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iCorrVision-2D: An integrated python-based open-source Digital Image Correlation software for in-plane measurements (Part 1)

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ABSTRACT

The main purpose of this work is to present a new fully-customizable out-of-the-box open-source 2D Digital Image Correlation (2D-DIC) software, so-called *iCorrVision-2D*. It is implemented in Python, including image acquisition (grabber), numerical correlation and post-processing modules. The proposed software has an intuitive graphical user interface to support selecting all main correlation parameters, calibration and region of interest. The *iCorrVision-2D* software stands out over other open-source projects due to the great number of functionalities and the control of all important inputs, such as correlation domain, approach (spatial and incremental) and matching criterion, displacement filtering, interpolation techniques, strain window and reconstruction shape functions. Results demonstrate that the *iCorrVision-2D* software is robust and can be used to measure full-field displacements and strains with satisfactory accuracy and precision. For out-of-plane measurements, *iCorrVision-3D* will be presented in Part 2 (*iCorrVision-3D*, SoftwareX, 2022).

Code metadata

Current code version	V1.04.22
Permanent link to code/repository used for this code version	https://github.com/ElsevierSoftwareX/SOFTX-D-22-00075
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 *requirements.txt* file is provided
If available Link to developer documentation/manual	https://github.com/jcadf/iCorrVision_2D/tree/main/UserGuide
Support email for questions	joaocadf@id.uff.br, luizcsn@id.uff.br, jmc.xavier@fct.unl.pt

1. Motivation and significance

In the onset of the digital revolution era, image-based technologies have been emerging. These technological developments have unfold several full-field optical techniques (FFOTs) for solid and fluid mechanics [1]. These methods provide contactless, field information in contrast with counterpart devices from which a single scalar quantity can be measured. Accordingly, the assessment of field measurements has brought novel insights into computational and experimental solid mechanics, levelling both numerical and experimental approaches [2]. Due to their increasingly utilization, the metrology, standardization, uncertainty quantification and conformity assessment are still under great developments to attend industrial and research demands. Therefore, to consolidate these advanced experimental techniques, their metrological assessment have been continuously addressed [3,4].

The Digital Image Correlation (DIC) is a confirmed non-contact optical method in experimental mechanics used to evaluate full-field deformation measurements [5]. DIC has been typically developed using a subset-based approach (local DIC) [6], in contrast with both finite element-based (global DIC) [7] or Fourier-based approaches [8]. In recent years, there have been an increased

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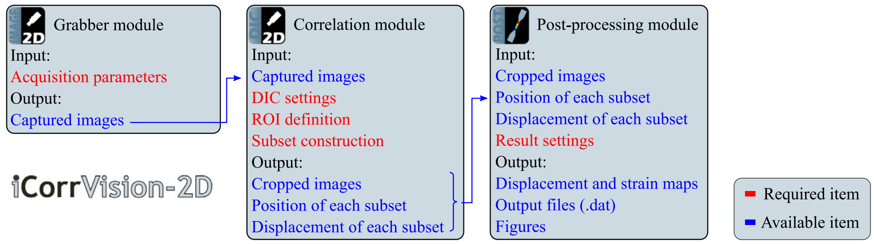


Fig. 1. Workflow of the *iCorrVision-2D* software.

number of papers, reported in the literature, referring to DIC [9]. This method is rather flexible, less expensive than interferometric counterparts and has been applied on several applications, over a large spectrum of length scales. DIC has been used to address in-situ monitoring measurements [10], non-destructive tests [11] and for damage evaluation [12]. Besides, tension [13], compression [14] and shear [15–17] classical tests have been coupled with DIC to enhance data reduction. Moreover, full-field data, as provided by DIC, has been the foundation of a new generation of mechanical tests dealing with inverse material parameter identification from single test configurations [18,19]. Furthermore, the complex behaviour of soft tissues have been investigated [20] and several fracture tests were analysed based on post-processed DIC displacement fields [21]. It is known that the latter is one of the most challenging experimental tests due to kinematic discontinuity fields and DIC has been gaining ground in the scientific community of fracture mechanics, mainly in $\mathcal{J}$-Integral and cohesive law estimations [22,23].

There are already a number of commercial DIC solutions available in the market, including *Correlated Solutions* [24], *GOM* [25], *MatchID* [26] and *LaVision* [27]. They typically meet the requirements of an out-of-the box solution to the end user, even if, most often, at the cost of black box procedures. However, from an academic perspective, these software can be expensive and often the back-end structure of the algorithms is not completely understood or available for users. Consequently, there have been a growing interest among the scientific community in developing both open-source and free access DIC software to overcome these limitations, as, for instance, *Digital Image Correlation Engine* (*DICe*) [28], *NCorr* [29], *py2DIC* [30,31], *μ DIC* [32], *RealPi2dDIC* [33], *ADIC2D* [34], *YADICS* [35] and *ALDIC* [36]. Nevertheless, among these solutions, some free access codes were written on licensed platforms (*e.g.*, *NCorr* [29], *ADIC2D* [34] and *ALDIC* [36]) or have limited capabilities with regard to professional versions. Moreover, the open-source solutions most often do not provide a fully integrated DIC measurement ecosystem including image acquisition, image calibration, and further post-processing for data analysis. On the other hand, some important DIC setting parameters including, for instance, sub-pixel interpolation factor are not open for modifications among the closed-source software. Taking into account the open-source projects, such modifications should be addressed in the source code. Therefore, the end user must have prior knowledge of computational languages to adapt the interpolation algorithm. In this context, there is still a gap within open-source DIC projects in fulfilling a complete system, with direct full access of main setting parameters from an intuitive interface and integrating the whole chain of measurements from image acquisition to post-processing modules. The *iCorrVision-2D* software has been developed to address these issues.

iCorrVision-2D is a complete fully-customizable open-source two-dimensional DIC software. Both front- and back-end structures were written in the Python computational language. The package includes image acquisition (grabber), correlation and post-processing modules. The correlation algorithm was implemented using the subset-based approach structured under a parallel computing strategy to reduce computational time. The software was developed and organized to highlight and give access to all relevant parameters required in a DIC analysis, which can be easily controlled and modified by the user. *iCorrVision-2D* can be used to evaluate the displacement and strain full-field maps in several academic, commercial and industrial applications. For instance, *iCorrVision-2D* was already used to assist material characterization [37], investigate the deformation homogeneity of mechanical samples [15,16] and perform $\mathcal{J}$-Integral and kinematic parameters estimation from fracture tests [22,38].

2. Software description

The front- and back-end structures of the *iCorrVision-2D* software were written in Python, which is a dynamic, open-source and object-oriented computational language widely used in several engineering projects. Due to the large open-source image processing and visualization libraries, such as *OpenCV* [39] and *Matplotlib* [40], respectively, the use of Python is justified in this software. Three modules (grabber, correlation and post-processing) were embedded into an integrated user-friendly graphical interface that was designed to maintain the project intuitive for the user. The advantage of this approach is that an unique platform can be used to cover the whole workflow when carrying out DIC measurements and analyses. The code was organized as a package with modules wrapped in a single source file. Moreover, to handle the project dependencies, a requirement file is provided to create a suitable virtual environment. Nevertheless, it can also be easily assessed from executable files (.exe) that are also available in the project repository.

2.1. Software architecture

The *iCorrVision-2D* software was developed under three integrated modules: (1) image acquisition module, responsible for capturing a sequence of images during a given event or experimental test; (2) digital image correlation module, in which the image correlation among the data set is actually carried out; and (3) post-processing module, used to reconstruct strain maps. Fig. 1 illustrates the software workflow from image acquisition to the visualization of results.

2.2. Software functionalities

The functionalities of each module is covered in the following subsections.

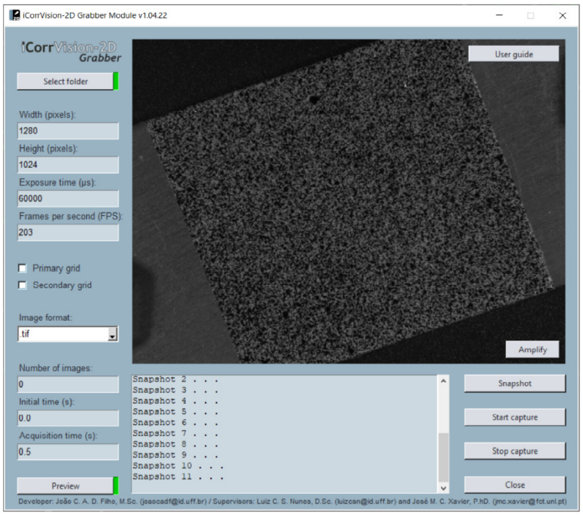


Fig. 2. *iCorrVision-2D Grabber* module.

2.2.1. Grabber module

The *iCorrVision-2D Grabber* for image acquisition with a single camera is presented in this section. The main relevance of this module is to provide a complete platform for image capture. Fig. 2 illustrates the GUI of the *iCorrVision-2D Grabber* module. As it can be seen, the user can adjust the relevant acquisition parameters, such as the width and height of captured images in pixels, the pixel exposure time, the frequency in frames per second (FPS), the image format and the acquisition time in seconds. The latter is sensible to the exposure time and frequency. Acquisition can be configured to capture images at the beginning with different time intervals. This functionality is welcome when the user needs more information at the beginning of a test. This module was constructed using the open-source *pypylon* library available for Basler USB3.0 cameras customers [41]. Nevertheless, it is important to highlight that the software has the potential to integrate other camera drivers with support to Python. The end user should have enough computational knowledge to perform such modification.

2.2.2. Correlation module

The image correlation itself can be addressed by the *iCorrVision-2D Correlation* module, shown in Fig. 3. From this module the user has total control of several important parameters, such as reference subset size (RSS), search subset size (SSS), number of steps (Nx and Ny in x_{11}- and x_{22}-directions, respectively), subset step size (ST), interpolation strategy, calibration, angle adjustment, in which all captured images can be rotated before correlation considering a given angle in degrees, displacement filtering, contrast adjustment, configuration selection, that can be selected between Eulerian and Lagrangian approaches, correlation function, template selection and correlation criterion. It is worth mentioning that some of these key setting parameters are just neither available nor intuitive to users on several open-source or commercial DIC software. The level of customization was prioritized in the current project. Therefore, the correlation can be fully-tuned according to each case study. Moreover, a parallel computing was implemented and the number of processors (threads) can be also selected by the user.

The proposed module is a subset-based local DIC, in which the region of interest (ROI) is discretized in subregions (subsets) where the correlation is carried out at different deformation stages. The *iCorrVision-2D Correlation* module has an integrated ROI selection interface where the subsets can be constructed. Among stages, images can be correlated spatially either with regard to the reference image (undeformed configuration) or incrementally, by matching the current image with an updated reference image. The incremental approach should be avoided when possible, since the measurement error is accumulated at each step in the iterative algorithm. Usually, the incremental matching should be only used when large deformations are observed in such a way that the deformed subregion can no longer be recognized (decorrelation issues will occur) [42].

The `cv2.matchTemplate` function available in the *OpenCV* library was used in this module [39]. It allows the selection of the most appropriate correlation function and criterion to be considered in the image correlation. It should be highlighted that this function has already been used in other open-source solutions, such as *py2DIC* [30,31]. Figs. 4(a) and 4(b) illustrate the bi-cubic spline interpolation that can be used to reach subpixel accuracy. It is known that the use of such interpolation function can lead to lower systematic errors [43,44]. The captured image can be resized before carrying out the correlation by means of the k_b factor (see Fig. 4(a)). Besides, the correlation coefficient matrix can be interpolated using a factor of k_a and a kernel size of 5×5 pixels^2 to refine the position of the peak of correlation according to the selected criterion. It is pointed out that the interpolation strategy is not typically available for modifications among commercial and open-source software.

The rigid shape function is used in the *iCorrVision-2D Correlation* module to compute the full-field displacement ($\mathbf{u}$) as follows

$$\mathbf{u} = \mathbf{x} - \mathbf{X}, \tag{1}$$

where $\mathbf{X}$ is the reference configuration (position) vector and $\mathbf{x}$ is the current (deformed) configuration vector. Since the subset-based local DIC is used, the discrete displacement can be noisy. Nevertheless, in order to overcome this limitation, a filtering algorithm can be applied to smooth out the displacement signal using a gaussian kernel with preselected size.

2.3. Post-processing module

One facility of the *iCorrVision-2D* software is the complete integrated visualization module. Fig. 5 shows the *iCorrVision Post-processing* module in which all important parameters for visualization of the correlation and kinematic fields can be selected. For instance, using this module it is possible to control the appropriate strain window and the reconstruction shape function to compute full-field strain from displacements. The bilinear (Q4) and biquadratic (Q9) Lagrange polynomial shape functions can be used to numerically approximate the in-plane displacement fields inside the strain window, according to the respective expressions,

$$u_{ii}^{Q4} = a_{ii} + b_{ii}m + c_{ii}n + d_{ii}mn \text{ and} \tag{2}$$

$$u_{ii}^{Q9} = u_{ii}^{Q4}(m,n) + e_{ii}m^2 + f_{ii}n^2 + g_{ii}m^2n + h_{ii}mn^2 + i_{ii}m^2n^2, \tag{3}$$

where (m, n) is the centroid of the strain window and $a_{ii} - i_{ii}$, with $i = 1, 2$, are the polynomial coefficients. The 4 $(a - d)$ and 9 $(a - i)$ coefficients of the bilinear and biquadratic shape functions, respectively, are estimated in this post-processing module using the non-linear least squares method addressed by the `scipy.optimize.curve_fit` function, available in the *sciPy* optimization library [45]. From the adjusted displacements, the strains can be theoretically obtained using the Green Lagrangian strain tensor as follows

$$\mathbf{E} = \frac{1}{2}(\mathbf{F}^T\mathbf{F} - \mathbf{I}) \text{ with } \mathbf{F} = \partial\mathbf{u}/\partial\mathbf{X} + \mathbf{I}, \tag{4}$$

where $\mathbf{F}$ is the deformation gradient tensor and $\mathbf{I}$ is the identity matrix. It is known that the gradients are extremely sensible to the reconstruction shape function and the size of the strain window. Therefore, care must be taken by the user when adjusting these parameters.

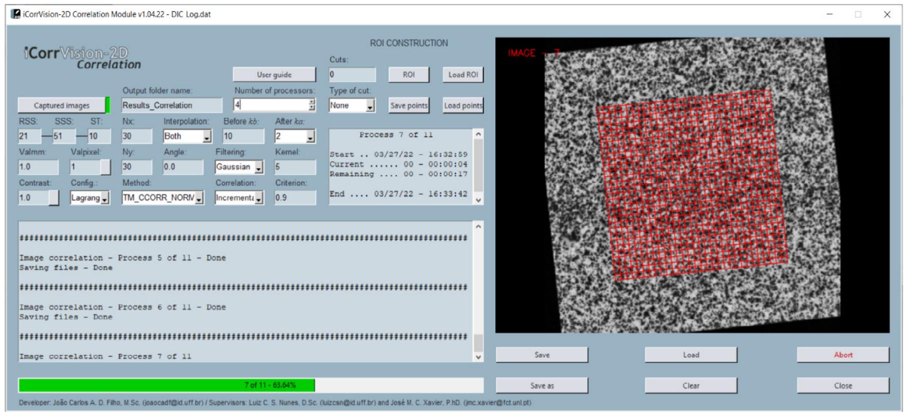


Fig. 3. *iCorrVision-2D Correlation* module.

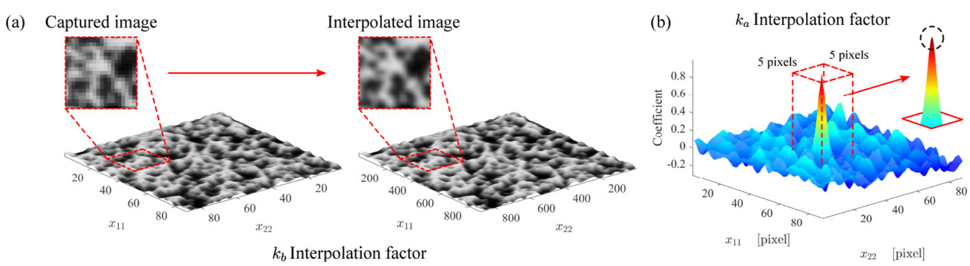


Fig. 4. Interpolation strategy of *iCorrVision-2D Correlation* module using bi-cubic spline interpolation. (a) Captured image interpolation and (b) correlation coefficient matrix interpolation.

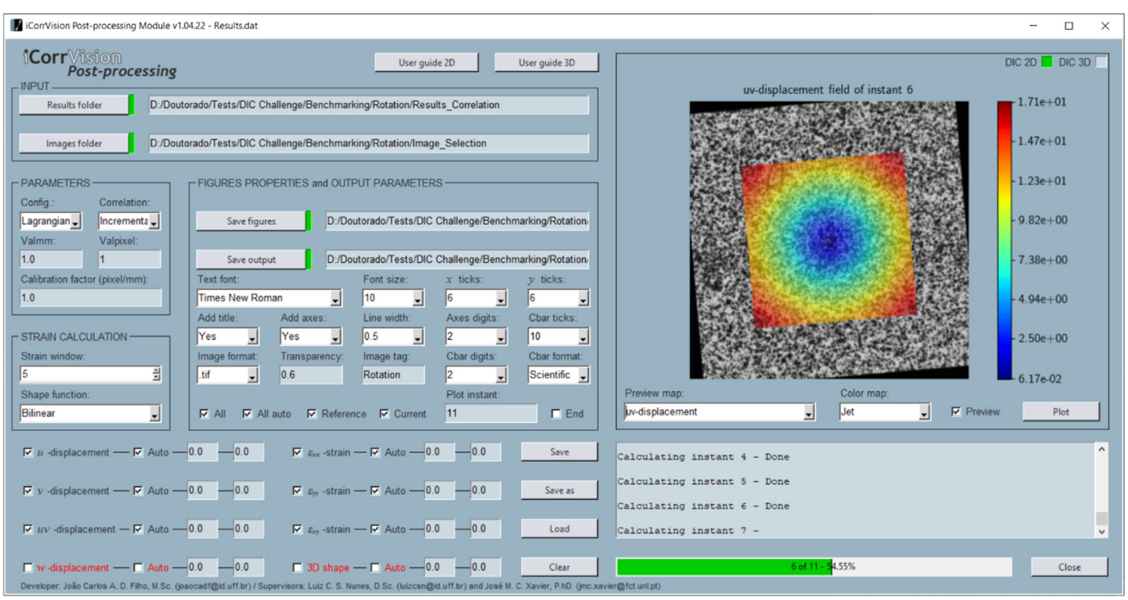
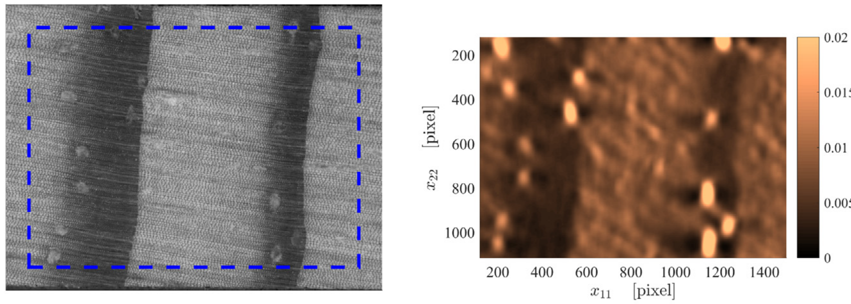


Fig. 5. *iCorrVision Post-processing* module.

3. Illustrative example

Since one of the main applications of DIC with regard to experimental mechanics is the material characterization, an experimental tensile test was used as an illustrative example of *iCorrVision-2D*. Here, the reconstruction of the heterogeneous strain fields, generated by the morphology of a biological tissue under a uniaxial loading, was studied. The *iCorrVision-2D Grabber* module can be used to capture sequential set of images (.tiff) using a single high resolution camera and predefined acquisition parameters (image width, height, format and frequency of acquisition). In particular, the purpose was to analyse the reconstruction of the gradient fields across a gauge section of about 7 × 5 mm^2 on the transverse plane of *Pinus pinaster* Ait. wood when submitted to a uniaxial tensile stress state [46]. Fig. 6(a) illustrates the growth ring structure and considered ROI (blue dashed rectangle). The correlation was performed using the *iCorrVision-2D Correlation* module using the reference and deformed captured images with the DIC settings identified in



(a) (b)

Fig. 6. (a) Growth ring structure with depicted ROI (1424 × 1036 pixels^2) and (b) ϵ_{11}-strain of the *Pinus pinaster* Ait. wood case study evaluated by *iCorrVision-2D*.

Table 1
DIC settings used to configure the *iCorrVision-2D Correlation* module.

DIC setting parameter	Value
Reference subset size (RSS)	21 pixels
Search subset size (SSS)	121 pixels
Number of steps in x_{11}- and x_{22}-directions	(142,103)
Subset step size (ST)	10 pixels
Calibration (Valpixel) and (Valmm)	1 pixel/1 mm
Displacement filtering	None
Correlation function	Normalized Cross Correlation
Correlation criterion	0.9
Interpolation factor	$k_b = k_a = 10$
Configuration	Lagrangian
Correlation approach	Spatial
Angle of rotation	0°

Table 1. The calibration itself was carried out using a simple conversion from pixel to mm.

After carrying out the correlation, the user can configure the *iCorrVision Post-processing* module to extract the displacement and strain full-field maps. The output of the *iCorrVision-2D Correlation* module was uploaded and the strain calculation parameters, figures properties and output parameters were selected. Taking into account this illustrative example, the strain window (SW) of 5 pixels and the bilinear (Q4) shape function (SF) were considered. Fig. 6(a) depicts the ϵ_{11}-strain field signal reconstruction obtained from *iCorrVision-2D* without displacement filtering. It is clear that the growth ring structure can be easily observed through the reconstructed signal (for further information, see Ref. [46]).

Besides, an extensive validation was performed in Appendix A using the challenges proposed by the International Digital Image Correlation Society (iDICs) that are especially recommended to certificate new DIC algorithms [3,4]. The additional case studies in Appendix A can also illustrate the capabilities and functionalities of *iCorrVision-2D*.

4. Impact

The *iCorrVision-2D* software can be implemented in several academic, commercial and industrial workplaces. For instance, this powerful easy-to-use Digital Image Correlation software can be used to evaluate the in-plane displacement and strain full-fields to perform the characterization of new materials, in-situ monitoring, fracture analysis and reconstruction of inhomogeneous morphology of particular materials (biological tissues and composites). Great effort has been made in this work to develop a complete integrated fully-customizable software with an intuitive GUI, including the grabber, correlation and post-processing modules. All main DIC settings are available for modifications by the user. The main purpose here is to provide the total control of the DIC settings using a simplified out-of-the-box solution. Taking into account the correlation module, the parallel computing was implemented to reduce the computational time. From the built-in modules, there are no need of third-party instances to perform the image acquisition and post-processing of data. Furthermore, no programming skills are required for the users of *iCorrVision-2D* as a ready-to-use executable file is also provided in the software repository. Since *iCorrVision-2D* is an open-source software developed in Python, continuous development can be carried out by external users to improve the existing modules and include new features. Also, new camera libraries with support to Python can be integrated in the grabber module to increase the range of compatible cameras.

5. Conclusions

This work addressed the development of a fully-customizable open-source two-dimensional Digital Image Correlation (2D-DIC) software, named *iCorrVision-2D*. The proposed software was entirely coded in Python, which is an interpreted high-level general-purpose programming language. All main DIC settings can be controlled by the user from an easy-to-use GUI. A frame grabber and post-processing modules were also developed for image acquisition and data visualization, respectively, without the necessity of using third-party software. The development of this software was a first milestone of the roadmap towards the development of an open-source 3D-DIC project, that is covered in the second part of this work. Additionally, to investigate the potentialities of *iCorrVision-2D*, some real lab tests can be performed in future works.

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 Coordination of Higher Education Personnel Improvement. Jose Xavier reports financial support was provided by Foundation for Science and Technology.

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Appendix A. Supplementary data

The validation tests of the *iCorrVision-2D* software can be found in Validation_iCorrVision2D.pdf.

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.softx.2022.101131.

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