



Original software publication

iCorrVision-3D: An integrated python-based open-source Digital Image Correlation Software for in-plane and out-of-plane measurements (Part 2)



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ABSTRACT

This work presents an out-of-the-box python-based open-source 3D Digital Image Correlation (3D-DIC) software for both in-plane and out-of-plane full-field measurements, denoted by *iCorrVision-3D*. The software includes an integrated stereo grabber for image acquisition, stereo calibration, numerical stereo correlation and post-processing modules. The main objective is to provide a complete integrated 3D-DIC system for users. All important DIC setting parameters can be easily controlled by the user from an intuitive graphical interface. For instance, the interpolation strategy and correlation techniques that are usually not open for users are available for modifications in *iCorrVision-3D*. The proposed software can be used in a great number of applications in engineering. Results indicated that the *iCorrVision-3D* software is robust and accurate in reconstructing the 3D shape of objects and in evaluating the out-of-plane full-field displacement of specimens being tested.

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Code metadata

Current code version	V1.04.22
Permanent link to code/repository used for this code version	https://github.com/ElsevierSoftwareX/SOFTX-D-22-00076
Code Ocean compute capsule	-
Legal Code License	GNU GPL v3.0
Code versioning system used	GIT
Software code languages, tools, and services used	Python 3.8
Compilation requirements, operating environments & dependencies	The <i>requirements.txt</i> file is provided
If available Link to developer documentation/manual	https://github.com/jcadv/iCorrVision_3D/tree/main/UserGuide
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1. Motivation and significance

Digital Image Correlation (DIC) is a non-contact optical method well established nowadays in experimental solid mechanics [1]. While the two-dimensional DIC (2D-DIC) can be employed to extract the in-plane full-field measurements of a planar test piece under a given mechanical or thermal loading, the three-dimensional DIC (3D-DIC) can be used to evaluate both in-plane and out-of-plane full-field measurements of regular and irregular surfaces. Since its formulation in early 1980's, the DIC method

has been continuously improved over the last decades [2]. Several technological advancements in terms of the hardware of the optical systems were achieved and image-based algorithm performance was improved. Moreover, non-conventional single-camera-based optical arrangements were recently developed to reduce the 3D-DIC associated cost [3–6]. Such contactless method can be implemented in several engineering applications, such as material characterization [7], evaluation of sample deformation homogeneity [8–10], damage investigation [11], in-situ monitoring [12], non-destructive tests [13] and fracture tests [14,15]. Considering the 3D-DIC, a great number of scientific works were developed to extract the out-of-plane full-field maps of samples subjected to tension [16], shear [17], compression [18], fracture

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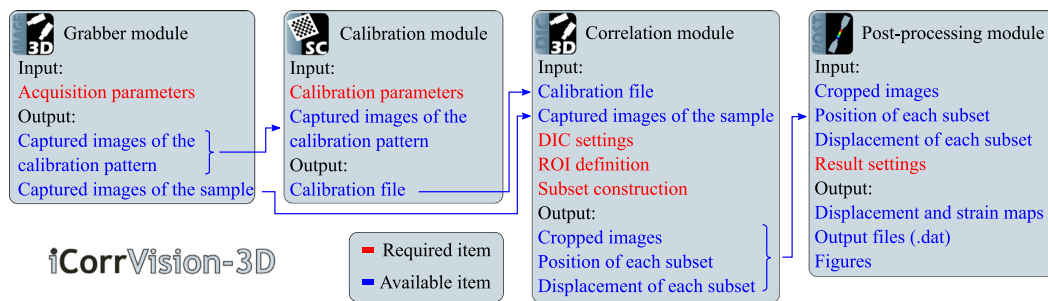


Fig. 1. Workflow of the *iCorrVision-3D* software.

and fatigue tests [19] and perform the 3D reconstruction of specimens [20].

Several proprietary closed-source software have been developed and improved over the last decade to handle bi- and tri-dimensional DIC measurements. For instance, *Correlated Solutions* [21], *GOM* [22], *MatchID* [23], *LaVision* [24], *Dantec Dynamics* [25] and *Eikosim* [26] can be highlighted. Additionally, there are a large quantity of open-source 2D-DIC solutions in the scientific community for in-plane full-field measurements. For example, the *Digital Image Correlation Engine (DICE)* [27], *NCorr* [28], *py2DIC* [29], μ *DIC* [30], *RealPi2dDIC* [31], *ADIC2D* [32], *ALDIC* [33], *UFreckles* [34], *YADICS* [35] and *PRedIC* [36] were recently developed. Taking into account the out-of-plane measurements, the *DICE* [27], *ADIC3D* [37] and *MultiDIC* [38] open-source projects can be highlighted. However, low effort have been carried out so far to build a fully-customizable open-source 3D-DIC system. Moreover, some of the available 3D-DIC open-source software are often written in licenced platforms (for example, *Matlab* [37,38]), limiting their usage among the open-source users who cannot afford such expensive licences. Low-cost 3D-DIC systems were proposed in recent years [3–6], but few attempts were conducted to reduce costs with regard to stereo-DIC software. Furthermore, as previously pointed out in the first part of this work (*iCorrVision-2D*, SoftwareX, 2022), the main DIC setting parameters are usually not available for modifications by the user from the graphical interface. For instance, neither the interpolation strategy nor the correlation algorithms are accessible in both open- and closed-source DIC software. The user must have high programming skills to develop and modify the source code in view of implementing the interpolation and correlation algorithms on the open-source software.

In order to tackle these issues, *iCorrVision-3D* has been developed as a new out-of-the-box open-source 3D-DIC software. This is an easy-to-use software thought to be intuitive for the new users. The integrated modules can maintain the whole stereo-DIC project (grabber, calibration, correlation and post-processing) open-source from stereo image acquisition to the visualization of results. Moreover, all main DIC settings are open for modifications, including the interpolation algorithm, correlation function and criterion, displacement smoothing and the number of desirable threads to run the correlation in parallel. In fact, this software comprehends a continuation of a Part 1 work, in which the open-source *iCorrVision-2D* software was presented, tested and validated (*iCorrVision-2D*, SoftwareX, 2022). From the *iCorrVision-3D* software, the user can perform several DIC-based tests in view of reconstructing the 3D shape and in evaluating the in-plane and out-of-plane full-field measurements of both planar and nonplanar specimens.

2. Software description

The *iCorrVision-3D* open-source software was developed in Python computational language, including the front- and back-end structures. The software was built around well-known open-source and free libraries available in Python. For instance,

OpenCV [39] and *Matplotlib* [40] were used for image processing and visualization, respectively. The *Tkinter* [41] was adopted to construct an intuitive user-friendly graphical interface. Four built-in modules (stereo grabber, stereo camera calibrator, stereo correlation and post-processing) were created with all main settings available for modifications. Each module was compacted in executables files to overcome installation problems. However, a requirements text file is available for Python users who are used to virtual environment development.

2.1. Software architecture

The *iCorrVision-3D* software was constructed to cover the entire workflow of 3D-DIC measurements, *i.e.*, from image acquisition to the visualization of results, as illustrated in Fig. 1. Therefore, four integrated modules were developed: (1) stereo image acquisition module, in which a sequence of image pairs (left and right cameras) can be captured; (2) stereo calibration module, that is used to extract the extrinsic and intrinsic parameters to perform the 3D reconstruction and the correction of lens distortion on the captured image sets; (3) stereo digital image correlation module, in which the stereo and temporal correlation are carried out; and (4) post-processing module, responsible for evaluating the strain maps. The latter was first presented in *iCorrVision-2D* to perform the post-processing of the in-plane data. From this work, this module was updated to comport the out-of-plane measurements.

2.2. Software functionalities

In the next sections, the functionalities of each module of the *iCorrVision-3D* software is properly addressed with all required theoretical background.

2.2.1. Grabber module

Fig. 2 illustrates the open-source stereo image acquisition module, so-called *iCorrVision-3D Grabber*. The user can modify different acquisition parameters to define the field of view (FOV), the exposure time and the frequency in frames per second (FPS). The acquisition of stereo-pairs can be configured to capture initial states with different time steps to obtain more information at the beginning of experimental tests. The primary and secondary grid lines can be activated to assist the correct camera-lens positioning and alignment to avoid assembling errors. Moreover, the flip check can be used to switch between the master (left) and slave (right) cameras.

This module was constructed using the *pypylon* library [42] available for Basler camera users to perform the communication between the hardware (cameras) and software (*iCorrVision-3D Grabber*). However, for other camera manufactures, the project can be gradually extended.



Fig. 2. *iCorrVision-3D Grabber* module.

2.2.2. Stereo calibration module

The calibration of the camera-lens optical system is the first step towards the stereo correlation analysis. The *iCorrVision-3D* software includes an integrated calibration module (*iCorrVision-3D Calibration*) that was developed using the *OpenCV* image processing library [39] based on the calibration method proposed by Zhang [43]. The intrinsic and extrinsic camera parameters that are necessary to conduct the correction of lens distortion and reconstruct the 3D shape can be estimated using the *iCorrVision-3D Calibration* module. The calibration is performed using the captured stereo pairs of a given calibration pattern. The advantage here is to make available an integrated open-source calibration suite to avoid the use of licenced and third-party platforms to carry out the calibration analysis and reduce the dependence on programming skills.

It should be remembered that the distortion-free projection on the camera sensor $\tilde{\mathbf{p}}_c = [x_1^c, x_2^c, 1]^T$ of a given 3D material point $\tilde{\mathbf{p}}_w = [x_1^w, x_2^w, x_3^w, 1]^T$ can be represented by

$$s^c \tilde{\mathbf{p}}_c = \mathbf{K}_c [\mathbf{R}_c | \mathbf{t}_c] \tilde{\mathbf{p}}_w, \quad \text{with } \mathbf{K}_c = \begin{bmatrix} f_1^c & \gamma^c & c_1^c \\ 0 & f_2^c & c_2^c \\ 0 & 0 & 1 \end{bmatrix}, \quad (1)$$

where subscript and superscript c represent the camera-lens set (m for master and s for slave), s^c is a scale factor, \mathbf{R}_c and \mathbf{t}_c are the rotation matrix and translation vector (extrinsic parameters), respectively, that transforms the world coordinate system (WCS) in the camera coordinate system (CS) and \mathbf{K}_c is the camera intrinsic matrix. f_1^c and f_2^c are the focal lengths in pixels, c_1^c and c_2^c are the coordinates of the principal point (optical center) in pixels and γ^c is the skew factor. Superscript c represents the camera indices.

For an accurate calibration, the non-linear optical distortion of lens should be included in the calibration model. The lens distortion can be compensated replacing the image point coordinates $[x_1^c, x_2^c]^T$ by the distorted normalized coordinates $[x_1^{dc}, x_2^{dc}]^T$ as follows

$$\begin{bmatrix} x_1^{dc} \\ x_2^{dc} \end{bmatrix} = \underbrace{\left(1 + k_1 r^2 + k_2 r^4 + k_3 r^6\right)}_{\text{Radial distortion}} \begin{bmatrix} x_1^c \\ x_2^c \end{bmatrix} + \underbrace{\begin{bmatrix} 2p_1 x_1^c x_2^c + p_2 \left(r^2 + 2(x_1^c)^2\right) \\ p_1 \left(r^2 + 2(x_2^c)^2\right) + 2p_2 x_1^c x_2^c \end{bmatrix}}_{\text{Tangential distortion}}, \quad (2)$$

where k_1^c , k_2^c and k_3^c are the radial distortion coefficients, p_1^c and p_2^c are the tangential distortion coefficients and $r^2 = (x_1^c)^2 +$

$(x_2^c)^2$. Since the distortion coefficients depend exclusively on the camera-lens set, these coefficients also belong to the intrinsic parameters of the camera. As can be seen, this procedure should be done for each camera in the stereo rig. The camera parameters are estimated using the global Levenberg–Marquardt optimization algorithm to minimize the re-projection error.

The stereo extrinsic parameters (\mathbf{R} and \mathbf{t}) can be obtained by computing the transformation equations between each camera-lens set as follows

$$\mathbf{R} = \mathbf{R}_s \mathbf{R}_m^{-1} \quad \text{and} \quad (3)$$

$$\mathbf{t} = \mathbf{t}_s - \mathbf{R}_s \mathbf{R}_m^{-1} \mathbf{t}_m, \quad (4)$$

where subscripts m and s denote the master (left) and slave (right) cameras, respectively.

Using the *iCorrVision-3D Grabber* module, it is possible to capture stereo images of a given calibration pattern. The software was constructed for a checkerboard calibration pattern type. Nevertheless, other calibration patterns can be added in future releases, such as the dot grid calibration pattern. The main principle consists in finding the vertices in the checkerboard pattern and use each material point in 3D world to compute the intrinsic and extrinsic parameters.

Fig. 3 illustrates the *iCorrVision-3D Calibration* module. Taking into account the checkerboard calibration pattern type, the checker size and the number of vertices in x_{11} - and x_{22} -directions are available for modifications. The calibration file (.csv format) can be generated containing the rotation matrix (\mathbf{R}) or the euler angles (θ , ϕ and ψ), that can be selected by the user. This functionality is important to promote the direct conversation between different DIC software.

2.2.3. Correlation module

The *iCorrVision-3D Correlation* module is presented in this section. 3D-DIC corresponds to an extension of 2D-DIC method. Fig. 4 illustrates the interface of the stereo correlation module of the *iCorrVision-3D* software. All main DIC settings are available for modifications, including the interpolation strategy that is usually a black-box in both open- and closed-source software. The captured images can be resized before correlation using the k_b factor. Moreover, the peak of correlation in the correlation coefficient matrix can be interpolated by means of the k_a factor using a kernel size of 5×5 pixels² after correlation. The bicubic splines were employed for both interpolation strategies. Moreover, the correlation strategy can also be selected by the user. The incremental strategy is directly addressed to reduce the computational cost with consequent high propagated errors [44]. Alternatively, the

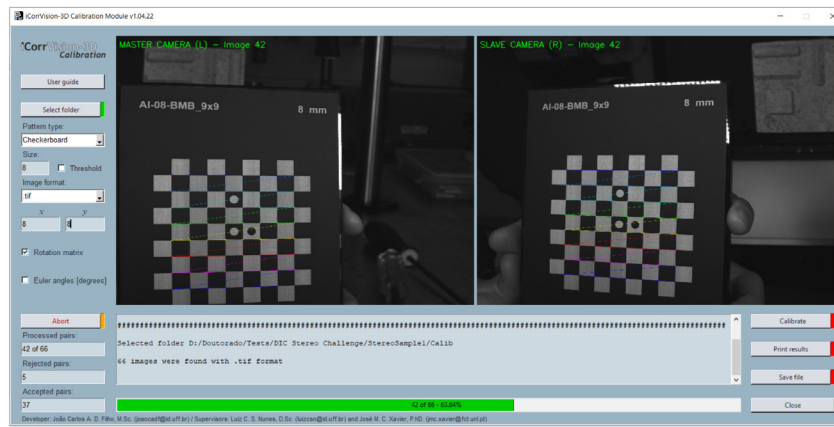


Fig. 3. iCorrVision-3D Calibration module.

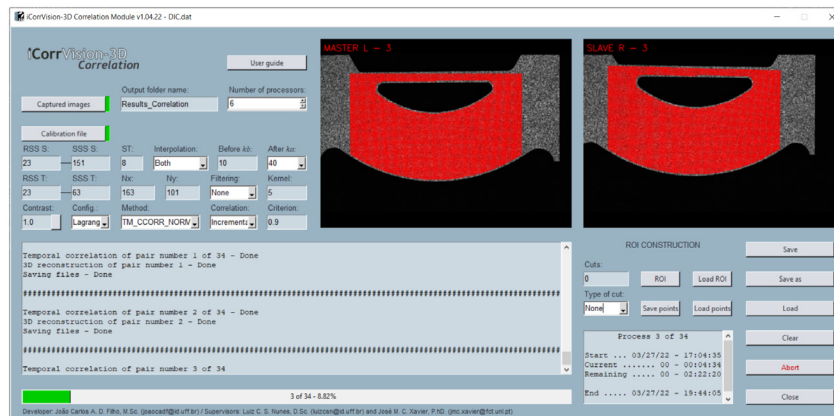


Fig. 4. iCorrVision-3D Correlation module.

spatial strategy can be selected to mitigate correlation errors to standard lower bounds, however, the computational cost can be significantly higher when compared to the incremental strategy. The stereo and temporal correlation were constructed to run in parallel to reduce computational time and the user can adjust the number of allocated processors. Nevertheless, the software identifies automatically the number of available processors.

The stereo correlation (between the left and right images) is performed in the reference image (i_0) and the temporal correlation is carried out between images acquired using the same camera-lens set (i.e., left images or right images). The user can also select the correlation function available in the *OpenCV* image processing library [39] and the correlation criterion.

The 3D reconstruction can be performed using the output of the stereo correlation that comprehends the position and displacement of the 2D points in pixels on each camera frame. In 3D-DIC, the main existing 3D reconstruction methods include the least-squares method (LSM), optimal method (OM), midpoint method (MM) and geometrical optimal method (GOM). The *iCorrVision-3D Correlation* module uses the LSM to perform the triangulation-principle-based 3D reconstruction. This method was employed due to its high computational efficiency with precision similar to other methods (OM, MM and GOM) studied in the literature [45]. The main principle of the 3D reconstruction is the correlation of the WCS with the master (MCCS) and slave (SCCS) camera coordinate system by solving the following system of equations

$$\mathbf{x}^w = \left[(\mathbf{M}^T \mathbf{M})^{-1} \mathbf{M}^T \right] \mathbf{b}, \quad (5)$$

where \mathbf{x}^w is the point in the WCS (written in MCCS) and \mathbf{M} and \mathbf{b} are functions of the intrinsic and extrinsic parameters obtained by calibration using *iCorrVision-3D Calibration* module. For further information, see Ref. [45].

As can be seen, the results were written in the WCS or MCCS (left camera). However, it is also important to rewrite the results in the specimen coordinate system, denoted by SPCS. This can be accomplished using the given referential transformation

$$\mathbf{x}^{sp} = \mathbf{R}_{sp}^{-1} (\mathbf{x}^w - \mathbf{t}^{sp}), \quad (6)$$

where \mathbf{x}^{sp} is the point in the SPCS and \mathbf{R}_{sp} and \mathbf{t}^{sp} are the rotation matrix and translation vector, respectively, between the WCS and SPCS.

2.2.4. Post-processing module

The out-of-plane post-processing was included in the *iCorrVision Post-processing* module presented in Part 1 (*iCorrVision-2D*, SoftwareX, 2022). It should be emphasized that the post-processing to handle out-of-plane measurements was constructed under the same computational basis of the in-plane post-processing module using the concept of strain window and local fitting regression. The end user can select the most appropriate Lagrange polynomial shape functions (bilinear or biquadratic) to fit the in-plane and out-of-plane full-field displacements inside the strain window. From this new release it is possible to compute the 3D reconstruction and the out-of-plane full-field displacements (x_{33} -direction) of samples subjected to experimental tests. Data are stored in both world coordinate system (WCS) and specimen coordinate system (SPCS). Therefore, the user does not need to perform further coordinate transformations for the visualization of results.

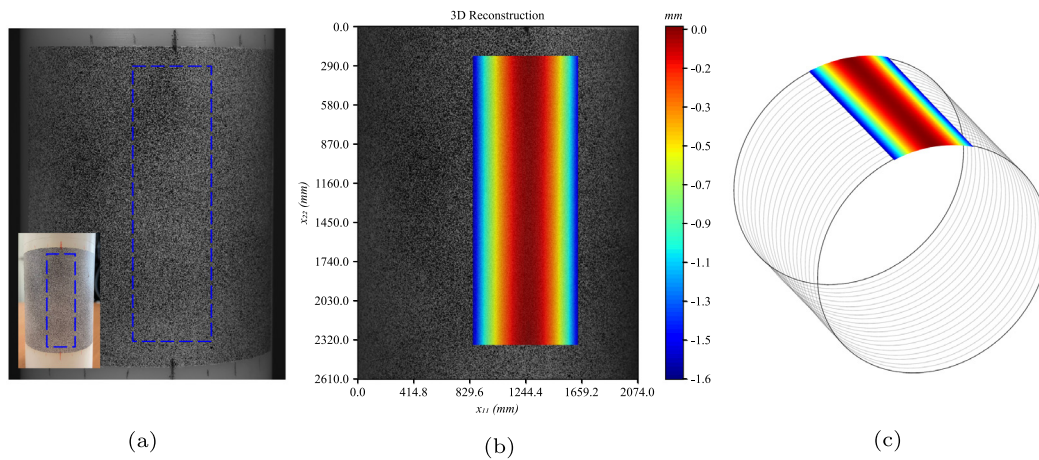


Fig. 5. (a) Considered ROI (780×2138 pixels²), (b) 3D reconstruction map evaluated by *iCorrVision-3D* and (c) 3D representation of the cylinder surface.

3. Illustrative example

The *iCorrVision-3D* software can be used in a great number of applications to obtain the 3D reconstruction of objects and evaluate both in-plane and out-of-plane displacement maps of specimens. An experimental static test was performed to reconstruct the 3D shape of a cylinder with known dimensions (52.2 ± 0.025 mm of diameter). The objective here is to estimate by stereo correlation the diameter of the cylinder. One stereo pair was captured to perform the stereo correlation and 100 stereo pairs of a checkerboard calibration pattern were acquired to perform the system calibration. The stereo image pairs can be captured using the *iCorrVision-3D Grabber* module with proper acquisition parameters. A 6.1-inch iPhone 11 (Apple Inc., USA) with (1792×828 pixels² – physical size of 140.65×64.99 mm²) was used to display the synthetic calibration pattern with 10×7 control points (corner points) with a regular square size of 6 mm. The *iCorrVision-3D Calibration* module was used to generate the calibration file to be used in the correlation module.

Fig. 5(a) illustrates the considered ROI located at the middle portion of the given cylinder. The stereo correlation was performed using the *iCorrVision-3D Correlation* module, considering a reference subset size for stereo correlation (RSS S) of 27 pixels, search subset size for stereo correlation (SSS S) of 401 pixels and subset step size (ST) of 2 pixels with no displacement filtering. The interpolation strategy was configured using the interpolation factors of $k_b = 2$ and $k_a = 40$. Fig. 5(b) illustrates the 3D shape reconstruction of the cylinder and the measured diameter was equivalent to 52.2006 ± 0.1290 mm obtained by the *iCorrVision-3D Post-processing* module. Therefore, a relative error of 0.0012% was obtained. As can be noticed, the *iCorrVision-3D* software can reconstruct the shape of the given object at the ROI domain with great precision, as shown in Fig. 5(c).

Apart from this illustrative example, several validation and benchmarking tests were addressed in Appendix A using the synthetic and experimental datasets of the Stereo-DIC Challenge [46]. The available case studies are required to certificate new 3D-DIC software and to maintain the project updated with regard to the new challenges proposed by the International Digital Image Correlation Society (iDICs). These tests should also be considered as illustrative examples of the proposed software.

4. Impact

The use of the 3D-DIC optical method is strictly recommended when the test piece is subjected to out-of-plane displacements or the surface of interest is not perfectly planar. Moreover, it

can also be used to reconstruct the 3D shape of objects. The great number of applications includes several engineering areas inserted in both academic and industrial/commercial workplaces. There are a few open-source 3D-DIC software available in the scientific community. Among them, almost none allow an integrated workflow with complete built-in modules responsible for image acquisition, calibration, correlation and post-processing. Usually, 3D-DIC open-source users are condemned to use other open-source software or licenced solutions to perform stereo DIC measurements. From the *iCorrVision-3D* software, this issue is solved by allowing a complete 3D-DIC workflow. *iCorrVision-3D* can be totally customized according to each test, since all main DIC setting parameters are open for modifications by the user from the GUI, including the interpolation strategy to reach sub-pixel level. A large number of scientific projects can benefit from this software and the spread of 3D-DIC measurements can be a consequence of the *iCorrVision-3D* software. In addition, the open-source algorithm can be continuous developed to optimize the existing modules and build up new features and functionalities to improve *iCorrVision-3D*.

5. Conclusions

iCorrVision-3D is an out-of-the-box fully-customizable open-source 3D Digital Image Correlation (3D-DIC) software that can be employed to extract the 3D reconstruction and evaluate the in-plane and out-of-plane displacement maps of specimens. This integrated python-based solution (stereo grabber, stereo calibration, stereo correlation and post-processing modules) was developed to maintain the whole DIC measurement analysis under the same computational chain, without the necessity of using other software for image acquisition, calibration and for visualization. The proposed software can be used in several applications in engineering and should assist the spread of 3D-DIC measurements in a great number of research fields. For instance, there are already some works being developed using *iCorrVision-3D* with regard to the material characterization of fiber-reinforced soft biological tissues. As a final remark, the implementation of high accuracy calibration models and the compatibility of different calibration patterns should be addressed in future works to improve the accuracy of the *iCorrVision-3D* software.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Joao Filho reports financial support was provided by

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Appendix A. Supplementary data

The validation and benchmarking tests of the *iCorrVision-3D* software can be found in Validation_iCorrVision3D.pdf.

Supplementary material related to this article can be found online at <https://doi.org/10.1016/j.softx.2022.101132>.

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