 的限制, 这种 initializa, 程序可以提供更好的解决方案相比, 有相同的离散化, 但没有获得正规化 [29]。

–Although this regularization is a filter, it should not be confused with a filtering performed in a post-processing stage. The former is applied together with the registration procedure, and hence the filtered field is evaluated on its registration quality, while the latter has lost DVC: Achievements and Challenges 57 its connection with the images, and hence the detrimental effect of filtering on registration cannot be estimated.

——尽管这个正则化是一个过滤器, 它不应该被混淆为过滤在后处理阶段执行。前一起注册应用程序, 因此过滤领域注册质量评估, 而后者已经失去了": 成就和挑战 57 与图片的连接, 因此过滤的不利影响注册无法估计。

If the linear elastic problem used for the regularization is not trusted, then a small regu- larization length scale is to be chosen, and regularization will only provide an effective "shape function" with nicer regularity properties than standard finite elements. Alternatively, if identifi- cation is aimed at, then ideally an infinite regularization length scale will leave enough freedom to account for arbitrary boundary conditions, and this without negative incidence on the value of the residual. Conversely, a wrong constitutive law will lead to higher residuals and hence minimizing the residuals (as usually carried out in DVC) with respect to the constitutive parameters is an identification procedure (i.e., “integrated” if the regularization length is infinite).

如果用于正则化的线弹性问题是不可信的, 然后小 regu——larization 长度范围内选择, 和正则化只会提供一个有效的“形状函数具有更好的规律特性比标准有限元素。另外, 如果 identifi -阳离子旨在理想无限正规化长度范围就会留下足够的自由占任意边界条件, 这没有负面发病率剩余的价值。相反, 一个错误的本构法律将导致更高的残差, 因此最小化残差 (通常在” 关于本构参数 (即是一个识别过程。,“集成” 如果正规化长度是无限的)。

3.5.3 Extension to nonlinear regularization The above regularization was set to the simplest form that could be introduced without interfer- ence with naturally expected displacements. Thus the lowest order linear differential operator was selected. It was very recently extended to hyperelasticity (i.e., in a finite strain framework [76]), and applied to cardiac magnetic resonance images. However, there is no first principle argument that would prevent from using any more sophisticated nonlinear laws. In the field of applied math- ematics, other nonlinear regularizations have been proposed [58]. For instance, rather than using an L2 -norm of the unknown field or of a differential operator acting on it, other norms have been proposed such as Lp Z 2/p TpReg [u] = |L(u)|p dx (29) When L is the symmetric part of the gradient, and p = 2 this form looks like an elastic energy density. When p tends to 1, the (nonlinear elastic) behavior would look like perfect plasticity.

3.5.3 扩展非线性正规化上面的正则化是最简单的形式, 可以引入不干涉- ence 自然预期位移。因此, 最低阶线性微分算子被选中。这是最近扩展到超弹性 (即。, 在一个有限应变框架 [76]), 并应用于心脏核磁共振图像。然而, 没有第一原理论证, 防止使用任何更复杂的非线性规律。在应用数学领域——ematics 其他非线性合法化提议 [58]。例如, 而不是使用一个未知领域的 L2 范数或微分算子作用于它, 等规范提出了 Lp 2 Z / p TpReg [u] = | L (u) | p dx(29) 当 L 是对称梯度的一部分, 和 p = 2 这种形式看起来像一个弹性能量密度。当 p 趋向于 1,(非线性弹性) 的行为看起来像完美的可塑性。

When p is less than 1, a softening branch develops implying loss of convexity. In fact convexity (p 1) is a very convenient property that ensures the existence of a unique minimum and hence 58 A. Buljac et al.

当 p 小于 1, 软化分支发展暗示凸性的损失。事实上凸性 (p 1) 是一种非常方便的属性确保存在一个独特的最低, 因此 58。Buljac et al。

an independence with respect to the algorithm used to minimize the functional. On the other hand, p 1 tends to concentrate high strain over small supports, a feature called “localization instability” frequently met in plasticity and damage theories [126]. When dealing with cracks, it is very useful to be able to concentrate strains (up to displacement discontinuity) over a support that should finally coincide with a possible crack. Hence, here, what is usually a major difficulty for numerical modeling becomes an advantage. In such a case, one would appreciate both con- vexity and localization ability, thereby leading to p = 1. Higher order L operators could also be considered, such as those expressing balance of inner nodes but for a nonlinear elastic law mimicking perfect plasticity.

独立的算法用于最小化的功能。另一方面,p 1 倾向于高应变集中在很小的支持, 一个功能叫做“定位不稳定”经常在塑性和损伤理论 [126]。当处理裂缝, 它是非常有用的能够集中菌株 (位移不连续) 支持, 应该最后与一个可能的裂纹。因此, 在这里, 通常数值模拟的主要困难是什么成为一个优势。在这种情况下, 人会欣赏 con - vexity 和定位能力, 从而导致 p = 1。高阶 L 运营商也可以考虑, 如表达内心的平衡节点但对于非线性弹性法模仿完美的可塑性。

3.5.4 Application to cracked sample The flexural test discussed in Section 3.2.2 is again considered to show the effect of elastic regular- ization. For comparison purposes, Figure 13(a,d) shows the displacement field in the longitudinal direction, and the maximum principal strain when unregularized DVC is run with 12-voxels el- ements (see Figure 12). Figure 13(b,e) shows the same fields when regularized DVC is run with a regularization length of 120 voxels with the same mesh. The dimensionless root mean square correlation residual is slightly higher (i.e., 2.67

3.5.4 申请了样品 3.2.2 节中讨论的弯曲测试又被认为是弹性的影响规律——ization。作为比较, 图 13 (a, d) 显示了在纵向方向上位移场, 和最大主应变 unregularized ” 的运行与 12-voxels el -元素 (参见图 12)。图 13 (b, e) 显示了相同的字段与正则化正规化” 的运行时长度为 120 像素点具有相同的网格。无量纲均方根相关剩余略高 (即。2.67

DVC: Achievements and Challenges 59 (a) (b) (c) (d) (e) (f) Fig. 13 Foamed gypsum subjected to 4-point flexure. 3D renderings of the longitudinal displacement (expressed in voxel,1 voxel 50 m) and measured with regularized DVC with different regularization kernels: (a) no regularization (or vanishing regularization length), (b) elastic law with large length = 120 voxels, (c) damage law with small length = 12 voxels. Corresponding maximum equivalent strain for the same three laws shown respectively in (d), (e) and (f). The same mesh is used in all cases.

”: 成就和挑战 59 (a) (b) (c) (d) (e) (f) 图 13 发泡石膏进行四点弯曲。3 d 渲染的纵向位移 (在体素表示,1 体素 50 m) 和测量与正则化” 的不同的正则化内核:(a) 没有正规化 (或消失的正规化长度),(b) 弹性法律大长 = 120 像素点,(c) 损害法律小长度 = 12 像素点。相应的最大等效应变相同的三定律分别显示在 (d), (e) 和 (f)。在所有情况下都使用相同的网格。

To localize the strain field, the regularization is relaxed by using a damage variable [94]. A final calculation is then run with no damage and a very small regularization length (i.e., 12 voxels) in order to only filter out high frequency fluctuations. The root mean square correlation residual is equal to 2.65

本地化应变场、正规化放松通过损伤变量 [94]。最后计算然后运行没有损伤, 一个很小的正则化 (即长度。12 像素点) 只为了滤除高频波动。均方根相关剩余等于 2.65

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3.6 Integrated DVC The limit of a diverging regularization length scale $\to \infty$ is also well-defined. It reduces the search space for u(x) to U1 that is now defined as the kernel of the operator L[u]. Therefore, the dimensionality of this space is much reduced, as typically a unique solution for u can be computed when boundary conditions are fixed. Allowing for some variability of the constitutive parameters (and possibly also boundary conditions) all gathered into a column vector p, allows the set of all mechanically admissible displacement fields to be defined as an affine space about a nominal p0 vector u(x, t; p) = u0 (x, t; p0) + si (x, t; p0)(p − p0) (30) where si is the sensitivity of the displacement field with respect to pi (i.e., si (x, t; p0) = u/ p(x, t; p0)). In the above expression the dimensionality of the displacement field is that of the unknown vector p. This generally very small dimensionality implies also a much reduced value of the uncertainties as compared to less guided DVC approaches. One example of such an approach where the number of unknowns was turned from several 105 down to about 10 can be found in Ref. [23]. The advantage of such approaches is that the measured kinematic field is also statically admissible (in the finite element sense). However, the difficulty is that the parameterized constitutive law has to be realistic as compared to expectation. In some cases, elasticity is clearly sufficient [23, 21]. In some other cases, elastoplastic postulates were tuned at meso [93] or micro [31] scales.

3.6 集成陷落的限制不同正则化长度尺度 →∞ 也是明确的。它减少了搜索空间的 u (x) U1 现在定义为内核的运营商 L (u)。因此, 这个空间的维数降低, 通常作为一个独特的解决方案时你可以计算边界条件是固定的。允许一些变化的本构参数 (也可能和边界条件) 都聚集到一个列向量 p, 允许所有机械容许位移字段的集合定义为一部关于名义 p0 的仿射空间向量 u (x, t;p) = 情况 (x t;p0) + si (x, t;p p0) (−p0)(30), 如果位移场的敏感性对 (即。si (x, t;p0) = u / p (x, t;p0))。在上面的表达维度的位移场是未知向量 p。这通常非常小的维度也意味着减少不确定性的价值得多比少指导" 的方法。这种方法的一个例子, 未知的数量从 105 下降到 10 几个文献 [23] 中可以找到。这种方法的优点是, 静态测量运动领域也容许 (有限元意义上)。然而, 困难的是, 参数化的本构律法必须是现实与期望。在某些情况下, 弹性显然是足够的 (23 日 21)。在其他一些情况下, 弹塑性假设在调内消旋 [93] 或微 [31]。

In the following integrated DVC will be applied to a pre-cracked parallelepipedic sample made of spheroidal graphite cast iron (Figure 14(a)) and subjected to tensile loading by using the testing machine shown in Figure 7(a). The same procedure as discussed in Refs. [133, 132, 185] was followed in the sample preparation. The cross-section of the sample is 1.6 × 1 mm2 . The DVC: Achievements and Challenges 61 specimen is loaded in seven incremental steps (Figure 14(b)). The first two scans of the reference configuration allow displacement uncertainties to be evaluated.

在以下集成" 将被应用到一个 pre-cracked parallelepipedic 样本由球墨铸铁 (图 14 (a)) 和受拉伸载荷通过试验机如图 7 所示 (一个)。参考文献中讨论的过程一样。(133、132、185) 后的样品制备。样品的横截面是 1.6×1 平方毫米。": 成就和挑战 61 标本在七增量加载步骤 (图 14 (b))。前两个扫描参考配置允许位移的不确定性的评估。

A complete scan of the sample corresponds to a 360° rotation along its vertical axis, during which 1,000 radiographs are acquired with a definition of 1, 944 × 1, 536 pixels. Each scan lasted less than 20 min. The physical voxel size is 7.2 m, and the reconstructed volume is encoded with 8-bit deep gray levels. In the following, the mesoscopic behavior will be studied. The constitutive equation investigated hereafter is Ludwik’s law [136] associated with J2 plasticity and isotropic hardening described by a power law function of the cumulative plastic strain.

完整的扫描样本对应一个 360° 旋转沿垂直轴, 在这期间有 1000 片获得的定义 1,944×536 像素。每次扫描持续不到 20 分钟。物理体素的大小是 7.2 m 和重建体积与 8 位编码深度灰色的水平。在下面, 介观的行为研究。本构方程研究了以后是 Ludwik 定律 [136] 与 J2 可塑性和各向同性硬化所描述的一个幂律函数的累积塑性应变。

The integrated DVC code, Correli 3.0 [121], is a Matlab implementation that uses in a non intrusive way a finite element code to compute the spatiotemporal sensitivity fields in addition to the current estimates of the displacement fields and reaction forces [93]. The inputs to such simu- lations are the measured displacements of top and bottom boundaries of the ROI. In the present case, the commercial finite element package Abaqus/ Standard is used with its built-in constitutive laws. C++ kernels compute all the other data needed to perform DVC analyses, namely, the DVC matrix [M], the instantaneous voxel residuals (x, t), and the instantaneous nodal residual vector b(t). Binary MEX files were generated and called in the Matlab environment to compute the Hessians and residual vectors to be utilized in the Newton scheme introduced above.

集成” 的代码,Correli 3.0[121], 是一个 Matlab 实现非侵入性的方式, 使用有限元代码计算时空敏感字段除了当前估计的位移场和反应部队 [93]。输入这样的形式——措施是顶部和底部边界的测量位移的 ROI。在目前的情况下, 商业有限元软件包使用其内置的本构有限元分析/标准的法律。c++ 内核计算所需的所有其他数据执行” 的分析, 即” 矩阵 [M], 瞬时体素残差 (x, t) 和瞬时节点剩余向量 b (t)。二进制墨西哥人文件生成, 在 Matlab 环境中计算的麻布和残余向量利用牛顿方案介绍。

Figure 14(b-d) summarizes the identification results for the mesh considered in the present analysis. To account for the presence of the crack, a node splitting technique is used. The shape of the crack surface is obtained by first running T4-DVC with no crack (i.e., global DVC with 4- noded tetrahedra and linear shape functions). The characteristic element size is equal to 12 voxels (Figure 14(c)). From the gray level residuals of unregularized DVC with no crack, the shape of the crack surface is determined [185].

图 14(罪犯) 总结了鉴定结果网认为在目前的分析。占裂纹的存在, 一个节点分割技术是使用。裂纹表面的形状是通过第一次运行 T4-DVC 没有裂纹 (即。全球” 的分散开 4 -四面体和线性形状函数)。特征元素大小等于 12 像素点 (图 14 (c))。灰度残差的 unregularized 陷落没有裂纹, 裂纹表面的形状决定 [185]。

At convergence, the hardening modulus is found to be equal to 1300 MPa and the hardening exponent is equal to 0.4. The yield stress for an offset of 0.2

在收敛, 找到硬化模量等于 1300 MPa 和硬化指数 = 0.4。的屈服应力抵

消 0.2

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When the measured load history is compared to the corresponding predictions (Figure 14(b)), significant differences are observed. The global residuals are significantly higher than the mea- surement uncertainties (i.e., 10 times higher). This is an indication of model errors. At least three origins can be invoked in the present case. First, the geometry of the cracked surface is not fully consistent with the experiment. Second the mesh is not fine enough to properly capture mechan- ical fields via FE simulations. Third, the constitutive law is only an approximation of the actual behavior.

当测量负载历史相比, 相应的预测 (图 14 (b)), 显著差异。全球剩余工资明显高于 mea -肯定是不确定性 (即。,10 倍)。这是一个迹象表明模型错误。至少有三个起源在目前的情况下可以调用。首先, 裂纹表面的几何形状不完全与实验一致。第二网格不够好正确捕获机械 ical 字段通过有限元模拟。第三, 本构定律只是一个近似的实际行为。

At convergence of the integrated DVC code, the gray level residuals are very low (Figure 14(d)) in comparison with the reference microstructure (Figure 14(a)), except in the immediate vicinity of the crack . This result can be explained by the fact that the mesh is not fine enough to precisely describe the cracked surface. It is worth noting that mesh refinement could be used for integrated DVC as opposed to regular DVC analyses for which the spatial resolution cannot be decreased at will (see Section 4.1). In the other areas of high residuals, it is rather due to the boundary conditions that were not perfectly captured with unregularized (due to the fineness of the mesh).

在集成融合” 的代码, 残差灰色水平非常低 (图 14 (d)) 相比, 参考微观结构 (图 14 (a)), 除了附近的裂缝。这个结果可以解释的事实网格不够好来精确描述裂缝的表面。值得注意的是, 网格细化可用于集成陷落而不是常规” 的分析, 不能随意降低空间分辨率 (见 4.1 节)。其他领域的高残差, 而是由于边界条件不完全捕获与 unregularized(由于网状的细度)。

On average, the gray level residuals are only 25

平均而言, 灰度残差只有 25

DVC: Achievements and Challenges 63 (a) (b) (c) (d) Fig. 14 Identification results via 4D registration. (a) Orthoslice of the gray level volume of scan #1. (b) Comparison of measured and predicted load levels. (c) T4 mesh used in the present study. (d) 3D rendering of the thresholded gray level residuals of scan #8 In the present case, the chosen mesh is not too fine so that DVC and integrated DVC results can be compared. This is generally not the case as integrated DVC allows very fine meshes to be used [93, 29, 31]. The RMS difference between measured and computed displacement fields is equal to 0.5 voxel. This level is to be compared with the measurement uncertainty. With the chosen discretization, the standard displacement uncertainty is equal to 0.06 voxel. The RMS difference is 8 times the displacement uncertainty, again signalling a model error. To understand where 64 A. Buljac et al.

": 成就和挑战 63 (a) (b) (c) (d) 图 14 鉴定结果通过 4 d 登记。(一)Orthoslice 灰度扫描 # 1 的体积。(b) 的比较测量和预测负荷水平。(c) T4 网用于本研究。(d) 的 3 d 渲染阈值灰度残差的扫描 # 8 在目前的情况下, 所选择的网不太好, 这样陷落和集成" 的结果可以比较。这种情况一般不作为集成" 允许使用极细网格 (93,29 日,31)。RMS 测量和计算位移场的区别 = 0.5 体素。这个水平是与测量的不确定性。选择离散化, 标准位移等于 0.06 体素的不确定性。RMS 的区别是 8 乘以位移的不确定性, 又信号误差模型。了解,64。Buljac et al。

the displacement discrepancies are located, Figure 15 shows the displacement fields measured by DVC and integrated DVC for the next to last scan. It is worth remembering that the Dirichlet boundary conditions of integrated DVC are measured data (via regular DVC). Consequently, the displacement errors cancel out at upper and lower surfaces of the considered ROI. However, very close to it the differences are quite significant. This is due to uncertainties in the boundary conditions. Some filtering could used by using verification tools [93]. The other area where the largest gaps are observed in the cracked zone. This is to be expected because of model errors discussed above.

位移的差异, 图 15 显示了位移场测量的陷落和集成陷落在未来持续扫描。值得记住的是, 集成陷落的狄利克雷边界条件测量数据 (通过定期")。因此, 位移误差抵消了上、下表面的 ROI。然而, 非常接近它的差异非常显著。这是由于边界条件的不确定性。一些过滤可以使用验证所使用的工具 [93]。其他地区最大的差距是观察破裂区。这是可以预料到的, 因为上面所讨论的模型错误。

(a) (b) (c) Fig. 15 3D renderings of the longitudinal displacements (expressed in voxels) of scan #7. (a) DVC measure- ments, (b) integrated DVC at convergence, and (c) difference of the two The fact that gray level residuals, load residuals and displacement residuals have levels less than ten times the measurement uncertainties shows that the simple elastoplastic model considered herein should not be discarded. However, it should be enriched to account for damage especially at the last load level where all residuals increase significantly. There is clearly some room for progress by improving the numerical model along all the lines discussed above.

(a) (b) (c) 图 15 的 3 d 渲染纵向位移 (在体素表达) 的扫描 # 7。的力量 (a) " 的措施,(b) 集成陷落在收敛, 和 (c) 差异的两个灰度残差, 负载残差和位移剩余工资水平低于 10 倍的测量表明, 简单的弹塑性模型不确定性考虑本不应丢弃。然而, 它应该丰富占伤害尤其是在最后负载级别所有残差显著增加。显然是有进步的空间, 提高了数值模型在上面讨论的所有行。

DVC: Achievements and Challenges 65 3.7 DVC for NDE purposes Considered from an abstract standpoint, DVC is the art of computing image differences taking into account possible deformations between images. Differences arising from distortions could be erased by taking them into account through corrected images ge.

": 成就和挑战 65 3.7 " 的濒死经历的目的从抽象的角度看," 是一种艺术, 计算图像之间的差异考虑可能的变形图像。差异引起的扭曲会被考虑成通用电气通过修正图像。

Although most previous examples were taken from mechanically loaded specimen, this is not compulsory. In particular, industrial manufacturing implies the production of a large number of parts of about the same microstructure. DVC can be used for the comparison between a "master piece" and any produced part. Here the displacement field is not physical, but it reflects variable distortions due to the manufacturing process. Some of them could be deemed acceptable and some others not. As such DVC would then provide an NDE of the production line. Additionally residuals would evidence irreducible flaws that are topological differences.

尽管大多数先前的例子来自机械加载试样, 这不是强制性的。特别是, 工业制造意味着大量的生产部分相同的微观结构。" 可用于对比产生的 "主人" , 任何部分。位移场不是身体上的, 但它反映了变量扭曲由于制造过程。他们中的一些人可能会被视为可接受的和其他一些不是。因此" 将提供一个濒死经历的生产线。此外残差将证据不可约拓扑差异的缺陷。

A natural field of applicability of these concepts is NDE of woven composites. These composite materials are becoming key in many applications mainly due to their very attractive specific prop- erties (e.g., strength to weight ratio). They are conformed by yarns (reinforcement phase) woven after a three-dimensional pattern and held together by a resin (matrix phase). The increasing interest in these materials has generated a high demand for proper characterization methods as well as for accurate simulations.

这些概念的自然领域的适用性是编织复合材料的濒死经历。这些复合材料成为关键在许多应用程序中主要是因为他们非常有吸引力的特定道具——erties(例如, 强度重量比)。他们符合纱线 (强化阶段) 后三维编织模式和在一起由一个树脂 (矩阵阶段)。对这些材料产生了越来越浓的兴趣高的需求适当的表征方法, 以及准确的模拟。

In this context, DVC provides a quantitative evaluation of continuous deformations (e.g., stretching and bending of yarns) that may define acceptable/unacceptable weaving distortions due to resin impregnation or infiltration, molding, curing as well as for a qualitative insight into the detection of weaving abnormalities (e.g., missing yarn, bad positioning, loop). The former are called "metric differences," while the latter are called "topological differences" (see Figure 16) as they cannot be reconciled by a simple continuous deformation of the medium [204, 152].

在这种情况下," 提供了一个定量评价连续变形 (例如, 纱线的拉伸和弯曲), 定义可接受的或不可接受的编织扭曲由于树脂浸渍或渗透, 成型, 养护以及定性见解编织的检测异常 (例如, 失踪的纱, 不好定位, 循环)。前者被称为 "指标差异" , 而后者则被称为 "拓扑差异" (见图 16), 因为他们无法和解的一个简单的连续介质的变形 (204、152)。

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Fig. 16 Residual field. The lowest values are made transparent to allow for visualization of the largest differ- ences. In this particular test case, two yarns were omitted in one weaving as compared to the reference one. The black dotted curves are drawn by hand to guide the reading along the missing yarns. Residuals highlight differ- ences that cannot be resolved by a deformation of the medium, and thus referred to as “topological differences.” This example illustrates the potential of DVC for NDE applications Then the use of DVC under a multiresolution isotropic approach [152] for two different manu- factured samples allows for the measurement of relative displacements and subsequent estimation of relative strains (deformations). These calculated relative strains are not a result of any loading prescribed to the sample, but rather of the many phenomena present during the manufacturing process that result in slightly different samples.

图 16 余场。最低的值是由透明的允许最大的不同- ence 可视化。在这个特殊的测试用例, 两个在一个编织纱线被省略了与参考。黑色虚线手工绘制的曲线是指导阅读一起失踪的纱线。残差突出不同- ence 无法解决的变形介质, 因此被称为“拓扑差异。”这个例子说明了潜在的濒死经历的”应用的使用多分辨率下”的各向同性的方法 [152] 为两种不同的人工制作样品允许测量的相对位移和后续评估的相对压力 (变形)。这些计算相对株不是任何装载规定样品的结果, 而是在场的许多现象在生产过程中, 导致样品略有不同。

Extending this concept to cases where the gray levels may vary (as discussed in Section 3.1.2) offers a very convenient framework for the comparison between a real part (e.g., x-ray scanned after production) and its theoretical model (e.g., CAD, weaving model, or mesh). As such, the studied sample is considered as in a so-called deformed or warped configuration with respect to the virtual reference. This reference configuration corresponds to the ideal weaving pattern, as can be defined by virtual models (FE, CAD). The procedure allows woven composites volumes (obtained from tomography) to be unwarped into a more convenient representation [153].

这一概念扩展到灰色的水平的情况可能会有所不同 (3.1.2 节讨论) 提供了一个非常方便的框架比较真实的一部分 (例如,x 射线扫描后生产) 及其理论模型 (如 CAD, 编织模式, 或网格)。因此, 研究样本被认为是在一个所谓的变形或扭曲配置对虚拟参考。这个引用配置对应的理想编织模式中, 可以定义为虚拟模型 (铁、CAD)。过程允许编织复合材料卷 (从断层扫描)unwarped 更方便表示 [153]。

As expected for woven fabrics, it is important to identify and follow the weaving process itself (i.e., the yarns) from a tomographic image. DVC in such cases may offer a very convenient alternative to segmentation since topology is preserved. The transformation between model and DVC: Achievements and Challenges 67 actual part allows for the transfer of whatever feature available from one world into the other one. For instance, if yarns are labelled in the model, their label can immediately be transferred onto the actual image. If a mesh has been tailored to the model, it can be mapped without effort onto the actual geometry. Shape metrology can be obtained for free. Clearly, manual intervention is possible for extracting such information. Needless to say, this is a tedious and time consuming operation that could suffer from operator bias and lack the required resolution. Alternatively, advanced image processing methods are also available. However they often are too specialized or overly sensitive to slight changes on the input image (i.e., resolution, noise, artifacts) or to the material itself.

如预期的机织物, 重要的是识别并按照织造过程本身 (即。纱线) 层析图

像。” 在这种情况下可能会提供一个非常方便的替代分割自拓扑保存下来。之间的转换模型和陷落: 成就和挑战 67 年实际允许一部分转移的特性从一个世界到另一个可用。例如, 如果纱线模型中的标签, 标签可以立即转移到实际的图像。如果网格被量身定做的模型, 它可以映射没有努力到实际的几何。形态计量学可以免费获得。很明显, 人工干预可能提取这些信息。不用说, 这是一个繁琐和费时的操作, 可能受到运营商的偏见和缺乏所需的分辨率。另外, 先进的图像处理方法也可用。然而他们往往太专业或轻微变化过于敏感输入图像 (即。、分辨率、噪声、工件) 或材料本身。

In Figure 17, a modified version of the multiresolution isotropic approach helps to overcome the challenge imposed by the poor texture provided by the discretized (i.e., voxelized) version of the weaving model and succeeds in properly relating it to the tomographic image of the manufactured sample. The resulting mapping is used to display the shear strain magnitude onto the virtual model.

在图 17 中, 多分辨率各向同性的修改版本的方法有助于克服挑战由离散 (即穷人提供的纹理。voxelized) 版本的编织模式和成功有关的正确, 那么它的层析图像制造样品。生成的映射是用于显示剪切应变级到虚拟模型。

Fig. 17 Example of a computed virtual strain field obtained from a tomographic image projected onto the corresponding virtual model of the textile. The color encoding refers to the shear strain xy , where (x, y) is the front plane 68 A. Buljac et al.

图 17 的例子计算虚拟应变场从层析获得纺织品的图像投影到相应的虚拟模型。颜色编码指的是剪切应变 xy, 其中 (x, y) 是前 68 飞机。Buljac et al。

In general, DVC applied to composite materials offers applications ranging from NDE of com- posite parts up to the validation of new weaving architectures for composite structures. Moreover, it improves over current NDE tools since they may not provide enough information to detect subtle deformations (and even not so subtle ones) such as those originated from the aforementioned “topological differences.” This section shows that in particular for (demanding) industrial applications DVC offers un- precedented opportunities at very low cost. Segmentation usually proceeds from the smallest scale toward the larger ones and hence topology is not securely preserved. The advantage of DVC over classical approaches is that the large scale features, and in particular topology, are preserved in the mapping.

一般来说,” 应用于复合材料提供了应用程序从濒死经历的 com—— “部分的验证新纺织结构复合结构。此外, 它改善了当前的濒死经历的工具, 因为它们不能提供足够的信息来检测子框架, 变形 (甚至不那么微妙的) 比如起源于上述 “拓扑差异。“本节显示, 尤其是 (要求) 工业应用” 以非常低的成本提供了联合国——有先例的机会。分割通常从最小的规模向更大的收益, 因此拓扑不安全地保存。陷落在经典方法的优点是, 大规模的特性, 特别是拓扑中, 保存的映射。

4 Uncertainty and bias quantifications 4.1 Uncertainty quantifications As discussed above, DVC is an ill-posed problem. To circumvent this difficulty, the needed regular- ization is often implicitly introduced through the choice a kinematic basis for the sought solution.

4 的不确定性和偏差量化 4.1 不确定性量化正如上面所讨论的," 是一个不适定问题。绕过这个困难, 需要定期 ization 往往是隐式地引入了通过选择运动的基础上寻求解决方案。

Relaxation of this regularization, as motivated by enhanced spatial resolution, is unavoidably ac- companied with a degradation of the measurement uncertainty [18, 131, 122, 46, 243]. This effect has been referred to as the "curse of displacement resolution versus spatial resolution in DIC" [96].

放松的正规化, 出于提高空间分辨率, 难免 ac -有退化的测量不确定性 (18、131、122,46 岁,243]。这种效应被称为 "位移分辨率和空间分辨率 DIC 的诅咒" [96]。

There are various ways of estimating the uncertainties of correlation techniques [46]. When only one acquisition is available, artificial motions i.e., generally uniform translations are applied to create a new volume that is subsequently registered with the reference volume [197, 14, 133, 95, 137, 46]. For extended DVC, the prescribed translation was uniform or discontinuous to probe the uncertainties associated with discontinuous enrichments [192, 185]. This first type of analysis mainly probes the interpolation scheme of the gray levels to achieve sub-voxel resolutions.

有多种方法估算的不确定性相关技术 [46]。当只有一个收购是可用的, 人工运动。, 一般应用统一的翻译来创建一个新的卷, 后来注册的参考卷 (197、14、133、95、137 年 46)。长", 规定的翻译统一或不连续调查与不连续充实相关的不确定性 (192、185)。第一类型的分析主要探讨了灰度级插值方案实现 sub-voxel 决议。

DVC: Achievements and Challenges 69 The second type of approach also uses only one reference volume but consists of adding noise to create a new volume, which is correlated with its noise-free reference [123, 122]. The advantage of such approaches is that i) closed-form solutions can be derived, and ii) their predictions can be validated against actual DVC calculations [122, 156, 93]. The sensitivity to noise is addressed in this type of procedure.

":69 年的成就和挑战第二种类型的方法也只使用一个参考卷但由添加噪音来创建一个新的卷, 这是与它的无噪声的引用 (123、122)。这类方法的优点是, 我) 封闭解决方案可以派生, 可以根据实际进行验证和 ii) 预测" 的计算 (122、156、93)。对噪声的敏感性是解决这种类型的过程。

Last, the two previous sources of uncertainty can be probed in a more reliable way when the same type of analysis is performed with real experimental data [18, 134, 97, 131, 46]. Such is the case when analyzing two consecutive scans of the sample in a given loading state (it may also be unloaded) with preferably a deliberately introduced motion between the two acquisitions. The main advantage is that both sources of error are investigated at the same time for the material of interest. For computed tomography, different displacement resolutions have been reported when the displacement is prescribed along or perpendicular to the rotation axis [97, 131]. Further, the general tendencies observed with DVC approaches are higher measurement uncertainties when compared with DIC [134, 97]. When using regularized approaches, the levels could be reduced to those reached in 2D-DIC [122, 214].

最后, 前两个不确定性的来源可以探索在一个更可靠的方法执行相同类型的分析与实际实验数据 (18、134、97、131、46)。情况就是这样在分析两个连续扫描的样品在给定加载状态 (也可能卸货), 最好是故意引入运动两者之间的收购。主要优势是错误的来源都是调查同时感兴趣的材料。计算机断层扫描, 不同位移分辨率已报告当位移沿规定或垂直于旋转轴 (97、131)。此外, 一般的倾向与" 的方法是观察到更高的测量不确定性与迪拜国际资本相比 (134、97)。当使用正则化方法, 可以减少这些水平达到 2 d-dic (122、214)。

Let us note that there are few comparisons between local and global approaches to DVC [122, 137, 169, 93, 168]. Overall, it is found that the measurement uncertainties are of the same order of magnitude when the total number of kinematic unknowns are similar. There is however an additional bonus for the standard displacement resolution (i.e., of the order of 20

让我们注意, 很少有比较本地和全球" 的方法 (122、137、169、93、168)。总的来说, 发现相同的数量级的测量不确定性时运动未知数的总数是相似的。然而有一个额外的奖金标准位移分辨率 (即。订单的 20

In the sequel, some very recent results obtained for laminography are summarized. Contrary to tomography, the laminography technique [82, 88] enables for in-situ imaging of studied regions in plate-like samples but involves incomplete sampling, which may increase the measurement uncertainty. Laminography is still a recent imaging technique [87, 89]. Consequently, there is a 70 A. Buljac et al.

续集, 一些非常最近对辐射分层照相术结果进行了总结。断层相反, 辐射分层照相术技术 (82、88) 使原位成像研究地区的平板状样品但包含不完整的抽样, 这可能增加了测量的不确定性。辐射分层照相术仍然是一个最近的成像技术 (87、89)。因此, 有一个 70 年。Buljac et al。

need for metrological assessment of the measured displacement fields and the corresponding strain fields [156, 28]. The uncertainty levels are estimated by following the last presented method that includes multiple scans prior to the experiment itself: –repeated scan - bis: two scans are acquired without any motion between the two acquisitions.

需要计量的评估测量位移场和相应的应变场 (156 年,28)。水平估计的不确定性之后, 最后一个方法, 包括多个扫描实验本身: 前——重复扫描- bis: 两个扫描获得没有任何运动两者之间的收购。

–rigid body motion - rbm: two scans are acquired when a rigid body motion is applied prior to the second acquisition. This case is deemed difficult [156] because the reconstruction artifacts (e.g., rings) do not follow the motion and may severely bias the displacement measurements.

-刚体运动元: 两个扫描获得的刚体运动时前第二次收购。这种情况下被认为是困难 [156] 因为重建工件 (例如, 戒指) 不遵守运动和位移测量可能严重偏见。

To assess the contribution induced by rigid body motions bis and rbm cases are compared. These effects will be probed for three different materials: –aluminum alloy AA2139 grade (i.e., Al-Cu-Mg alloy), with intermetallic volume fraction de- termined to be 0.45

评估的贡献由刚体运动 bis 和疟疾病例进行了比较。这些影响将对三种不同的材料: 铝合金 AA2139 年级 (即。、Al-Cu-Mg 合金), 金属间化合物体积分数 de -时间 0.45

–aluminum alloy AA2198 grade (i.e., Al-Cu-Li alloy), which has no initial porosity and 0.3

-铝合金 AA2198 年级 (即。,Al-Cu-Li 合金), 没有初始孔隙度和 0.3

–commercial nodular graphite cast iron (EN-GJS-400 [29, 28, 206]), which represents another class of materials with different microstructural length scales (Figure 2(c)).

球墨铸铁——商业 (en -数次- 400[206]29 日 28 日), 代表另一个类的材料具有不同微观结构长度尺度 (图 2 (c))。

The listed materials are analyzed by first conducting DVC analyses to measure displacement fields. The latter ones are interpolated to account for rigid body motions, both translations and rotations. The identified rigid body motions are then extracted from measured fields resulting in an estimation of the measurement errors [131]. The root mean square error associated with each displacement component is then computed, whose average u will be reported for C8-DVC.

上市材料进行分析, 首先进行” 的分析测量位移场。后者的插值占刚体运动, 两个平移和旋转。所确定的刚体运动然后从测量领域中提取导致测量误差的一个估计 [131]。与每个位移组件相关联的均方根误差计算, 平均 u C8-DVC 将报道。

The size ‘ of each C8 element is the length expressed in voxels of any edge. Different element DVC: Achievements and Challenges 71 sizes are considered, namely, 16, 24, 32, 48 and 64-voxel elements. Figure 18 shows the standard displacement uncertainty as a function of the element size. In the figure, repeated scans (i.e., bis cases) are shown with solid lines while rigid body motion (rbm) cases are depicted with dashed lines.

每个 C8 元素的大小的体素表达的长度的任何优势。不同的元素”:71 尺寸是成就和挑战, 即 16 日,24 日,32 岁的 48 和 64 -体素元素。图 18 显示了元素的标准位移的不确定性作为一个函数的大小。在图中, 重复扫描 (即。bis 例) 和实线所示, 刚体运动组织遏制案件与虚线描绘。

Mean displacement resolution (voxels) 10 0 2139 T3 rbm 2139 T8 bis 2139 T8 rbm 2198 T3 bis -1 2198 T3 rbm 10 2198 T8 rbm Cast Iron bis -2 10 20 30 40 50 60 70 Element size (voxels) Fig. 18 Standard displacement uncertainty as function of the element size for the analyzed materials These results illustrate the displacement uncertainty versus spatial resolution compromise to be made in DVC analyses [197, 123, 122], which is a signature of the ill-posedness of the underlying problem. It can be expressed by a power law relationship [197, 131] A +1 u = (31) ‘ where A is a constant expressed in voxels [131, 156].

Mean displacement resolution (voxels) 10 0 2139 T3 rbm 2139 T8 bis 2139 T8 rbm 2198 T3 bis -1 2198 T3 rbm 10 2198 T8 rbm Cast Iron bis -2 10 20 30 40 50 60 70 Element size (voxels) Fig. 18 Standard displacement uncertainty as function of the element size for the analyzed materials These results illustrate the displacement uncertainty versus spatial resolution com-

promise to be made in DVC analyses [197, 123, 122], which is a signature of the ill-posedness of the underlying problem. 它可以表达的幂律关系 (197、131)A + 1 u = (31) , 一个是一个常数表达的体素 (131、156)。

AA2198 T8 bis case has overall the lowest uncertainty values. The amount of rigid body in case of AA2198 T8 rbm is small and mainly in the direction of the rotation axis (i.e., artificial rings do not move) and it can be considered as equivalent to a bis case. This is why AA2198 T3 bis and AA2198 T8 rbm results almost coincide. However, when larger rigid body motions are applied to the AA2198 microstructure, significant degradations occur as can be seen in the example of AA2198 T3 rbm.

AA2198 T8 bis 案件总体不确定性值最低。刚体的数量的 AA2198 T8 遏制很小, 主要在旋转轴的方向 (即。、人工戒指不要移动), 它可以被认为是相当于一个国际清算银行的情况。这就是为什么 AA2198 T3 bis 和 AA2198 T8 元结果几乎一致。然而, 当大的刚体运动是应用于 AA2198 微观结构, 显著退化发生可以看到 AA2198 T3 遏制的例子。

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Conversely, the AA2139 microstructure (with initial voids) is less affected by rigid body mo- tions. AA2139 T8 rbm and AA2198 T3 rbm have almost identical size/position of the region of interest and amount of rigid body motion but still the relative gap between the corresponding bis and rbm cases are not identical. This case highlights an additional criterion concerning DVC uncertainty for laminography data, namely, its sensitivity to rigid body motions associated with the sample geometrical features (e.g., notch, drilled holes, crack). According to these results, a mi- crostructure with intermetallic particles only (i.e., without voids and thus showing less contrast) is more sensitive to the detrimental effect of rigid body motions.

相反,AA2139 微观结构 (与初始孔隙) 由刚体 mo, 影响较小。AA2139 T8 遏制和 AA2198 T3 遏制几乎相同的大小/感兴趣的区域的位置和数量的刚体运动, 但仍然相对差距相应的 bis 和遏制情况并不完全一样。本例中突出了一个额外的准则关于" 辐射分层照相术数据的不确定性, 也就是说, 其灵敏度刚体运动与样品相关的几何特性 (例如, 切口, 钻洞, 裂纹)。根据这些结果,mi - crostructure 只金属间化合物颗粒 (即。少, 没有空洞, 从而显示对比) 更敏感的刚体运动的不利影响。

Even though cast iron represents another class of materials with different microstructural scales (Figure 2(c)) the reported displacement resolution virtually coincides with bis uncertainty levels for aluminum alloys. When compared to tomography resolutions [131] of the same type of material (cast iron) but not the same resolution (i.e., side length of one voxel is 3.5 m), laminography is more challenging than tomography since there is a difference of at least a factor of 3 between the two uncertainty levels [28].

虽然铸铁代表另一个类的材料具有不同微观结构尺度 (图 2 (c)) 报道位移分辨率几乎伴随着铝合金 bis 的不确定性水平。断层扫描分辨率 [131] 相比, 相同类型的材料 (铸铁), 但不一样的分辨率 (即。, 体素的边长是 3.5 m), 辐射分层照相术比断层更具挑战性, 因为是至少 3 倍的区别两者之间的不确定性水平 [28]。

When successful, DIC/DVC calculations yield gray level residuals reduced to the level of noise (e.g., in the case of correlations between initial and artificially deformed initial images there is almost a one to one correspondence between the normalized RMS residual (by dynamic range √ f) and the dimensionless noise level 2 [99]). In the studied example (bis and rbm cases shown in Figure 18), the overall noise level (i.e., acquisition and reconstruction) is unknown but can be estimated by the RMS value of the residual at convergence. Figure 19 shows the best and worst cases from Figure 18 normalized by the overall noise level calculated from the corresponding residual fields. When controlled by white Gaussian noise, nodal displacement uncertainties divided by the noise level are expected to follow a power law of the element size ‘ with an exponent −3/2 [122]. The results in Figure 19 show that this dependence is not observed. This may be due DVC: Achievements and Challenges 73 to the occurrence of ring artifacts, which are observed in Figure 2 and which are clearly more significant than random noise for these cases.

一旦成功,DIC / ” 计算收益率灰度残差的水平减少噪声之间的相关性 (例如, 初始和人为变形初始图像几乎没有归一化均方根之间的一一对应残余 (通过动态范围 √f) 和无量纲噪音级别 2 [99])。在研究的例子 (bis 和疟疾病例如图 18 所示),(即整体噪声水平。、采集和重建) 是未知的, 但可以估计的剩余均方根值的收敛性。图 19 显示了图 18 的最佳和最坏情况归一化的整体噪声水平计算出相应的剩余字段。由高斯白噪声时, 节点位移除以噪声不确定性将遵循幂律指数的元素大小的 −3/2 [122]。图 19 中的结果表明, 该不是观察到的依赖。这可能是由于”: 成就和挑战 73 环的发生工件, 也观察到在图 2 中, 显然是更重要的比随机噪声对这些病例。

Normalized displacement resolution (-) 2 10 2198T3 bis 2139T3 rbm 10 1 10 0 10 -1 20 30 40 50 60 70 Element size (voxel) Fig. 19 Standard displacement uncertainty normalized by the (estimated) noise standard deviation as a func- tion of the element size for the two aluminium alloys. The solid lines show −3/2 power laws that would be expected in the case of white Gaussian noise as controlling uncertainty. This seems not to be the case In the present case, it appears that the uncertainty mainly comes from the laminography technique and its associated artifacts [88, 238]. The uncertainty levels are equal or higher with rigid body motions since some of the artifacts are not attached to the microstructure (e.g., phase- contrast edge enhancement) but intrinsic to the acquisition set-up (e.g., ring artifacts). This result calls for caution and it is advisable to acquire at least two scans in the reference configuration, if possible by slightly moving the setup between the two acquisitions, to evaluate the practical displacement and strain resolutions of the studied material.

归一化位移分辨率 (-)2139 2198 t3 bis t3 遏制 10 1 10 0 1 20 30 40 50 60 70 元素大小 (体素) 图 19 个标准位移 (估计) 噪声标准差标准化的不确定性作为一个函数, 两个铝合金元素的大小。实线显示 −3/2 次方的法律将在高斯白噪声的情况下, 控制不确定性。这似乎不是这样在目前的情况下, 似乎不确定性主要来自于辐射分层照相术技术及其相关的工件 (88、238)。水平相等或更高的不确定性与刚体运动以来的一些工件不附加到微观结构 (例

如, 阶段-对比边缘增强) 但内在收购设置 (例如, 环工件)。这个结果呼吁谨慎和建议参考配置中获得至少两个扫描, 如果可能的话, 稍微移动之间的设置两个收购, 评估的实际位移和应变分辨率研究材料。

4.2 Theoretical study of projection noise One important source of uncertainty (albeit not always dominant as seen in the previous examples) is the presence of noise in the images. This question, at least when the variance of noise is 74 A. Buljac et al.

4.2 理论研究投影噪声不确定性的一个重要来源 (虽然不总是占主导地位的如前面的例子所示) 在图像噪声的存在。这个问题, 至少在噪声的方差是 74。Buljac et al。

low enough, can be treated on a theoretical ground using perturbation analyses. They provide quantitative estimates of the influence of noise on the kinematic analysis. This is important inasmuch as the obtained estimates of the full covariance matrix can be further used to evaluate the uncertainty of parameters identified with the measured displacement fields [165]. Moreover, the explicit expression of the covariance matrix on the measured degrees of freedom allows the "best" metric to be tailored in order to perform this identification step. Best is not just arrogant, but among all unbiased methods (and an infinite number of them exist), the "best" one refers to the one that delivers the sought parameters with the least uncertainty.

足够低, 可以在地面使用摄动理论分析。他们提供了定量估计噪声的影响在运动学分析。这是很重要的, 因为获得的估计的协方差矩阵可以进一步用来评估的不确定性参数识别与测量位移场 [165]。此外, 协方差矩阵的显式表达式在测量自由度允许定制的"最佳"度量为了执行这识别的步骤。最好的不仅仅是傲慢的, 但在所有的方法 (和无限的存在) 的"最佳"指的是一个提供最低的要求参数的不确定性。

Before addressing the specific case of tomographic noise, let us first recall general DIC results that were obtained first for regular 2D-DIC [16, 99], but hold for all dimensionalities [122]. Let us consider that all images are corrupted by white and Gaussian noise, f (x) and g (x), for f and g respectively for the reference and deformed images (white in this context means that noise is spatially uncorrelated from pixel to pixel). The whiteness is not limiting and the same argument can be readily extended to an arbitrary spatial correlation. The Gaussian character is more limiting as it provides a very nice and comfortable stability property, namely, through linear operations (or through the linear tangent operators when the noise amplitude allows), noise will remain Gaussian, and hence the fluctuation of the measurement, here displacement fields, will also be Gaussian. Likewise the average of the noise being null, the obtained result will also be affected by a fluctuation whose expectation is null, which is to say the measurement is un-biased.

解决噪声层析的具体案例之前, 让我们先回想一般 DIC 的结果是第一个获得普通的 2 d-dic[99], 但保持所有向度:[122]。让我们考虑, 所有的图片都是被白高斯噪声, f (x) 和 g (x), 分别为 f 和 g 的参考和变形图像空间 (在这种情况下意味着白噪声是不相关的从像素到像素)。白度不限制和相同的论点很容易扩展到任意空间相关性。高斯字符是更多的限制, 因为它提供了一

个很好的和舒适稳定属性, 即通过线性操作 (或通过线性切运营商当噪声幅度允许), 仍将高斯噪声, 因此波动的测量、位移场, 也将高斯。同样的平均噪声是零, 得到的结果也会受到波动的预期为空, 也就是说测量是无偏见的。

Therefore, only variances are sufficient to characterize the noise-induced fluctuations of the result.

因此, 只有差异足以描述结果的噪音性波动。

When noise is non-Gaussian, it will tend to a Gaussian distribution, and the variance (and co- variances) are correctly computed with an argument based on Gaussian noise. However, higher order moments (that is 4th —or kurtosis —to start off with) have to be considered to see how close the measurement fluctuation is to a Gaussian distribution.

非高斯噪声时, 会倾向于高斯分布和方差 (和联合方差) 正确计算与论证基于高斯噪声。然而, 高阶的时刻 (即 4 -或峰度开始) 必须考虑如何关闭测量波动是一个高斯分布。

DVC: Achievements and Challenges 75 It can be noted that the situation is equivalent to the one where the noise affecting the reference image would be null and that of g would be an effective noise eg = g − f , white, Gaussian and of variance 2 2 , where 2 is that of each f or g . This observation gives an easier computation but the result does not depend on it. Introducing this noise in the images will induce an uncertainty u in the measured displacement. The latter is formally evaluated by exploiting the computation of the displacement with successive corrections using the Newton' s descend method. Equation (24) thus provides u = [N]† eg (32) This linear relationship implies that the result is unbiased, h ui = 0. The covariance matrix of this measurement noise is [Covu] = h u u> i where the angular brackets designate the expected value. From the above expression, the covariance matrix becomes [Covu] = h[N]† eg eg [N]†> i = ([N]> [N])−1 [N]> h eg eg i[N]([N]> [N])−1 (33) = 2 2 ([N]> [N])−1 ([N]> [N])([N]> [N])−1 = 2 2 [M]−1 The above result is remarkably simple and compact [122]. What is particularly convenient is that the practical use of the above covariance matrix is to introduce a "metric tensor" (i.e., Mahalanobis distance [140]) to appreciate a scalar product of such displacement fields as u · v = u> [Covu]−1 v. Hence, the appropriate norm to weigh the different degrees of freedom is written as kuk2 = 1/(2 2)u> [M]u, so that there is no need to invert the [M] matrix.

":75 年的成就和挑战它可以指出的情况下相当于一个噪音影响 g 的参考图像将是 null, 将是一个有效的噪声 eg = g− f, 白色, 高斯和方差 2, 2 是每个 f 或 g。这个观察给出了简单计算但结果不依赖于它。引入噪声在图像会引起测量位移的不确定性 u。后者是正式评估利用连续位移的计算使用牛顿下山法修正。方程 (24) 提供了 u = [N]† eg(32) 这种线性关系意味着结果是公正的,h u 我 = 0。这个测量噪声的协方差矩阵 h [Covu] = u u > 我在尖括号指定预期的价值。从上面的表达式, 协方差矩阵成为 [Covu] = h [N]† eg eg [N]†> i = ([N] > [N])−1 [N] > h eg eg 我 [N] ([N] > [N])−1(33) = 2 2 ([N] > [N])−1 ([N] > [N]) ([N] > [N])−1 = 2 2 [M]−1 上面的结果是非常简单和紧凑的 [122]。特别方便的是上面的实际使用协方差矩阵是引入"度规张量" (即。,Mahalanobis 距离 [140]) 升值等位移场的标量产品 u · v

= 你 > [Covu]−1v。因此, 适当的标准来衡量不同的自由度是写成 kuk2 = 1 /(2 2) 你 > [M] 你, 所以不需要逆矩阵 [M]。

To illustrate this result, the three microstructures shown in Figure 2 are considered in order to assess their sensitivity to noise. For that purpose, the 100 largest eigenvalues of [M]−1 (i.e., the lowest sensitivities of measured nodal displacements) for the studied microstructures and element size (‘=32 voxels) are shown in Figure 20. This information shows the isolated influence of the microstructure quality on the uncertainty. AA2198 T3 and T8 have higher eigenvalues than 76 A. Buljac et al.

为了说明这个结果, 图 2 所示的三个微观结构被认为是为了评估其对噪声的敏感性。为此,100 年的最大特征值 [M]−1(即。, 测量节点位移的敏感性最低) 研究微观结构和元素的大小 (’ = 32 像素点) 如图 20 所示。这个信息显示了孤立的组织质量不确定性的影响。AA2198 T3 和 T8 特征值高于 76。Buljac et al。

AA2139 T3 and T8 although in the final uncertainty analysis the opposite trend is observed. The heat treatment (T3 or T8) does not play a significant role here. The grading that is observed from AA2198, the most prone to noise, to AA2139 intermediate and finally cast iron, showing the least sensitivity to noise, is consistent with the intuitive appreciation of the richness of the microstructure. However, it has been seen above that the effective level of displacement uncertainty was rather close for these three materials. To solve this apparent contradiction, let us mention that the above covariance is the product of [M]−1 by the noise variance 2 2 , and from Figure 2, it seems that the noise level is not equal in all three cases (AA2139 with its more favorable microstructure is also affected by a stronger noise than AA2198). Moreover, the noise affecting these images seems more due to ring artifacts than random noise. This observation underlines the importance of additional influences (e.g., acquisition and reconstruction artifacts) on uncertainty.

AA2139 T3 和 T8 虽然在最后的不确定性分析观察到相反的趋势。热处理 (T3 或 T8) 并不扮演重要角色。评分从 AA2198 观察, 最容易产生噪音,AA2139 中间和最后铸铁, 显示了对噪声的敏感性, 是符合直观的欣赏丰富的微观结构。然而, 如上所述, 有效的水平位移的不确定性是相当接近这三个材料。为了解决这个明显的矛盾, 让我们提到上面的协方差的产物 [M] −1 的噪声方差 2, 从图 2, 噪音水平不平等似乎在所有三个案例 (AA2139 更有利的微观结构噪音也影响强于 AA2198)。此外, 噪声影响这些图片看起来比随机噪声由于环形工件。这一观点强调了额外的重要性的影响 (例如, 采集和重建工件) 的不确定性。

Fig. 20 The largest 100 eigenvalues of the inverse DVC matrix [M] for the studied microstructures and element size ‘=32 voxels DVC: Achievements and Challenges 77 4.3 How white is white noise? The above considerations work well for white noise. Such may be the case for the noise affecting radiographs, but the fact that the 3D volume is computed naturally introduces correlations in the volume and, ideally, this should be taken into account. Hence the following section aims at computing such correlations in the noise.

图 100 ” 的逆矩阵的特征值最大的 [M] 为研究微观结构和元素大小 = 32 像素点”: 成就和挑战 77 4.3 白噪声有多白? 上述考虑适合白噪声。这种可能的噪声影响射线照片, 但事实上,3 d 体积计算体积和自然地介绍了相关性, 理想情况下, 这应该被考虑。因此以下部分旨在计算此类噪声的相关性。

For the sake of simplicity, the case of parallel beam tomography is considered. 3D images, f (x), are obtained from an inverse Radon transform of the projections p(r,) [114] f (x) = S[p(r,)] (34) where r designates the coordinates in the detector space r = (r, z), z is parallel to the rotation axis, the angle of the sample for the projection, and p the projection, i.e., the cologarithm of the ratio of the radiograph intensity at position r to the beam intensity (flat field) at the same point. For a parallel beam the different slices perpendicular to the z axis are uncoupled, and are treated independently. The inverse Radon transform consists of computing a convolution (along r) of the projection by R(r) q (r, z) = R ? p(r, z,) (35) where F[R](k) = |k| is the so-called Ram-Lak filter [114]. The inverse Radon transform then reads Z f (x, y, z) = q (x sin( ) − y cos( ), z) d (36) 0 Let us assume a Gaussian white noise on projections h p (r, z) p (r 0 , z 0)i = 2 (r − r 0) (z − z 0) (37) with a uniform variance 2 . This noise in the projection, p , induces a noise in the reconstructed image, f , which has to be characterized. The linearity of the reconstruction implies that f is centered Gaussian noise as well. It is also to be observed, although this may be less intuitive, that 78 A. Buljac et al.

为了简单起见, 平行光束的断层。f (x), 3 d 图像从预测的氡逆变换获得 p (r,)[114]f (x) = S [p (r,)](34) 指定的坐标检测器空间 r = (r, z), z 是平行于旋转轴, 角度样本的投影, 投影和 p, 即。的余对数的比值 r 位置的 x 光照片强度梁强度 (平场) 在同一点。为平行光束不同片垂直于 z 轴分开, 并独立处理。逆拉东变换包括计算卷积 (r) 的投影 r (r) q (r, z) = r ?p (r, z,) (35),F [r] k (k) = | | 是所谓 Ram-Lak 过滤器 [114]。逆 Z 变换然后读取 f (x, y, Z) = q (x 罪 ( )−y cos( ),Z) d (36)0 让我们假设一个高斯白噪声预测 h p (r, Z) p Z(0, 0) = 2 (−r 0) (Z−Z 0)(37) 与一个统一的方差 2。这噪音投影, p, 导致重建图像中的噪声, f, 特点。重建的线性意味着 f 集中高斯噪声。它也被观察到, 尽管这可能不太直观,78。Buljac et al。

this noise is spatially stationary. In particular, the distance to the rotation axis plays no role. One way to show this property is to note that the rotation axis may be "moved" virtually by a mere translation of the different projections along r, by a quantity that depends on the angle . These translations have no effect on the image noise and hence no more on the reconstruction noise, from which stationarity results. Only the covariance of f is needed to fully characterize it Z h f (x) f (x0)i = 2 (z − z 0) S[(r − x, z)]S[(r − x0 , z)]dr (38) r Because of the decoupling of different z-slices and the statistical independence of the noise along the z axis, the resulting noise f is uncorrelated along the z direction. However, in the transverse, (x, y), plane, the spatial covariance of f has to be characterized.

这噪音空间静止。特别是, 转动轴之间的距离没有作用。显示该属性的一个方法是注意到转动轴可能会 “搬” 几乎仅仅沿着 r, 翻译不同的预测的数量取决于角 。这些翻译没有影响重建的图像噪声, 因此没有更多的噪音, 平

稳性的结果。的协方差 f 需要完全描述 Z h f (x) f (x0) i = 2 (Z−Z 0) 年代 ((r−x, Z)] 年代 ((r−x0, Z)) (38) r 博士因为不同 z-slices 的解耦和噪声的统计独立性沿 Z 轴, 产生的噪音 f 沿 Z 方向是不相关的。然而, 在横向 (x, y), 飞机, f 的空间协方差特征。

It may be further noted that f is isotropic, so that the correlation function only depends on the relative distance between points x and x0 (provided they lie in the same plane, z = z 0), h f (x) f (x0)i = C(|x − x0 |) (z − z 0) where C(d) is the covariance of f for two points distant of d. The expression of C(d) is more easily computed in Fourier space, as the power spectrum of p is uniform in the wavevector. The only subtlety comes from the denser sampling of noise close to the rotation axis, in Fourier space increasing the noise variance as 1/|k|, which is exactly compensated by the Ram-Lak filter. Hence, the power spectrum of noise in Fourier space is uniform, and the covariance reduces to a delta (Dirac) distribution in real space. Theoretically, in spite of the highly correlated steps involved in the inverse Radon transform (i.e., the back- projection may appear to build up long-range correlations) the reconstructed image displays white noise. Thus, the appropriate similarity measure, as discussed in the previous section, reduces to that of quadratic differences.

可能进一步指出, f 各向同性, 所以相关函数只取决于点之间的相对距离 x 和 x0(只要他们躺在同一个平面上,z z = 0), h f (x) f (x0) i = C (x−x0 | |) (z−z 0), C (d) 的协方差 f 两点遥远的 d。C (d) 的表达更容易在傅里叶空间中, 计算的功率谱 p wavevector 是一致的。唯一的微妙来自密集采样噪声接近旋转轴, 在傅里叶空间增加噪声方差为 1 / k | |, 这正是 Ram-Lak 滤波器的补偿。因此, 噪声功率谱的傅里叶空间是统一的, 和协方差减少 (狄拉克) 分布在现实空间。从理论上讲, 尽管高度相关步骤的氡逆变换 (即。, 背面投影似乎建立远程相关性) 重建图像显示白噪声。因此, 合适的相似性度量, 正如上一节所讨论的, 减少了二次的差异。

However, in practice, the sampling of angles is not continuous, and some small scale details in the representation of voxels are always present. The effective noise is never actually white at the pixel scale, but displays a slight broadening and possibly anti-correlations that come from details of the implementation. If one wants however to see how good/bad the approximation of white DVC: Achievements and Challenges 79 noise is, it is fairly easy to generate a series of projections that consists of uncorrelated Gaussian noise p with the very same format as the projections to be exploited, compute the inverse Radon transform of this noise with the used reconstruction code (one single slice is sufficient) and finally compute its pair correlation function. The latter usually departs slightly from the Dirac distribution, apart from nearest neighbor pixels that may display nonzero correlations.

然而, 在实践中, 抽样的角度不是连续的, 和一些规模小的细节的代表体素是永远存在的。有效噪声是从来没有真正白色像素规模, 但显示略有扩大, 可能 anti-correlations 来自实现的细节。但如果人希望看到好的/坏的近似白": 成就和挑战 79 噪声, 它是相当容易产生一系列的预测, 由不相关的高斯噪声 p 与同一格式被利用的预测, 计算氡逆变换的噪音与重建使用代码 (一个单片就足够了), 最后计算其对相关函数。后者通常从狄拉克分布稍微

离开, 除了最近邻像素可能显示非零的相关性。

4.4 Measurement biases and artifacts In the previous sections, the roles of image noise, inter-voxel interpolation or displacement dis- cretization were emphasized. However, other effects such as artifacts inevitably present in tomog- raphy may affect the image quality (or fidelity), and in turn possibly bias DVC results. This may be especially dangerous as the quality of image registration may not be at fault, but the interpre- tation of the results may reveal inappropriate. In the following, various artifacts of 3D imaging systems are discussed and ways to immunize DVC against these effects, and x-ray tomography (because of its dominance in 3D imaging) is the first technique that is considered.

4.4 测量偏差和工件在前面的部分中, 角色的图像噪声,inter-voxel 插值或位移 dis - cretization 强调。然而, 其他影响, 如工件不可避免地出现在 tomog——raphy 可能影响图像质量 (或富达), 进而可能偏见" 的结果。这可能是特别危险作为图像配准的质量可能不是过错, 但结果可能揭示的宰相, 界定不合适。在下面, 各种工件的三维成像系统和方法讨论了对这些效应" 进行免疫接种, 和 x 射线断层扫描 (因为它的主导地位在 3 d 成像) 是第一个技术, 被认为是。

4.4.1 Ring artifacts Among classical artifacts, “rings” were already mentioned. This is a good illustration of the previous risk, namely when the material absorption coefficient is homogeneous, the main source of contrast in the reconstructed volume may be due to the artifactual rings. However, the latter are not bound to the material, and hence they do not move in the same way as the sample itself.

4.1.1 环形工件在古典构件, 已经提到的 “戒指”。这是一个很好的说明之前的风险, 即均匀吸收系数的材料时, 在重建体积对比的主要来源可能是由于 artifactual 戒指。然而, 后者并不是绑定到材料, 因此他们不会移动和样品本身以同样的方式。

Hence registration may provide displacement data such that rings are positioned on top of each other, that is for a null displacement, and not necessarily the actual one.

因此注册提供位移数据, 这样环定位在彼此之上, 是零位移, 不一定是真正的一个。

Very often the detector exhibits spatially random bias but that is steady in time (and hence in), det (r, z). (A similar effect may result from imperfect flat-fields.) Some tomographs now come with a translation of the detector during scan rotation, and these motions are then further 80 A. Buljac et al.

经常探测器展览空间随机偏差, 但稳定时间 ( ), 因此, det (r, z)。(类似的效应可能由于不完美的平面场。) 一些层析 x 射线摄影机现在有一个翻译的探测器在扫描旋转, 然后这些运动进一步 80。Buljac et al。

numerically corrected by a mere translation of the projection. This procedure averages out the bias for a large part, and the reconstructed volumes are typically of better quality. Otherwise these biases give rise to “rings” or “half-rings” depending on the spanned angles during the scan.

数字仅仅纠正翻译的投影。这个过程平均的偏见很大程度上, 和重建卷

通常是更好的质量。否则这些偏见产生"环"或"half-rings"期间根据跨越角度扫描。

For the aluminium alloys of Figure 2, rings are clearly visible. If the bias itself can be described as Gaussian noise in space, the resulting noise in the image now displays the same ring features in their spatial correlation.

图 2 中, 铝合金的环是清晰可见。如果偏见本身可以被描述为高斯噪声在空间, 产生的噪声在图像现在显示相同的环特性的空间相关性。

This type of noise presents a nice case study for DVC. A first strategy is to introduce explicitly the possible bias, so that an acquired volume is written as p fˆ(x, y, z) = f (x, y, z) + r (x2 + y 2 , z) (39) and thus the DVC problem consists of the determination of both the kinematics and the detector bias det . To this aim, it is to be noted that the deformed image is affected by the same bias, but because of the deformation of the sample and its rigid body motions, the corrected image geu suffers from a "scrambled" version of this detector bias. The quadratic difference similarity measure thus takes a more complicated expression X S= ĝ(x + ux , y + uy , z + uz) − fˆ(x, y, z) x (40) p p 2 − det ((x + ux)2 + (y + uy)2 , z + uz) + det (x2 + y 2 , z) This expression looks like a difficult problem to tackle. However, it can be noted that the de- tector noise is assumed to be small, and hence one may solve the above minimization iteratively.

这种类型的噪声为" 提供了一个很好的案例研究。第一个策略是显式地引入可能的偏见, 这一收购体积是写成 p fˆ(x, y, z) = f (x, y, z) + r (x2 + y, z)(39), 因此" 的问题包括确定 det 运动学和探测器的偏见。这一目标, 要指出的是, 变形图像受到同样的偏见, 但是因为样品的变形和刚体运动, 纠正图像 geu 患有"炒"版本的这个检测器的偏见。二次不同相似度衡量, 因此需要一个更复杂的表达式 X S =ĝ(X + 用户体验,y + uy z + 是乌斯)−fˆ(X, y, z) X (40) p p 2− det ((X + 用户体验)2 + (y + uy) 2, z + 是乌斯)+ det (x2 + y, z) 这个表达式看上去就像一个难以解决的问题。然而, 它可以指出, 德- tector 噪音被认为是小, 因此可以解决上述迭代最小化。

More precisely, one may initialize the solution of the problem as in standard DVC, that is neglect- ing det . Once a first determination of the displacement has been estimated, one may obtain a first estimate of f , fest and det , using first the average of the reference fˆ and corrected deformed f as fest , and from the difference fˆ − fest , an angle-average provides an estimate for image (ĝ) u det . With the latter, a new estimation of both fest and gest is produced, from which DVC will refine the determination of the kinematics, and iteratively, better and better determinations of the bias and kinematics will be obtained.

更准确地说, 一个可能初始化问题的解决方案在标准", 这是忽视- ing det。一旦首先确定位移估计, 可能获得第一个估计的 f, 节日和 det, 使用前的平均参考 ˆ 和矫正变形 f 作为节日, 和不同 fˆ− 电影节, 一个 angle-average 提供估计的图像 (ĝ)u det。后者, 一个新的评估产生的节日和武功, 从" 将完善运动学的决心, 和迭代, 更好的和更好的决定偏差和运动学将获得。

DVC: Achievements and Challenges 81 Yet another possibility, if time allows, is to acquire several images of the sample without any mechanical loading, but only rigid body motions. In that case, it is rather straightforward to estimate this motion very precisely and the above procedure may provide a prior determination of det with very few iterations. Equipped with this determination, images can be pre-corrected before performing DVC, and the detector bias should no longer affect the results.

":81 年的成就和挑战另一个可能性, 如果时间允许, 是收购的几个图像样本没有任何机械负荷, 但只有刚体运动。在这种情况下, 而是直接估计这个运动非常精确和上面的过程可能会提供一个之前确定 det 用很少的迭代。配备这种决心, 图像可以 pre-corrected 执行陷落之前, 和探测器偏见应该不再影响结果。

An alternative route is to devise a similarity measure that is unaffected by the detector bias.

另一种路线是设计一种相似性测量探测器偏压的影响。

For instance, a projection operator, P , is introduced such that gf = P [f] and defined as Z gf (r, z) = f (r cos( ), r sin( ), z) d (41) 0 and its complementary hf = Q[f] p h(x, y, z) = f (x, y, z) − gf (x2 + y 2 , z) (42) Because this linear operator filters out the detector noise as can be observed from Q[fˆ] = Q[f] or Q[det] = 0, a similarity measure that is based on the quadratic norm of Q[fˆ − (ĝ) f] can be u considered. However, the projector Q is tuned to fˆ but not to (ĝ) f , and hence this similarity u measure is only an approximation. To mend this difficulty, det would have to be estimated in turn, correct fˆ and ĝ and iterate, and this would be equivalent to the previous route. As earlier mentioned for the discussion about the similarity measure, the most secure way to proceed is to explicitly describe the type of perturbation that affects the measurement, and determine all the parameters (and/or fields) that are involved in the measurement. This general rule allows the user to judge in the end whether the determined quantities (i.e., both measurements of interest but also artifacts) are consistent with the prior knowledge (or at least assumptions) used to analyze the case under consideration.

P, 例如, 一个投影算符是这样介绍女朋友 = P [f] 和定义为 Z gf (r, Z) = f (cos( ),r 罪 ( ),Z) d (41)0 及其互补高频 = Q [f] P h (x, y, Z) = f (x, y, Z) −gf (2 x2 + y, Z)(42) 因为这个线性算子过滤掉探测器噪声可以观察到从 Q [fˆ]= [f] 或 Q(det) = 0, 相似度度量是基于二次规范的 Q [fˆ−(ĝ)f] 你可以考虑。然而, 投影仪的 Q 是调谐 fˆ 而不是 f(ĝ), 因此这种相似性 u 措施只是一个近似值。修理这个困难, det 必须估计, 正确 fˆĝ 和迭代, 这就相当于以前的路线。早些时候提到讨论的相似性度量, 最安全的方式进行明确描述扰动影响测量的类型, 并确定所有参数 (和/或字段) 所涉及的测量。这个一般规则允许用户来判断最终决定是否量 (即。, 测量感兴趣的而且工件) 是一致的先验知识 (或者至少假设) 用于分析考虑。

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4.4.2 Beam hardening In lab tomographs, the x-ray source has generally a broad distribution of energies. X-ray absorption however depends on the frequency (or energy). Nevertheless, reconstruction softwares usually treat the beam as if it were monochromatic. The differential absorption of x-rays with wavelength means that as the ray penetrates into the solid, its spectrum concentrates onto the least absorbed frequencies, a phenomenon called "beam hardening." The consequence of beam hardening is that the outer layer of the sample will appear as being more absorbent than the core. Such an effect is however generally innocuous for DVC as it is a systematic effect that is attached to the sample.

在实验室 10/24/11 射束硬化层析 x 射线摄影机, 能量的 x 射线源通常广泛分布。然而取决于 x 射线吸收频率 (或能量)。然而, 重建软件通常治疗光束, 就好像它是单色。微分吸收 x 射线波长意味着当光线穿透固体, 其频谱集中到至少吸收频率, 这种现象称为 "射束硬化。"射束硬化的结果是, 样品的外层将出现比核心吸收剂。这种效果对" 然而通常是无害的, 因为这是一个附加的样本系统的影响。

However, in some cases, beam hardening will be responsible for the formation of shadows behind a high or low density inclusion. These shadows are geometric effects that are of geometric origin and will not rotate with the sample. One should be extremely careful with such effects, and residuals should be examined carefully.

然而, 在某些情况下, 射束硬化的形成将负责阴影背后的高或低密度夹杂物。这些阴影几何效应几何的起源和不旋转的样本。一个应该非常小心这样的效果, 残差应该仔细检查。

Let us note that when the material is made of a single phase (or when this provides a good approximation), it is possible to correct this beam-hardening effect with a procedure due to Herman [91] that consists of nonlinearly rescaling the gray levels.

让我们注意, 当材料是由单相 (或者当这提供了一个很好的近似), 可以纠正这种 beam-hardening 效果过程由于赫尔曼 [91], 由非线性尺度改变灰色的水平。

4.4.3 Spurious motion during scan Another difficulty comes from the possible motion of the specimen during one scan. This risk is reduced by the possibility of performing high-speed scans at synchrotron beamlines [32, 143].

4.4.3 假动作在扫描标本的另一个困难来自于可能的运动在一次扫描。这种风险是减少的可能性进行高速扫描在同步加速器 beamlines [143]。

Yet because of an applied mechanical load during a scan, it is difficult to exclude motions due to viscous relaxation, or to delayed damage or plastic flow. In such cases, the reconstructed image appears to be blurred, and DVC may produce erroneous results or at least uncertain ones, prone to high noise. If residuals are not examined in details, such phenomena may go unnoticed. Similarly instead of the sample motion, it may be the rotation axis of the scan that does not remain steady.

因为应用的机械负荷在扫描期间, 很难排除运动由于粘性放松, 或延迟损害或塑性流动。在这种情况下, 重建的图像似乎是模糊, 和" 可能会产生错误的结果或至少是不确定的, 倾向于高噪音。如果残差不了细节, 这种现象可能会引起注意。同样的样本运动, 它可能是扫描的旋转轴不保持稳定。

DVC: Achievements and Challenges 83 These effects are common ones in tomography but the coupling of tomography with in-situ testing aggravates such risks.

":83 年的成就和挑战这些影响是常见的断层的断层, 但耦合等原位测试加剧的风险。

Within the same type of artifacts, let us mention a last one due to the change in the source- sample distance in cone-beam setups in between the reference and the deformed image. Such a motion induces a magnification change that should not be interpreted in mechanical terms, especially for small strains [131, 233]. Micrometer-scale displacements of the source may induce a dilation that can easily be confused with a mechanical strain in terms of order of magnitude. As a consequence, an excellent thermal stability is required to prevent such spurious kinematics. Many recent lab systems have a thermal regulation that limits this bias. This last remark underlines the need for comprehensive analyses to fully assess the sources of measurement uncertainties.

在同一类型的工件, 让我们提到一个最后一个由于改变源——样本之间的距离在 cone-beam 设置参考和变形图像。这样的运动放大变化不应解释在机械方面, 特别是对于小株 (131、233)。源可能引起膨胀的宏观尺寸位移, 可以很容易地与机械应变混淆的数量级。因此, 一个优秀的热稳定性是需要防止这种虚假的运动学。许多最近的实验室系统热管理, 限制了这种偏见。最后的话突显出需要全面分析充分评估测量不确定的来源。

In Section 5.6, it will be seen that working directly with projections (i.e., radiographs) rather than reconstructed volumes (via P-DVC [124]), first makes the problem less relevant because of the reduction in acquisition time that can be made drastic, and second opens the possibility of performing individual corrections on the projections.

5.6 节中, 将会看到, 直接与预测 (即工作。射线照片), 而不是重建卷 (通过 P-DVC[124]), 第一次让问题不那么重要, 因为可以大幅减少采购时间, 其次打开上执行个体修正预测的可能性。

4.4.4 OCT For full-field Optical Coherence Tomography, the volume consists of a stack of images coming from successive depths within semi-transparent materials. Since no computation is needed to construct the volume, the sources of artifacts are much less numerous. However, as earlier mentioned, OCT is prone to noise, and moreover this noise is depth-dependent. In a similar spirit comes a specific feature of shadowing, namely, under a particle or feature that is a strong scatterer, the intensity of (coherent) light may be too small to permit the detection of further scatterers. If the motion of the sample moves a particle from a hidden to a visible position or vice-versa, registration may not provide a faithful account for motion. In such cases, which resemble the shadows cast by very absorbing features in x-ray tomography [229], a mask should be introduced, which would 84 A. Buljac et al.

4.4.4 10 月为细致的光学相干断层扫描, 包括一堆图片来自连续的深度在半透明材料。因为不需要计算构造体积, 工件不太大量的来源。然而, 正如之前提到的,10 月是容易产生噪音, 而且这噪音与深度有关的。在一个类似的精神阴影的一个特定的特性, 即在一个粒子或功能, 是一个强烈的散射体, (相干) 光的强度可能太小, 允许进一步散射的检测。如果样品移动粒子的运

动从一个隐藏的可见的位置, 反之亦然, 登记可能无法提供一个忠实的运动。在这种情况下, 非常类似于阴影的吸收特征 x 射线断层扫描 [229], 应该引入一个面具,84 a。Buljac et al。

correspond to the visible "horizon." Any variation that affects a position that is beyond the horizon should not be utilized. This may be compared to edge effects in classical DIC [99] when a feature present in the region of interest for the reference image is pushed outside the field of view in the deformed image, or conversely appears in the deformed image without being visible in the reference one. Using a frame to delineate a reliable ROI is a good strategy. The difficulty in the case of OCT is that the frame edge should be based on the total scattered intensity rather than being at fixed depth. Thus a direct modeling of OCT should be used to decide on the trusted part of the image and hence of the corresponding kinematics.

对应于可见 "地平线。"任何变化影响超越地平线的位置不应使用。相比, 这可能是边缘效应在经典 DIC[99] 当一个功能在该地区利益的参考图像视野之外的变形图像, 或相反地出现在变形图像而不可见的参考。使用一个框架来描绘一个可靠的 ROI 是一个很好的策略。困难在 10 月是帧边缘应基于总散射强度而不是以固定深度。因此 10 月的直接建模应该用于决定信任形象的一部分, 因此相应的运动学。

4.4.5 Conclusions Many different modalities exist. Each one with its specific artifacts that, to some extent, can be modelled. It is through this modeling that progress can be made in the interpretation of the images so that artifacts, rather than being a limitation with uncontrolled consequences, can be tamed to be as transparent as possible to DVC analyses, even if not taken into consideration in the reconstruction of 3D images.

4.4.5 结论许多不同形式存在。每个有其特定的工件, 在某种程度上, 可以模仿。正是通过这个建模, 可以取得进展的解释图像构件, 与不受控制的后果, 而不是一个限制可以驯服尽可能透明" 的分析, 即使不考虑重建的 3 d 图像。

5 Challenges 5.1 Material microstructure The first generic difficulty with 3D imaging is that the actual microstructure of the material can hardly be modified in the bulk in order to enhance contrast. Some attempts were made (e.g., by adding particles [18, 77, 25, 146] or revealing grain boundaries [135] for x-ray CT) but at the expense of changing the behavior of the investigated material. This is particularly true when studying ductile of brittle fracture [94]. Model materials were also considered for which the attenuation contrast was sufficient [207, 69]. Natural materials such as wood (thanks to its cellular DVC: Achievements and Challenges 85 microstructure) enabled DVC analyses to be successfully performed [68, 70]. Similarly, low density wood fiberboards could be studied via DVC [222].

5 挑战 5.1 材料微观结构第一通用的 3 d 成像困难的实际微结构材料很难被修改以提高对比度。有人试图 (例如, 通过添加粒子 (77,146) 或揭示晶界对 x 射线 CT[135]) 但以牺牲改变的行为调查材料。尤其如此, 当研究脆性断裂韧性 [94]。模型材料也考虑衰减对比是足够的 (207、69)。天然材料如木材 (由于其细胞": 成就和挑战 85 微结构) 启用" 的分析是成功执行 (68、70)。同样, 低密度纤维板木材可以通过" 的研究 [222]。

This is a major difference with 2D DIC, where a homogeneous or transparent material can always be painted with a speckle pattern, where the experimentalist can fine-tune the homogene- ity, pattern correlation length, and contrast more or less at will. In synchrotron facilities, the use of phase contrast can enhance the differences between material phases, and make them visible on the x-ray radiographs. Variants of this technique can be used on lab scale tomograph with polychromatic sources. Thus, this difficulty pushes DVC to deal with microstructures that can be very faint, with very few contrasting phases, possibly with a contrast that is not very salient as compared to reconstruction artifacts (Figure 2). Robustness when dealing with such sparse contrast textures is a major challenge that limits a priori the recourse to DVC for well contrasted materials (e.g., biological tissues [209, 12, 199, 195, 194, 242], foams [207, 197] and cellular materi- als [68]) or material with a large proportion of inclusions [127, 69, 133]. It is worth noting that even for very low contrasted materials such as aluminum alloys, DVC analyses were shown to be feasible [156] and yielded strain fields whose analysis was very precious in the understanding of the flat-to-slant transition in ductile tearing [158, 157].

这是一个主要的区别与 2 d DIC, 均匀、透明材料总是可以画上了散斑图, 实验者可以微调 homogene——密度、模式相关长度, 或多或少和对比。在同步加速器设施, 相衬的使用可以增强材料阶段之间的差异, 并使他们可见的 x 光射线照片。变异可以使用这种技术的实验室规模的层析 x 射线摄影机与多色的来源。因此, 这个困难推动” 处理微观结构可以非常微弱, 用很少的对比阶段, 可能不是很突出的对比与重建工件 (图 2)。处理这种稀疏纹理对比时鲁棒性是一个主要的挑战, 限制了先验陷落的追索权对比材料 (例如, 生物组织 (209,12,199,195,194,242], 泡沫细胞 (207、197) 和马特里-als[68]) 或材料夹杂物的大部分 (127、69、133)。值得注意的是, 即使对于非常低的对比材料, 如铝合金、陷落分析被证明是可行的 [156] 和屈服应变场的分析非常珍贵的理解 flat-to-slant 过渡韧性撕裂 (158、157)。

The occurrence of reconstruction artifacts (such as rings) becomes very detrimental when the contrast due to the natural microstructure of the material is as poor as discussed previously (see Sections 4.1 and 4.4). It is therefore very important to address these cases in order to make DVC useful for a broader class of materials. Let us stress that if numerically filtering images prior to a DVC analysis (e.g., ring artifacts can be significantly reduced [183]) is always an option, it is safer to include this filter in the similarity measure, or to leave as an unknown the effect to be filtered out, in order to validate the consistency of the assumption(s) made, and check that the filter did not affect the true microstructure. Last, let us note that when some information is 86 A. Buljac et al.

重建构件 (如环) 的发生变得非常有害的对比时由于天然材料微观结构改变的贫穷如前所述 (见章节 4.1 和 4.4)。因此很重要的解决这些情况下为了使” 用于更广泛的一类材料。之前让我们压力, 如果数值滤波图像” 的分析 (例如, 环工件可以显著减少 [183]) 一直是一个选择, 这是安全包括相似性度量这个过滤器, 或离开一个未知的过滤效果, 以验证假设的一致性 (s), 并检查过滤器并不影响真正的微观结构。最后, 我们注意到当一些信息是 86。

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discarded and still an acceptable spatial resolution is sought, suited regularization strategies are very helpful [199, 102, 195, 115, 123, 122].

丢弃, 还是寻求一个可接受的空间分辨率, 适合正则化策略非常有用 (199,102,195,115,123,122]。

5.2 DVC algorithms DVC calculations are becoming very involved even for local approaches because of the large size of volumes to be registered. A critical aspect is related to the initialization of the DVC code. One strategy used in local DVC is the global starting point and the information transfer approach.

" 5.2 " 的算法计算变得非常涉及甚至本地方法, 因为大尺寸的卷注册。的一个重要方面是相关的初始化" 的代码。一个策略用于当地的陷落是全球起点和信息传递的方法。

The locations of displacement measurement are ordered by the distance from a global starting point. That point is given special handling, possibly with user intervention. Transferring results to nearby points creates reliable starting points for the final optimization steps.

位移测量的位置距离下令从全球的起点。这一点是特殊处理, 可能与用户干预。结果转移到附近的点为最终的优化步骤创建可靠的起点。

Multiscale approaches, as discussed in Section 3.3 are a very convenient way for initialization purposes. Such schemes speed up the DVC calculations, and more importantly, they often prevent the DVC code to be trapped in secondary minima. This type of strategy is particularly important when dealing with large deformations [197, 97]. An alternative route is to start DVC calculations with large sub-volumes or elements and gradually refine [74] by initializing the new calculations with the previously converged solution. In the case of large deformations, there is always the possibility of updating the reference configuration, which becomes the deformed configuration of the previous calculation. So-called incremental DVC procedures have been implemented [103, 30, 157]. It is worth remembering that displacement fields have then to be interpolated in order to have access to cumulative displacement fields. Special care should be taken when computing strain fields, in particular in the large transformation framework (i.e., depending on the type of updating strategy, Lagrangian or Eulerian strain descriptors will be computed [223]). Alternatively, the mesh can be advected in order to make the nodes follow the same material points.

多尺度方法, 如 3.3 节中讨论是一个非常方便的方式进行初始化。这样的计划加快" 的计算, 更重要的是, 他们经常防止" 的代码被困在次要的最小值。这种类型的策略是特别重要的在处理大变形 (197、97)。另一种途径是开始" 的计算与大 sub-volumes 或元素, 逐步完善 [74] 通过初始化新的计算之前融合解决方案。在大变形的情况下, 总有更新的参考配置的可能性, 这成为变形前的配置计算。所谓增量" 的程序已经实现 (103,157)。值得记住的是, 位移场然后被替换, 以获得累积位移场。应特别注意当计算应变场, 特别是在大型转换框架 (即。, 这取决于类型的更新策略, 拉格朗日和欧拉描述符计算 [223])。另外, 网格可以流水为了使分节点遵循相同的材料。

The computation of the deformed volume corrected by the current estimate of the displacement field requires gray level interpolations to be performed for all voxels belonging to the ROI, and DVC: Achievements and Challenges 87 more than once for local approaches with overlapping subvolumes. The algorithms being iterative, such operations are repeated numerous times. To avoid such repeated interpolations lookup tables can be pre-computed [170] in order to accelerate DVC runs.

变形量的计算位移场的当前估计需要纠正的灰度插入执行所有体素属于 ROI, 和": 成就和挑战 87 年不止一次为当地与重叠子卷的方法。迭代的算法, 这样操作是重复很多次。为了避免这种重复插入查找表可以预先计算 [170] 为了加速陷落。

Local approaches have been shown to scale well when parallelized using multiple CPUs and multiple CPU threads. Likewise, these approaches are a natural fit for the massively multi- threaded computation power of graphics processing units (GPUs) [122, 7, 75, 235]. Since DVC is usually concerned with very large data sets, the number of measured kinematic degrees of free- dom are generally numerous. For global DVC it has been proposed to describe displacement fields in separated forms for spatial dimensions. Such a specific form can be introduced in the formal- ism of DIC/DVC, retaining only the dominant mode repeatedly until the residual level has been exhausted [80]. This way of handling the problem is written within the framework of PGD [39, 120] in which the different modes are introduced and the separated form is inserted directly in the variational formulation of DVC. Another route may be provided by domain decomposition methods applied to DVC. It has been followed in DIC analyses [176], but was not yet applied to DVC. However, because most of the computation cost is related to the correction by the measured displacement field of the deformed volume the CPU time gain is not spectacular, up to now, in comparison with standard implementations. When optimized global frameworks also scale nearly perfectly for multi-threading [121]. This is achieved by grouping voxels locally and sending each group to a different CPU thread.

当地的方法已被证明很好地进行扩展并行使用多个 CPU 和多 CPU 线程。同样, 这些方法是一种适合大规模多螺纹计算的图形处理单元 (gpu) (122, 75, 235)。陷落以来通常关心的是非常大的数据集, 数量的测量运动程度的自由——dom 通常无数。为全球" 的提出了描述位移空间维度字段以分离的形式。这样的具体形式可以引入 DIC 的正式- ism /陷落, 只保留主要模式反复, 直到耗尽剩余水平 [80]。这种处理方式问题是写的框架内 PGD[120] 介绍了不同的模式和分离的形式直接插入陷落的变分公式。另一条路线可能提供的域分解方法应用于陷落。之后在 DIC 分析 [176], 但尚未应用于陷落。然而, 因为大部分的计算成本相关的校正测量位移场的体积变形获得的 CPU 时间并不壮观, 到目前为止, 与标准相比实现。当规模优化的全球框架也几乎完全多线程 [121]。这是通过分组每组体素在本地和发送到另一个 CPU 线程。

Four dimensional analyses, namely, performing DVC analyses over space and time have begun very recently [93]. Time regularization will have some interest provided a sufficient number of scans is available in the analysis. It will also make the calculations even more involved and some of the above routes may turn out to be very useful (e.g., PGD [165]). It is believed that projection- based approaches are more suitable since they precisely provide much more temporal information than using fully reconstructed volumes at different levels of load.

四维分析, 即执行" 的分析从空间和时间已经开始最近 [93]。时间正则化将有兴趣提供足够数量的扫描分析中可用。它还将使计算更加涉及和上面的一些路线可能是非常有用的 (例如,PGD [165])。相信基于投影的方法更合适, 因为他们精确地提供比使用完全重建卷时间信息在不同级别的负载。

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5.3 Identification and validation The validation of material models using tomographic data still is in its infancy (see Section 3.4).

5.3 材料模型的识别和验证的验证使用层析数据仍然是处于起步阶段 (见 3.4 节)。

This first step is already very challenging for various reasons. First, in-situ (or ex-situ) testing is not yet performed routinely. The fact that more and more labs are equipped with in house tomographs will democratize experiments in such environments. Second, DVC itself has to be mastered in the case of difficult to very difficult microstructures (e.g., with small volume fractions of secondary phases [156, 158]). The simulations at the scale of 3D images are also very demanding in particular when nonlinear constitutive laws are selected.

第一步已经非常具有挑战性的由于各种原因。首先, 现场 (或让其它) 还不经常执行测试。这样的事实: 越来越多的实验室配备内部层析 x 射线摄影机将民主化等实验环境。第二," 本身必须掌握的情况很难很难的微观结构 (例如, 小体积分数的第二阶段 (156、158))。模拟 3 d 图像的规模也很要求特别是当非线性本构法律选择。

Figure 21 illustrates one possible route to validate numerical simulations at the microscale.

图 21 显示了一个可能的途径来验证数值模拟在微尺度。

Once sets of tomographic data are available (or by any other 3D imaging means), they can be used first to create meshes that are made compatible with the underlying microstructure revealed by 3D imaging [144]. When such meshes are created, finite element simulations can be run. However, there is still no control on their predictive character. The latter can be assessed by comparing computed displacement fields with their measured counterparts (via DVC). The distance between these two fields, when probed with respect to the measurement uncertainties, enables for relative comparisons between experimental and simulated data, the true solution being unknown. One additional step is to prescribe the measured boundary conditions to the numerical model. As underlined in Section 3.4, such approach is crucial in the validation step [206]. More importantly, it allows gray level residuals to be assessed not only for standard DVC analyses, but also for numerical simulations [29]. These residuals can be evaluated independently for DVC and numerical simulations. The two approaches are therefore probed individually and their merits (and shortcomings) are assessed in an absolute manner.

一旦套层析数据是可用的 (或通过其他任何 3 d 成像手段), 他们可以使用第一个创建网格, 兼容底层组织了 3 d 成像 [144]。当创建这些网格, 有限元模拟可以运行。然而, 仍然没有控制他们的预测。后者可以通过比较计算位移场与测量同行 (通过")。这两个领域之间的距离, 当探测对测量的不确定性, 使相对比较实验和模拟数据, 真正的解决方案是未知的。一个额外的步骤是规定测量数值模型的边界条件。正如 3.4 节中强调, 这样的方法在验证步骤 [206] 是至关重要的。更重要的是, 它允许将灰度残差评价不仅为标准" 的分析, 也为数值模拟 [29]。这些残差可以独立评估陷落和数值模拟。因此, 这两种方法对个人和他们的优点和缺点以绝对的方式评估。

DVC: Achievements and Challenges 89 T4gmeshg generation g T4gmesh C8/T4g C8-DVC FEgsimulations interp.

": 成就和挑战 89 T4gmeshg 代 g T4gmesh C8 / T4g C8-DVC FEgsimulations 插值函数。

p F uC8 uT4 ,FT4 F F 100g m 3Dgvolumes + gI-DVC Fmeas DVC FE Fig. 21 Schematic representation of methods that can be used for validation and identification purposes via numerical simulations at the microscale (adapted from Ref. [29]) Identification, which is the next step when validation is deemed insufficient, requires the use of numerous simulations in order to calibrate (or update) parameters of material models (Figure 21).

F uC8 uT4 p, FT4 F F 100 g m 3 dgvolumes + gI-DVC fmea DVC FE 图 21 的示意图表示方法, 可用于验证和识别目的通过数值模拟在微尺度 (改编自 Ref。[29]) 识别, 这是下一步验证认为不足时, 需要使用大量的模拟, 以校准 (或更新) 参数的材料模型 (图 21)。

Many identification techniques have now reached a reasonable degree of maturity in simpler situations (e.g., when using DIC data [5, 83]), which makes them good candidates to be tested in the context of DVC analyses. Yet they are challenged more severely in the context of 3D imaging because of generally higher measurement uncertainties in comparison with regular DIC. This observation may explain why very few studies have, up to now (see Section 3.4), been devoted to such endeavors.

许多识别技术已经达到一个合理的成熟程度在简单的情况下 (例如, 当使用 DIC 数据 [83]), 这使得他们优秀的候选人在陷落的背景下进行了测试分析。然而他们挑战更严重的 3 d 成像, 因为通常更高的测量不确定性与常规相比 DIC。这个观察可以解释为什么很少有研究, 到目前为止 (见 3.4 节), 致力于这样的努力。

The simulations become very demanding when microstructures are described very finely thanks to tomographic data (i.e., tomography or laminography typically give access to Gvoxel-volumes).

模拟时变得非常苛刻的微观结构非常精细描述由于层析数据 (即。、断层或辐射分层照相术通常给 Gvoxel-volumes 访问)。

For instance, each reconstructed volume can be obtained from a set of 6, 000 × 12-Mpixel radio- graphs (i.e., 144 Gbytes per considered step for 16-bit digitizations). For in-situ experiments the 90 A. Buljac et al.

例如, 每个重建卷可以从一组 6 日获得 000×12-Mpixel 电台图表 (即。,144 gb / 16 位数字化的步骤)。现场实验 90。Buljac et al。

typical number of scans now routinely exceeds ten, which leads to more than 1 Tbyte of data for a single experiment. The mere handling and visualization of such enormous amounts of data becomes challenging. Further, their processing is also becoming tedious. Model/data reduction strategies are one possible route to follow in order to ease and make the exploitation of such ex- perimental data far more efficient [165]. Similarly, much more developments should be performed regarding time and memory savings.

典型的扫描现在通常超过 10, 导致多名 Tbyte 数据的一个实验。仅仅如此大量的数据处理和可视化变得具有挑战性。此外, 处理也变得乏味。模型/数据简化策略是一个可能的路线遵循为了缓解和让剥削的 ex - perimental 数据更有效的 [165]。同样, 更多的发展应该执行关于时间和内存储蓄。

5.4 4D kinematic measurements from fast tomography One direction for addressing the challenge of resolving small time intervals has already been discussed in the introduction. Stupendous progress has been achieved in ultra-fast tomography scanned at synchrotron beamlines. Even crack propagation followed at 20 Hz showed the potential of such techniques for mechanical properties of materials. However, surprisingly, very few published studies made use of DVC to translate microstructure changes into 4D displacement (or velocity) fields. One exception though is due to one team that studied lithium batteries in operando [178, 65]. In these examples, DVC could inform on the strains, and hence ageing conditions under electrochemical changes, and finally provided a clear picture of the performance loss of such batteries.

5.4 4 d 运动学测量断层扫描一个方向快速解决的挑战, 解决小时间间隔已经讨论的介绍。已经取得了惊人的进展在同步加速器 beamlines 超高速断层扫描。甚至在 20 Hz 裂纹扩展后, 显示了这种技术的潜力材料的力学性能。然而, 令人惊讶的是, 很少发表研究利用" 的微观结构的变化转化为 4 d 位移 (或速度) 的领域。一个例外是由于一个团队, 研究锂电池在 operando (178、65)。在这些例子中," 可以通知株, 因此老化条件下电化学变化, 最后提供了一个明确的这种电池的性能损失。

It is nowadays a safe bet that fast tomography will open new avenues in experimental mechan- ics. Yet this remains for the most part a virgin and unexplored land. It is worth noting that as the turntable rotates faster, it may induce vibrations, thereby inducing additional artifacts (due to spurious motions) that will need to be accounted for at the reconstruction stage.

现在肯定是快速层析成象实验机械 ics 将开辟新的途径。然而, 这仍然是大部分处女和未开发的土地。值得注意的是, 随着转盘旋转速度, 它可能诱发振动, 从而产生额外的工件 (由于假动作), 需要占在重建阶段。

This hardware progress is however not an answer to the avalanche of data produced by in-situ experiments. On the contrary, this is an excellent way of generating more data in a short time. In the remaining part of this section different directions are listed, which give solid hopes on ways to actually decrease the needed experimental data, and hence achieve a better efficiency but not from DVC: Achievements and Challenges 91 a better accumulation of data. The different proposed routes deal with the ability to compress information with no (or a very modest) loss that have been proposed in the recent years. The first one, Section 5.5, aims at reducing the number of projections for reconstructing a tomographic volume, at the expense of formulating simple but generic assumptions on the microstructure. The second one, Section 5.6, is focussed on the displacement field and makes use of model reduction strategies, also devised initially to compress information with as little loss as possible, and with a control of the quality of the "reduction" performance.

这个硬件的进步但是不是答案产生的大量数据通过现场实验。相反, 这是一个非常好的方法在短时间内产生更多的数据。在本节的其余部分列出了不同的方向, 提供坚实的希望寄托在实际上减少所需的实验数据的方法, 从而达到更好的效率而不是从": 成就和挑战 91 更好的积累数据。提出不同的路线处理压缩信息的能力没有 (或一个非常温和的) 损失提出了近年来。第一个,5.5 节, 旨在减少层析重建的预测数体积, 以牺牲组织制定简单而通用的假设。5.6 节, 第二个是致力于减少模型的位移场和利用策略, 还设计了最初压缩信息尽可能少的损失, 和控制的"减少"的质量性能。

5.5 Volume data / duration of acquisition One limitation comes from the enormous amount of information in 3D images. This challenge is first met at the acquisition stage where a complete scan may require up to one hour or more in some cases, duration such that creep/relaxation may be responsible for a significant motion between the first and last radiographs. Thus one may be tempted to under-sample the orientations and collect fewer projections. The latter option is extremely appealing as it allows for much faster data acquisitions. However, without additional care, such an option generally involves very pronounced artifacts that differ from one reconstruction to the next and thereby compromise DVC.

5.5 体积数据/收购一个时间限制来自于大量的 3 d 图像的信息。这个挑战是第一次见到在采集阶段, 一个完整的扫描可能需要长达一小时或更多在某些情况下, 持续时间, 蠕变/放松可能负责一个重要的运动之间的第一个和最后一个射线照片。因此我们可能会少采样取向和收集的预测。后者的选择非常有吸引力, 因为它允许更快的数据收购。然而, 没有额外的护理, 这样的一个选项通常涉及很明显不同的工件从一个重建下从而妥协"。

However, numerous studies following the seminal contribution of Candès et al. [34] have shown that the use of some regularization strategies (and in particular the minimization of the total variation, TV) can compensate for the missing information when very few projections are acquired and provide excellent reconstructions. The key to the formidable success of such methods is the exploitation of some sparsity in the description of the to-be-reconstructed material. For instance, the chosen test case for the initial illustration of the benefit of TV-regularization was the Shepp- Logan phantom, a simple mathematical model of an idealized brain image, composed of few "phases," so that the boundary of those different phases, where the total variation is non-zero, 92 A. Buljac et al.

然而, 大量研究后的开创性贡献萤石等。[34] 表明, 一些正则化策略的使用 (特别是总变异的最小化, 电视) 可以弥补缺失的信息很少预测时获得并提供优秀的重建。这些方法的强大的成功的关键是开发一些稀疏的描述改造

材料。例如, 选择测试用例的初步说明的好处 TV-regularization Shepp -洛根的幻影, 一个简单的数学模型, 大脑一个理想化的形象, 由几个” 阶段, “所以这些不同阶段的边界, 总变异是零,92 a。Buljac et al。

was indeed sparse. And this sparsity is favored by using an L1 norm of the gradient (i.e., the total variation, TV), yet preserving convexity of the problem.

的确是稀疏的。这稀疏的使用梯度的 L1 范数 (即。、总变异、电视), 但保留问题的凸性。

The reliability of such approaches for medical diagnostics has sometimes been questioned [92] since, in this field in particular, it is essential to guarantee that the prior information brought by the regularization is valid (for instance, the presence of smooth gradients would invalidate this approach). Yet, the remarkable success of TV-regularization cannot be ignored, as having only few phases in a material is quite common. Some care is to be exercised, in order to apply such an approach, and in particular, correcting beam hardening is essential as this effect introduces a gradual change of gray levels from the boundary to the bulk of the sample, an effect that is not compatible with a discrete set of gray levels.

这种方法对于医学诊断的可靠性有时被质疑 [92] 以来, 尤其是在这一领域, 就必须保证之前的信息带来的正规化是有效的 (例如, 光滑的梯度的存在将这种方法失效)。然而,TV-regularization 非凡的成功是不容忽视的, 只有几个阶段材料是很常见的。一些保健运动, 为了运用这种方法, 特别是纠正射束硬化是必须的, 因为这影响了灰色的渐变水平从边界到大部分的样品, 效果不兼容一组离散的灰色的水平。

Operationally, a very elegant method, Discrete Algebraic Reconstruction Technique (or DART), has been proposed by Batenburg and Sijbers [9, 10]. It consists of coupling an algebraic recon- struction technique (SIRT) with a filtering of the reconstructed field in order to meet a constraint on the existence of a given number of phases (say only two for a binary reconstruction). The beauty of this algorithm is that it focuses only on the region in the image where some uncertainty remains and capitalizes the more secure determinations. Moreover, because of the interweaving of these two steps (SIRT and filtering), the approach has a rather low intrusiveness. Finally, DART has been also enriched with TV-regularization (TVR-DART), which adds some “surface tension” at interfaces [244]. Such an algorithm has the potential to achieve a very accurate reconstruction with a limited number of projections.

操作上, 一个非常优雅的方法, 离散代数重建技术 (或飞镖), 提出了由 Batenburg 和 Sijbers (9、10)。它由耦合一个代数侦察——教育技术 (SIRT) 的过滤重建领域以满足约束的存在一个给定数量的阶段 (比方说只有两个二进制重建)。该算法的优点是, 它只关注该地区在一些不确定性和资本化的形象更安全的决定。此外, 由于这两个步骤的交织 (SIRT 和过滤), 已经相当低侵入性的方法。最后, 飞镖已经还富含 TV-regularization (TVR-DART), 这增加了一些“表面张力”接口 [244]。这种算法有可能实现一个非常准确的重建与有限数量的预测。

One may fear that as the number of projections is reduced, the reconstructed volume will display progressively more uncertainty in its microstructure. Actually, this is not quite the case.

你可能担心随着预测数量的减少, 重建的体积将越来越显示其微观结构的不确定性。事实上, 并不是这样。

When the quality of the reconstruction is studied versus the number of projections, it is observed that the problem displays an abrupt "phase transition," from a solvable problem where the re- construction quality is very good to an unsolvable problem, where no solution is obtained [53].

当重建研究的质量和数量的预测, 可以看出这个问题显示突然"相变", 从一个可以解决的问题, 重新施工质量是非常好的一个解决不了的问题, 没有解 [53]。

DVC: Achievements and Challenges 93 It is difficult to theoretically qualify this abrupt transition, and determine the minimum number of projections required to reconstruct a solution, as it depends on the quantity of information present in the object to be reconstructed, and hence also on the additional information bought about by the regularization. However, even a very conservative estimate allows several orders of magnitude to be gained in acquisition time.

":93 年的成就和挑战很难在理论上符合这突然的转变, 并确定所需要的最小数量的预测重构一个解决方案, 因为它取决于对象的数量信息出现在重建, 因此也买的正规化的额外信息。然而, 即使是一个非常保守的估计可以在收购了好几个数量级。

In the safe convergence side, even if too little information is available for classical reconstruc- tion, it is important to note that each projection has a proper spatial resolution, and hence in order to achieve a proper match of the reconstructed volume with the available projections, an accurate determination of the microstructure features is called for. Therefore, the degradation of the reconstruction quality should not be imagined to be a progressive fuzziness of the boundaries (this would be forbidden by regularization). Rather, a more appropriate schematic picture is that the reconstruction is either excellent, or simply inaccessible. To the best of the authors' knowl- edge, the combination of regularized reconstruction, say using TVR-DART, and DVC has never been attempted (at least in published form). Such an association appears intuitively adverse to the usual requirement for accuracy. However, for the above mentioned reasons, intuition may not be of safe guidance. The above suggestion is a mere speculation at this stage.

在安全的融合方面, 即使信息用于古典 reconstruc 太少, 重要的是要注意, 每个投影都有适当的空间分辨率, 因此为了达到一个合适的匹配可用的体积重建与预测, 准确测定的微观结构特性。因此, 重建质量的退化不应该想象是一个进步的界限的模糊性 (这将禁止正规化)。相反, 一个更合适的图解是重建是优秀的, 或简单地访问。据作者的知识优势, 结合正则化重建, 使用 TVR-DART 说, 和" 从来就没有过 (至少在出版形式)。这样一个协会似乎直觉不良通常的精度要求。然而, 由于上述原因, 直觉可能不安全的指导。上面的建议是一个纯粹的猜测在这个阶段。

5.6 Projection-based DVC: fast 4D kinematic measurement The proposed approach to deal with fast 4D (space and time) measurement is called Projection- based Digital Volume Correlation (P-DVC) [124, 213]. Instead of working with reconstructed vol- umes as in standard DVC (whose acquisition time is one of the major limitation of CT, especially in laboratory facilities), it aims to measure the 4D displacement field from the comparison of a series of 2D projections (i.e., the projection at an angle (t) of the 3D microstructure) acquired at different times, t, angles, (t)) and loadings F (t). One reference 3D volume (using classical means) is assumed to be available in order to compute the correction term.

5.6 Projection-based 陷落: 快 4 d 运动测量该方法处理快 4 d(空间和时间) 测量称为投影-基于数字量相关性 (P-DVC) (124、213)。而不是处理重建卷——假设前提在标准”(采集时间的一个主要限制的 CT, 特别是实验室设施), 它的目标是测量 4 d 位移场的比较一系列的二维投影 (即。投影在一个角 (t) 的三维微结构) 收购了在不同时期,t, 角度, (t)) 和载荷 F (t) 一个引用 3 d 体积 (使用古典意味着) 被认为是可用以计算修正项。

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The similarity measure is here the squared difference of projections (since a white Gaussian noise is generally valid for projections). One set of projections is that of the deformed volumes p(r, t) at different loading steps (just one projection per loading step) and the other one is the corresponding projected reference image corrected by the displacement field, u. Registration (P- DVC) consists of minimizing this similarity measure X 2 TPDVC [u] = P (t) [f (x − u(x, t))] − p(r, t) (43) r,t where P is the projection operator in the direction of angle (t), and r the detector coordinate.

在这里的平方差异的相似性度量方法预测 (因为一个高斯白噪声通常是有效的预测)。一组预测变形量的 p (r, t) 在不同加载步骤 (每加载一个投影步骤), 另一个是相应的预测参考图像纠正了位移场、u。登记 (p - ”) 由最小化这种相似性测量 X 2 TPDVC [u] = P (t) (f (X−u (X, t)))−p r (r, t) (43), t, P 投影算符的方向角 (t) 和 r 探测器坐标。

As for usual DVC, in order to validate the procedure, the 2D residual field shows what has not been captured by the kinematic model (e.g., noise, artifacts of the detector, poor convergence, model error). It is defined as (r, t; u) = P (t) [f (x − u(x, t))] − p(r, t) (44) 5.6.1 Space-time regularization It is proposed to analyze the deformation of a sample using a reduced basis composed of Ns space shape functions (x) (e.g., from a finite element mesh) and Nt time functions (t) (e.g., Dirac distribution if no temporal regularization (free) is considered, polynomials, piecewise linear, or of higher degree) XNt X Ns u(x, t) = uij i (t) j (x) (45) i=1 j=1 where uij are the amplitudes of the displacement field associated with the chosen basis. Note that the time basis also offers the opportunity to include the time history coming from another modality. For instance, in the present case, a force measurement, F (t), is available. If the sample were linearly elastic, F (t) would be naturally relevant. One can also hybridize different signals (e.g., force and time), and any nonlinear functions thereof.

对于通常的陷落, 为了验证过程中,2 d 残留领域显示了尚未被运动学模

型 (如噪声、工件的探测器, 可怜的收敛, 模型误差)。它被定义为 (r t;u) = P (t) (f (x−u (x, t)))−p (r, t)(44) 5.6.1 时空正规化拟分析样品的变形使用减少的基础上组成的 Ns 空间形状函数 (x)(例如, 从有限元网格) 和 Nt 时间函数 (t)(例如, 狄拉克分布如果没有时间正则化 (免费) 被认为是, 多项式, 分段线性的, 或更高的学位)XNt x Ns u (x, t) = uij i (t) j (x) (45) i = 1 j = 1, uij 位移场的振幅与所选择的基础。注意时间的基础上还提供了包括历史的时间的机会来自另一个形态。例如, 在目前的情况下, 一个力测量,F (t) 是可用的。如果样品是线性弹性的,F (t) 将自然有关。一个也可以混合不同的信号 (例如, 力量和时间), 以及任何非线性函数。

DVC: Achievements and Challenges 95 In the case of a large number of unknowns, the computation of the Ns × Nt degrees of freedom may be costly. The so-called DIC-PGD framework has been developed to directly extract the dominant displacement modes (using space [175, 80] or space-time [111] separation) and provides big savings. However, for the sake of simplicity, this option is not followed herein. The minimization of TPDVC with respect to the displacement parameters u is performed using Newton' s descent method. This procedure requires the computation of the gradient and Hessian of TPDVC . They are built from the sensitivities sij (r, t) = P (t) [i (t) j (x) · feu (x)] (46) where feu (x) is the reference volume advected with the current (Eulerian) determination of the displacement field u, feu (x) = f (x−u(x, t)). (Note that in contrast with the previous presentation DVC, the reference image is to be advected to match the deformed volume projections, as only the latter is known, and not the deformed volume itself.) After each evaluation of the displacement corrections, or equivalently of its parameterization, u from a known displacement u(n) such as u(n+1) = u(n) + u, a correction of the 3D volume is performed so that the previous equation is used without approximation. The Hessian of TPDVC with respect to u and the right hand side vector are written as X Nijkl = sij (r, t)skl (r, t) r,t X (47) nij = P (t) [fe(x)u] − p(r, t) sij (r, t) r,t and thus one iteration is obtained by solving the following linear problem [N] u = n (48) 5.6.2 Experimental test case The test case for this study is an in-situ tensile test on a ductile cast iron sample. The geometry of the sample is shown in Figure 22(a). (Similar samples were studied in Refs. [219, 93].) The 96 A. Buljac et al.

": 成就和挑战 95 年大量未知的情况下,Ns×Nt 自由度的计算可能会代价高昂。所谓 DIC-PGD 框架开发直接提取主要位移模式 (使用空间 (175、80) 或时空分离 [111]), 并提供了巨大的储蓄。但是, 为了简单起见, 这个选项不是跟着。TPDVC 对位移参数的最小化你执行使用牛顿下降法。这个过程需要计算梯度和 TPDVC 黑森。他们由敏感性 sij (r, t) = P (t)[i (t) j (x) · 封地 (x)](46) 封地 (x) 是参考体积流水与当前 (欧拉) 确定位移场 u, 封地 (x) = f (x−u (x, t))。(注意与前面表示" 相反, 流水的参考图像与变形量的预测, 因为只有后者是已知的, 而不是变形体积本身。) 每次评估后的位移修正, 或者说它的参数化, 从一个已知位移你 u (n), 如你 (n + 1) = 你 (n) + u, 执行 3 d 体积的修正, 这样前面的方程没有使用近似。的黑森 TPDVC 你和右边矢量写成 X Nijkl = sij (r, t) skl r (r, t), t X (47) nij = P (t) (fe (X) u)−p (r, t) sij r (r, t), t, 从而获得一个迭代通过求解以下线性问题 [N] u = N(48)

5.6.2 实验本研究测试用例的测试用例是一种原位拉伸试验在球墨铸铁样品。样品的几何图 22 所示 (一个)。参 (类似的样本进行了研究。(219、93))。96 年的一个。Buljac et al。

central part (rectangular cross section of 1.31×0.91 mm2) is thinned with a radius of 20 mm in order to ensure that the specimen will fail in the ligament area and not in the grips. The sample, which was mounted in an in-situ tensile testing machine similar to that used by Buffière et al. [26] (Figure 22(b)), was scanned at LMT' s lab-tomograph (180 kV, 130 A, W target) at full resolution was equal to 10.4 m.

核心部分 (1.31×0.91 平方毫米的矩形截面) 是减少 20 毫米的半径, 以确保标本韧带地区将会失败, 而不是控制。示例, 这是安装在一个现场所使用的拉力试验机类似 Buffiere 等。[26](图 22 (b)), 在以前的扫描 lab-tomograph (180 kV、130 A W 目标) m 全分辨率等于 10.4。

(a) (b) (c) Fig. 22 In-situ tensile test with (a) the dog-bone sample used in the procedure with the regularization element, O O (b) the setup with 1 the testing machine with the carbon fiber composite loading tube, 2 the x-ray source, O3 the x-ray detector, and (c) a projection of the sample at angle k ° = −150 for step 110 with the projected spatial degrees of freedom Two flat-fields and one dark-field were acquired after conditioning and before the experiment in order to perform flat-field corrections. Each radiograph was averaged over 5 frames in order to reduce acquisition noise. The radiographs were cropped to a definition of 954×432 pixels so as to concentrate on the central part of the sample. The projections were obtained after flat-field normalization and standard beam hardening corrections with a third order polynomial [91] due to the high absorption of cast iron. Reconstructions and projections were performed with the DVC: Achievements and Challenges 97 ASTRA toolbox [227] making use of the Feldkamp-Davis-Kress (FDK) reconstruction procedure suited for cone beams [61].

(a) (b) (c) 图 22 原位拉伸测试 (a) 骨头样本与正则化过程中使用的元素,O O (b) 的设置 1 与碳纤维复合材料试验机加载管,2 x 射线源,O3 x 射线探测器,(c) 样本的投影角 k°= 150−110 步投影空间自由度两平面场和暗场条件反射后被收购, 在实验之前为了执行平面场修正。平均每个 x 光照片/ 5 帧收购, 以减少噪音。射线照片被剪裁的定义 954×432 像素, 以专注于样品的中心部分。预测后得到平面场标准化和标准的射束硬化校正三阶多项式 [91] 由于铸铁的高吸收。重构和预测进行了陷落: 成就和挑战 97 年阿斯特拉工具箱 [227] 利用 Feldkamp-Davis-Kress (FDK) 适合锥束重建过程 [61]。

The in-situ experiment consisted of three phases: –pre-load to 250 N in order to remove the backlash that would introduce rigid body motions; –complete scan of the reference state (250 N) that consisted of 600 radiographs captured at equally spaced angles ranging over a full 360° revolution. This scan took about 22 min. to be acquired; –continuous rotation of the sample with 50 acquisitions per revolution. 127 loading steps were captured during 300 s. The first 50 steps (i.e., 1 full rotation) were performed at constant load and were used to quantify the uncertainty. The remaining (starting from time step 50) were carried out with a continuous load change (from 250 to 750 N), which was controlled at a constant stroke rate of 2 m/s.

现场实验包括三个阶段: 预装 250 N, 以消除反弹将引入刚体运动;-参考状态的完整扫描 (250 N), 600 年由射线照片拍摄在等距的角度范围超过 360° 革命。这个扫描花了 22 分钟被收购;——连续的旋转样品 50 收购/革命。127 年加载步骤在 300 年代被抓获。(即第一个 50 步骤。1 完整的旋转) 进行恒定负载和被用来量化的不确定性。剩下的 (从时间步 50) 进行连续负载变化 (从 250 - 750 N), 这是控制在一个常数中风率 2 m / s。

The force measurement is shown in Figure 23 and could be used for future identification purposes.

力测量如图 23 所示, 未来可用于识别目的。

Fig. 23 127 force measurements of the tensile test starting from 250 N. A first complete revolution is performed at constant load, and the load is subsequently increased up to failure. The reference tomographic scan is acquired just before time 0.

图 23 127 力测量拉伸试验从 250 n . 执行第一次完整的革命在恒定负载, 负载是后来增加了失败。参考层析扫描之前获得时间 0。

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5.6.3 Results of the 4D spatiotemporal procedure It is proposed to focus on the central part of the sample where large plastic strains are expected.

5.6.3 四维时空过程的结果提出了关注的中心部分样品预计大型塑料品种。

A first evaluation of the transverse mean rigid body motions (i.e., perpendicular to the tensile axis) that occurred during the test is performed before displacement measurement. These rigid body motions are corrected from the projections. (This part is not detailed but it uses the same philosophy as previously presented).

第一次评价的横向的意思是刚体运动 (即。垂直于拉伸轴), 发生在测试执行之前位移测量。这些刚体运动预测的修正。(这部分不详细, 但它使用相同的哲学之前提出)。

Because the behavior is expected to be that of a plastic hinge (i.e., uniform displacement in the top and bottom part of the sample and large strains in the center), the chosen space regularization for the vertical displacement is to use one single element (with 8 nodes of size 200 × 200 × 200 voxels), each composed of a single degree of freedom, vertical displacement, with inside a trilinear interpolation, i.e., a reduced version of a C8 element where transverse displacements are neglected (since the mean transverse translation has already been corrected, this assumption neglects the transverse strains). In the top and bottom parts, the (uniform) displacement is chosen as a constant extension from the central cube face by continuity. The element is located in the central part as shown in Figure 22(a).

因为这种行为将塑性铰的 (即。、统一的位移在顶部和底部的一部分样本和大压力中心), 选择空间正则化的垂直位移是使用一个元素 (8 节点大小为 200×200×200 像素点), 每个组成的一个自由度, 垂直位移, 在三线性插值, 即。, 降低版本的 C8 元素横向位移在哪里被忽视 (自意味着横翻译已经被修正, 这种假设忽略了横向压力)。在顶部和底部的部分,(制服) 位移是选为一个常数扩展从中央立方体面临的连续性。元素位于中部如图 22 所示 (一

个)。

The time regularization is based on second order polynomials of the force measurement. A linear interpolation starting at time step 0 is added and another linear function with 0 value during time step [0,49] and linear during the load increase part 1 (t) = 1 2 (t) = F (t) 3 (t) = F (t)2 (49) 4 (t) = t 5 (t) = max(0, (t − 49)) The 4D problem is composed of 40 degrees of freedom (i.e., 5 time and 8 space shape functions, and respectively) and focuses on the region of interest corresponding to the projected cube DVC: Achievements and Challenges 99 element. Figure 24 shows the residual field change before and after registration. The residuals are rescaled to the dynamic range of the reference projection. It can be seen that a large part of the residual has been erased meaning that the kinematics has been well captured.

时间正则化是基于二阶多项式力的测量。线性插值从时间步 0 添加另一个线性函数 0 值在时间步 (0,49) 和线性负载增加一部分 1 (t) = 1 2 (t) = F (t) 3 (t) = F (t) 2(49) 4 (t) = t 5 (t) = max (0, t−49) 4 d 的问题是由 40 个自由度 (即。5 时间和 8 空间形状函数, 分别 和) 和感兴趣的关注该地区相应的投影数据集": 成就和挑战 99 元素。图 24 显示剩余磁场变化前后的登记。残差是新动态范围的参考投影。可以看出, 大部分剩余已经抹去这意味着运动学捕获。

(a) (b) ° Fig. 24 Projected residual field at angle k = −150 for step 110 (a) with no displacement field correction and (b) after the correction of the measured displacement. The black lines are the projections of the central cube element. Note that the gray level color bar (where gray levels are scaled to the full projection dynamic range) differs by a factor 2 The measured displacement for the 8 nodes at each loading step is shown in Figure 25(a). At the end of the experiment, the cube has been stretched in tension by about 11 voxels, or about 110 m. The gray level residual is quantified, in the region of interest (see Figure 25(b)), by the signal to noise ratio (SNR). The raw difference of projections leads to an SNR of 11.0 dB. The periodicity of about 25 time steps, which is seen in the initial residual, corresponds to the angles where the edges of the sample are aligned with the x-ray beam, namely, where the sensitivity to the radial displacement field is high. After the transverse translation correction, it increases to 23.4 dB. Finally, when the axial strain is accounted for as above described, the SNR reaches 26.8 dB.

(a) (b) 图 24° 预计剩余场角 k = 150−110 步 (a) 没有位移场校正,(b) 校正后的测量位移。黑色线条是预测中央立方体元素。注意灰度颜色条 (灰色水平扩展完整的投影动态范围) 的不同因子 2 的测量位移 8 节点在每个加载步图 25 所示 (一个)。在实验的最后, 立方体拉伸张力的体素, 或约 110 m。灰度残量化, 在该地区的利益 (见图 25 (b)), 由信号噪声比 (信噪比)。原始预测的差异会导致信噪比为 11.0 dB。约 25 次步骤的周期性, 这是在最初的残余, 对应的角边的样本与 x 射线是一致的, 即, 对径向位移场的敏感性很高。横向翻译校正后, 它增加到 23.4 分贝。最后, 当轴向应变占如上所述, 信噪比达到 26.8 分贝。

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(a) (b) Fig. 25 (a) Measured displacement of the 8 nodes. During the first revolution (t 50) a slight compression is visible, which is attributed to a relaxation phenomenon. In the increasing load part, the central region is stretched by approximately 11 voxels (or 110 m). (b) SNR history for the initial residual fields (1), the residuals corrected by (x, y) rigid body translations (2), and the final residual fields with all corrections (3) The 3D displacement for the 127 loading steps has been captured. Run in 300 s, this 4D procedure based on radiographs offers a fast measurement of the experiment with a gain of three orders of magnitude as compared to standard techniques. The entire procedure, including the experiment itself (after the initial tomography of the reference volume) and its analysis, is per- formed in approximately 10-15 minutes. A more complex and refined mesh could be used in order to characterize the kinematics more thoroughly. However, in order to avoid the increase of the number of degrees of freedom, regularization based on a mechanical model or other experimental observations would be welcome. Moreover, in 4D analyses, a proper generalized decomposition (PGD) approach is an alternative to focus on the most relevant modes and helps keeping the number de degrees of freedom at a decent level [111].

图 25 (a) (b) (a) 测量位移的 8 节点。在第一次革命 (t 50) 轻微压缩是可见的, 这是归因于一个松弛的现象。在增加负荷部分, 中部地区是拉伸 约 11 体素 (或 110)。(b) 信噪比历史初始残余字段 (1),(x, y) 的残差修正刚体翻译 (2), 和最终的残余字段与所有修正 (3)127 年的三维位移加载步骤已经被抓获。运行在 300 年代, 这个 4 d 过程基于射线照片提供了一种快速测量实验获得的三个数量级比标准技术。整个过程, 包括实验本身 (在最初参考卷) 的断层及其分析, 每-形成于大约 10 - 15 分钟。更复杂和细化网格可以使用为了描述运动学更彻底。然而, 为了避免自由度的数目的增加, 正规化根据力学模型或其他实验的观察将是受欢迎的。四维分析, 此外, 在一个合适的广义分解 (PGD) 方法是一种专注于最相关的模式, 帮助保持 de 自由度数量在一个体面的水平 [111]。

5.6.4 Perspectives The above example showed that a tremendous potential exists either to save time for getting the same information, or rather, to increase the time resolution at the same experimental time cost.

5.6.4 角度上面的例子表明, 存在一个巨大的潜在节省时间获得相同的信息, 或者更确切地说, 提高时间分辨率在同一实验时间成本。

Such a gain is obtained from a better definition of what is known and what is not, starting from DVC: Achievements and Challenges 101 the ultimate goal (e.g., mechanical properties), and progressively assembling from the accessible experimental data and the modeling a complete picture. Moreover, even if redundancy is reduced, as the primary information itself (i.e., the set of radiographs) has been severely deflated, it remains high enough to validate the assumed prior knowledge from residuals.

这种获得的获得一个更好的定义是什么, 从”: 成就和挑战 101 的最终目标 (例如, 机械性能), 并逐步组装的实验数据和建模一个完整的画面。此外, 即使冗余降低, 作为主要信息本身 (即。射线照片的集合) 已经严重了, 仍然能够验证假设先验知识从残差。

Stepping back to get a broader perspective, it is worth underlining the parallel that can be drawn in the two previous sections 5.5 and 5.6: –The former aimed at reconstructing the 3D microstructure from few projections, and required the introduction of prior knowledge on microstructure to allow for reconstruction with too few projections using standard tools.

退到后面, 让更广泛的角度来看, 值得强调的是, 平行, 可以在前两个章节 5.5 和 5.6:——前者旨在重建三维微结构的一些预测, 并要求引入先验知识的微观结构, 以便重建与预测使用标准工具太少。

–The latter aimed at reconstructing the 3D kinematic field from few projections, and required the introduction of prior knowledge on the mechanical behavior to allow for reconstruction with too few projections using standard tools.

——后者旨在重建 3 d 运动领域的一些预测, 并要求引入先验知识的力学行为, 以便重建与预测使用标准工具太少。

In both of these sections, more than two orders of magnitude gains were achieved on complex and realistic examples. It is to be stressed how remarkable is such a progress. Very few fields of research have experienced such a fantastic and sudden advance. Moreover, this huge gain did not originate from better equipments or facilities, but rather from a more intricate use of modeling and experiment. Such improvements are believed to be more the rule than the exception, and hence it is a unique opportunity for such 4D analyses to give a major impetus to the field of mechanics of materials (and structures).

在这两个部分, 超过两个数量级的涨势是实现复杂和现实的例子。是强调卓越的进步。很少研究领域经历了这样一个美妙的和突然的进步。此外, 这个巨大的获得并非来源于更好的设备或设施, 而是从一个更复杂的使用建模和实验。这样的改进被认为是比例外规则, 因此这是一个独特的机会等 4 d 分析给材料力学领域的一个主要推动力 (结构)。

6 Summary Over the last two decades, DVC has been made operational and reliable for very large classes of materials, wider than originally considered, and together with the progress of tomography and more generally 3D imaging modalities, it is today a very powerful experimental technique serving 102 A. Buljac et al.

6 总结在过去的二十年里, 取得了" 的操作和可靠的材料, 对于非常大的类更广泛的比最初认为, 与断层的进步和更一般的 3 d 成像模式, 今天是一个非常强大的实验技术服务 102 年。Buljac et al。

in particular the field of mechanics of materials. Commercial codes are now available, for local and global approaches, which makes DVC a tool that does not necessarily require the user to implement their own code. Further, the technique is gradually adopted by industry in the fields of nondestructive evaluation and mechanics of materials. This trend will require good practices to be formalized and possibly standards to be introduced.

尤其是材料力学领域。现在可以使用商业代码, 为当地和全球的方法, 使" 的一个工具, 并不一定要求用户实现他们自己的代码。进一步说, 这项技术正在逐步采用行业领域的无损评价和材料力学。这一趋势可能需要正式的良好实践和标准。

During the present decade, 3D imaging has been made more easily accessible thanks to the development of lab tomographs. X-ray microtomography has become the 3D microscope that enables mechanical tests to be performed in-situ. Coupled with DVC, they give access to a wealth of information that will enable progress in the understanding of material microstructures and their changes, as well as their mechanical behavior. One critical aspect is the way 3D images are reconstructed, and all the artifacts associated with the acquisition process during mechanical tests.

在当前的十年中, 已经取得了 3 d 成像更容易由于实验室层析 x 射线摄影机的发展。x 射线 microtomography 已成为三维显微镜, 使机械测试现场执行。再加上", 他们给获得丰富的信息, 使进展材料微观结构及其变化的理解, 以及他们的机械行为。一个关键方面是 3 d 图像的重建方式, 以及所有与收购相关的工件过程机械测试。

DVC is a very powerful tool to reveal them and even propose some corrections. These observations call for careful and systematic uncertainty and bias quantifications that not only depend on the contrast in the images but also on the physical and mathematical processes involved in their reconstructions.

" 是一个非常强大的工具来揭示他们甚至提出一些修正。这些观察呼吁谨慎和系统的不确定性和偏差量化, 不仅取决于图像的对比还涉及的物理和数学过程的重建。

In order to explicitly account for acquisition noise, different similarity measures were discussed.

为了明确占采集噪声, 不同的相似性措施进行了讨论。

They provide a probabilistic framework to image registration, which is not limited to DVC. It was shown how local and global approaches could be retrieved from such a framework. Further, the reconstructed volumes essentially display white noise properties (provided the radiographs themselves do) so that minimization criteria based on the sum of the squared differences are quasi optimal in terms of their least sensitivity to acquisition noise.

他们提供一个概率框架图像配准, 不限于陷落。这是表明局部和全局的方法可以从这样一个检索框架。进一步, 重建卷显示白噪声特性 (提供射线照片本身做的), 这样基于平方之和最小化标准差异是准最优的最小灵敏度收购噪音。

Ex-situ and more often in-situ tests have become a growing area in the field of solid mechanics.

让其它经常和原位测试已成为固体力学领域的增长区域。

Commercial (i.e., general purpose) testing systems are now available. The specific conditions associated with 3D imaging means will require the experimentalist to more often design their own loading devices in order to be compatible with the testing environment. Two options are possible.

商业 (即。, 现在可以使用通用测试系统。具体情况与 3 d 成像手段将要求实验者经常自己设计加载装置为了兼容测试环境。两个选项是可能的。

DVC: Achievements and Challenges 103 First the testing machine (and the sample) is put on the turntable of the imaging system. Second, the imaging system is built around testing machines (as the patient in a medical scanner). This second route is more delicate, but not impossible, when the protection to radiation has been carefully implemented.

":103 年的成就和挑战首先试验机 (样本) 的转台成像系统。第二, 成像系统是建立在测试机器 (如病人在医疗扫描仪)。第二个途径是更微妙的, 但不是不可能, 当保护辐射被认真执行。

In the majority of reported results so far, (local or global) DVC was used as a stand-alone technique that measures displacement fields. Strain fields are then deduced from the raw (displace- ment) measurements. This operation has to be well-mastered and understood since interpolations are required and remain usually implicit for the user. Even though such fields are prevalent for mechanical analyses, special care is to be exercised in their interpretation, in particular, in terms of uncertainties and associated correlations. Both kinematic fields carry a lot of information on the experiment per se and on its mechanical interpretation. When the user does not want to add a priori information, these general purpose codes provide a lot of qualitative and quantitative information about the test of interest. Until the end of the last decade, it was the only way DVC was used [11].

在大多数报道结果到目前为止,(本地或全球)" 的使用作为一个独立的位移场的技术措施。然后推导出应变场从原始 (,) 测量。这个操作必须 well-mastered 和理解因为需要插入并保持通常为用户隐式。即使等领域普遍存在的机械分析, 特别要注意在他们的解释, 特别是相关的不确定性和相关性。运动字段携带大量信息实验本身和其力学解释。当用户不想加入先验信息, 这些通用代码提供了大量的定性和定量信息感兴趣的测试。直到过去的十年中, 这是唯一的方法" 的 [11]。

More recently, it has been shown that measured data can also be integrated in numerical sim- ulations and vice versa. The introduction of mechanical modeling in the measurement procedure from regularization techniques is also a very powerful way of continuously tuning discretization effects of the kinematics and simultaneously shaking hands with the further exploitation of kine- matic data for mechanical behavior identification. As stressed through various examples, residual fields are very precious to validate all the assumptions used in DVC measurements, and to assess whether the partition between "explained" data, noise and artifacts is satisfactory. In such ap- proaches DVC is not a stand-alone tool, but one link out of many forming a chain between in-situ mechanical testing and mechanical identification and validation.

最近, 它已经表明, 测量数据也可以集成在数值 sim -较真, 反之亦然。测量过程中引入机械建模从正则化技术也是一个非常强大的方式不断运动学优化离散化的影响, 同时与母牛的进一步开发——握手电气自动方式力学行为识别的数据。强调通过各种例子, 剩余领域是非常宝贵的验证所用的所有假设" 的测量, 并评估是否 "解释" 数据之间的分区, 噪音和工件是令人满意的。在这样美联社——针对" 不是一个独立的工具, 但一个链接许多原位力学测试和机械之间形成了一个链识别和验证。

Further broadening the range of applications will require in situ experiments to be performed faster and possibly uninterrupted. Currently, lab tomographs require acquisition times lasting at 104 A. Buljac et al.

进一步扩大范围的应用程序将需要原位实验执行速度更快, 可能不间断。目前, 实验室需要收购时间持续在 104 层析 x 射线摄影机。Buljac et al。

least tens of minutes, which means that the load and displacement have to remain constant in order to ensure good reconstructions. Thanks to the beam power of third generation synchrotrons, subsecond scans are possible with the use of high speed cameras. However, spinning the sample and the loading device faster will inevitably reduce the quality of reconstructions if spurious motions are not accounted for. Another route is provided by spacetime analyses in which radiographs will be acquired on the fly. The latter ones will rely on projection-based DVC. It is envisioned that such techniques will open a new era of 4D tests that are performed in similar ways as conventional mechanical tests. This development will also imply new DVC implementations and maturing that couple reconstructions and displacement measurements.

至少十分钟, 这意味着载荷和位移必须保持不变, 以确保良好的重建。由于第三代同步加速器的束力, 次秒级扫描可能使用高速摄像机。然而, 旋转样品和装载设备更快的将不可避免地减少重建的质量如果假动作不占。另一条路线是由时空分析射线照片将被收购。后者的将依靠 projection-based 陷落。设想, 这些技术将打开一个新时代的 4 d 以相似的方式执行测试和常规机械测试。这种发展也将意味着新的" 的实现和成熟, 一些重构和位移测量。

The benefit of all the above mentioned approaches (be they local, global, regularized or inte- grated) is huge, and all methods and tools are readily available for the blossoming of 4D in-situ mechanical tests. These 4D analyses are now facing the massive amount of data to be processed efficiently, and that comes together with the impressive development of tomographic facilities and lab equipments. Unique opportunities were also mentioned, coming in particular from ap- plied mathematics through concepts in the vein of "compressed sensing" [35, 52] or tools such as "model reduction" [4].

所有上面提到的方法的好处 (他们是本地的, 全球性的, 正规化或强度-碎) 是巨大的, 和所有的方法和工具都是现成的 4 d 开花的原位力学测试。这些 4 d 分析现在面临着有效地处理大量的数据, 这是一起令人印象深刻的层析设备和实验室设备的发展。独特的机会也提到的, 特别是来自美联社——招摇撞骗数学通过静脉的概念"压缩传感" (35 岁,52) 或工具, 如"减少模型" [4]。

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