OPERATING INSTRUCTIONS RICO (Regularized Isochromatic Phase Map Computation) PROGRAMME

VERSION 2.0, March 2009

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Introduction

This document accompanies a new piece of software produced as a result of a research and cooperation between the Department of Mechanical Engineering at the Michigan State University (USA), the Department of Signal Theory and Communication at the Universidad de Alcalá (Spain), the University of Jaén (Spain) and the Politecnico di Milano (Italy). The software is intended to be complementary to previous software called 'COPA' described in [1]. The new software 'RICO' is more robust than COPA, since it can process correctly more complex photoelastic data, but the processing time is rather longer. It is based on a new algorithm which is described in [2]. The objective, as in COPA, is to process phase-stepped photoelastic images acquired in either a transmission or reflection polariscope, to obtain the unwrapped and continuous isochromatic fringe map. The input for the software are the six phase-shifted images obtained with the method developed by Patterson and Wang [3]. These six images can be opened in four different formats ('.six', '.cpa', '.mat' and '.bmp'), and the data output can be produced in several forms as described below (as images, profiles, '.txt' data matrixes or as '.mat').

Installation

The current RICO program is written in Matlab®, therefore you need to have the Matlab program installed in your computer.

Copy the RICO directory into any directory of your choice in your computer (a listing of the necessary files are shown in the Appendix). Open Matlab and select as 'Current Directory:' the RICO directory, or set a path to it (press 'File', 'Set path…', …). Write RICO in the Matlab command line and press enter. RICO Graphic User Interface (GUI) will appear as shown in Fig. 1.

Operation

To process photoelastic images, start from the top left and work leftwards and down using at least one button in each dark grey zone (see Fig. 1). The results of each operation will be shown in the figure space in the bottom left of the window and a red caption below the figure will give an instruction on what to do next.

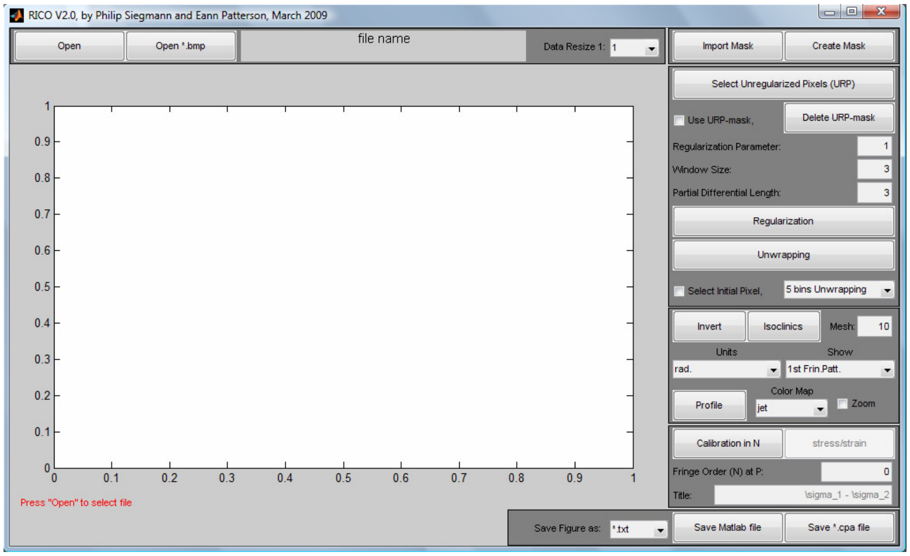


Fig. 1. The Matlab Graphic's User Interface (GUI) for the RICO program.

Data Acquisition

Data should be acquired using the six phase shifted fringe pattern from Patterson and Wang [3]. This six images can then be saved either as an '.six' file using the 'Catchsix' program, or also separately in six different '.bmp' files but enumerating each '.bmp' filename with the corresponding sequence number at the end of the filename, i.e.:

'filename1.bmp', 'filename2.bmp',…, 'filename6.bmp',

and all of them with the same 'filename'.

Other files that can be opened with RICO are: '.cpa' and '.mat' files. The '.cpa' file is created by RICO once the photoelastic data is opened, the advantage of using '.cpa' is that in this file the 'mask' and the 'URP-mask' are also saved. These two masks are explained in the following sections (Background Removal / Applying a Mask and Select the pixels that do not need to be regularized). It is also possible to open the six images saved in a '.mat' file (using Matlab), here you have to define a 3-dim matrix called 'six' in the following way:

$$six(:,:,1)=I_1,\ six(:,:,2)=I_2,\ldots,\ six(:,:,6)=I_6,$$

where I_1, I_2, …I_6 are the six phase-shifted images. If this matrix is saved as a '.mat' file, it can then be opened with RICO.

Use the ‘Open’ button to identify the appropriate file. Use ‘Open *.bmp’ button to identify the ‘.bmp’ files. Here you have to press ‘Control’ and, at the same time, select with the mouse the six ‘.bmp’ files.

After selecting the file to be opened the six phase-shifted fringe pattern images will be displayed in a new window. This window is removed automatically after a few seconds, and the first (dark field) fringe pattern is displayed in pseudo colour in the main window as shown in Fig. 2. Using the ‘Color Map’ drop down menu, three different color maps of the displayed figure can be selected (grey scale, and pseudo color: ‘jet’, and ‘hsv’)

Because of the slower processing time compared to the COPA program, RICO has the option to reduce the resolution of the data. Before opening the data you have to select the option using the drop-down menu ‘Data Resize 1:’ and the amount of reduction. If 1:1 is selected then there is no change in the resolution (default); if 1:0.75 is selected then the data resolution is reduced by 25%; if 1:0.5 is selected, then the data is reduced to half the resolution of the original data; and if 1:0.25 is selected, then the data resolution is reduced 75%. In Fig. 2 the data size has been reduced by 50%.

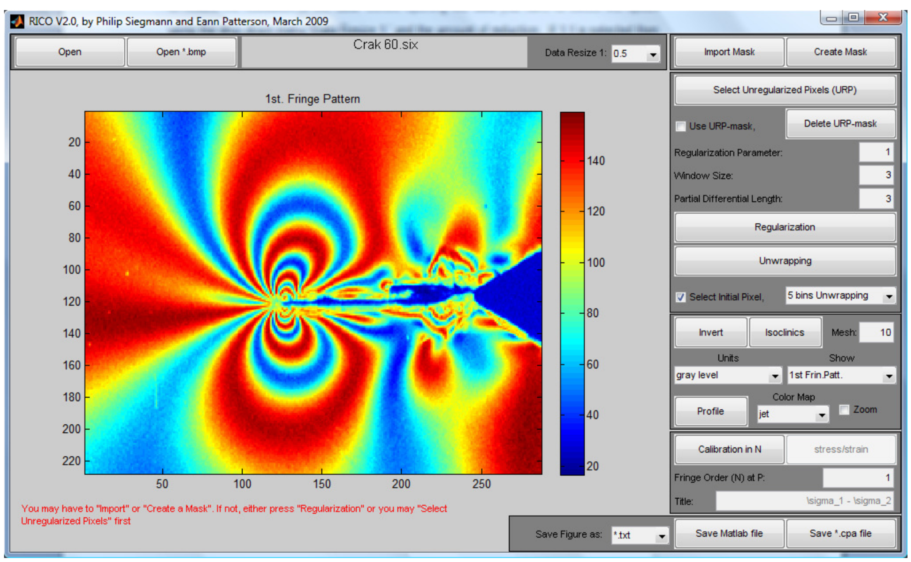


Fig. 2. After pressing ‘Open’ the dark field fringe pattern is displayed in pseudo colour. The resolution of the data has been reduced using 1:0.5, i.e. by 50%.

Background Removal / Applying a Mask

The dark grey box in the top right corner of the main window offers two choices: importing a mask or creating a new one. A mask that has been created by ‘Catchsix’ can be imported by opening a ‘.bng’ file via the ‘Import mask’ button. The mask is applied automatically and the background in the image will be removed in the figure displayed in the window. The data saved as '.cpa' may have included the mask and is therefore also loaded automatically by opening this kind of file. (The '.cpa' file, like a '.six' file, is an adapted '.bmp' file, but with a mask included).

Alternatively, a new mask can be created by pressing the 'Create Mask' button. A new window will appear (see Fig. 3) with the image corresponding to a dark field circular polariscope on the left and a series of buttons on the right. Here you can change the image used to create the mask, you can choose to define a mask using a circle, a polygon or any combination of these shapes. Select the required shape and follow the on-screen instructions. It is possible to cut out and enlarge an area of the image using the 'Cut out' button to define the area of interest. Once a shape has been defined you must indicate whether the area to be masked is inside or outside the shape using the buttons: 'Mask inside' or 'Mask outside' respectively. Press 'Finished Mask' to return to the main window. It is possible to use the functions repeatedly to build a complex shape for the mask. If a mistake is made you can either click the right mouse button during the input of points, or close the 'create mask' window without pressing 'Finished Mask' and start again.

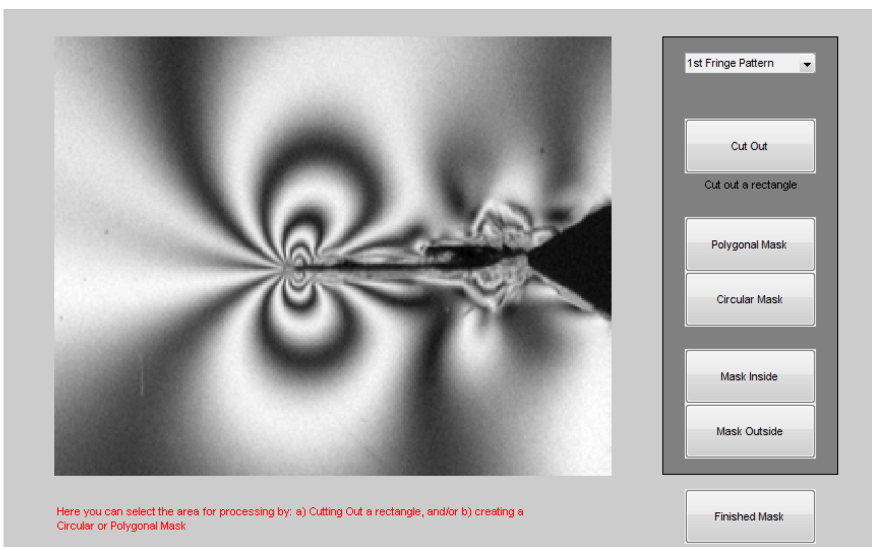


Fig. 3. The window that appears after pressing the 'Create Mask' button and which is used to create a mask.

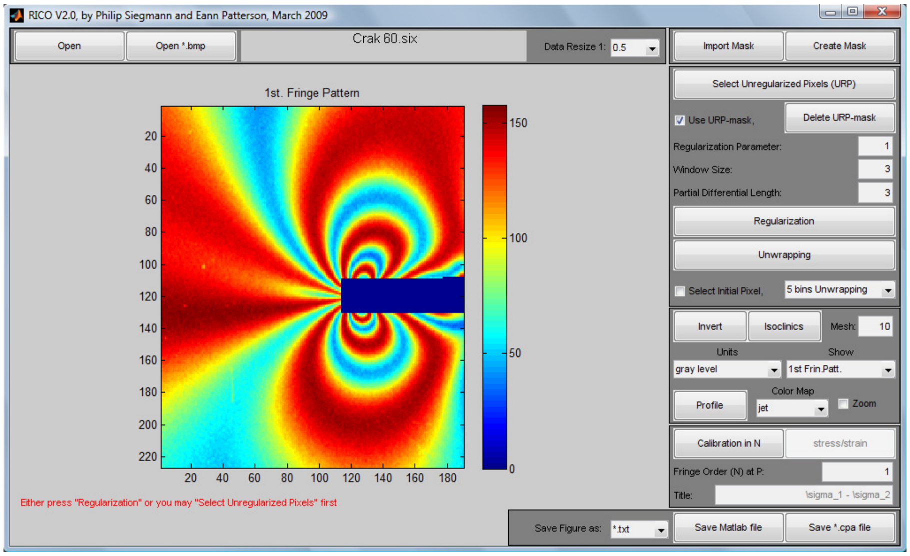


Fig. 4. Example of data that has been ‘cut’ and a mask applied.

Select the pixels that don’t need to be regularized (Optional)

In COPA the pixels are processed area-by-area and it is therefore faster than RICO which processes the image pixel by pixel. To reduce the processing time there is the option to create a mask to select pixels that do not need to be regularised (i.e. their relative retardation value does not need to be changed). This mask is called ‘URP-mask’ and is created by pressing ‘Select Unregularized Pixels’ in a similar way as the previous mask used for removing the background (see Fig. 5). It is recommended that you read the appendix to learn how to define the boundary of this mask, because you need to have some knowledge about the behaviour of the expected solution. The use of the URP-mask is optional, therefore tick the box ‘Use URP-mask’ if you want to use it in the following regularization process. Leave it unticked if you don’t want to use it. If this checkbox is activated and there is no URP-mask, the Regularization process is not performed. To delete the URP-mask press ‘Delete URP-mask’.

Note that the URP-mask, with the mask and the six phase shifted images, can be saved in the “.cpa” file.

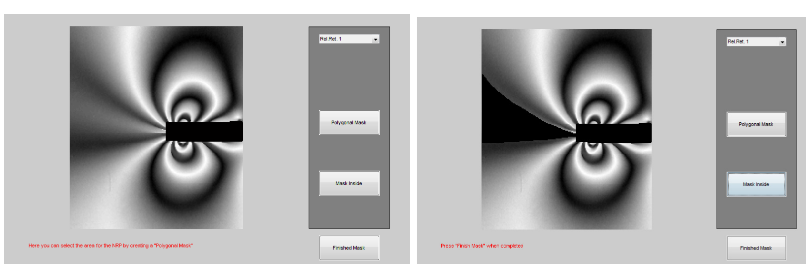


Fig. 5. Without URP-mask (left),and with URP-mask (right).

Regularization process (to obtain the Wrapped Relative Retardation)

The next step is to introduce the parameters used for the regularization process:

1. The Regularization Parameter (L_u),
2. The Window Size (w) used for the spatial dependence. The real window size is (2w+1)x(2w+1) pixels.
3. The Partial Differential Length, for calculating the partial derivatives, (Units are pixels).

These parameters are defined and discussed in more detail by Siegmann et al [2]. The Window Size and the Partial Differential Length must non-zero, positive, integer values.

There is not a specific criterion for selecting the best parameters. However there is a dependence on the fringe density (i.e the rate of change relative retardation), the noise and the resolution.

The viable value of the Regularization Parameter lies between 0.1 and 4 (approx.), and varies with the fringe density, i.e. a higher fringe density requires a higher value (above ~2).

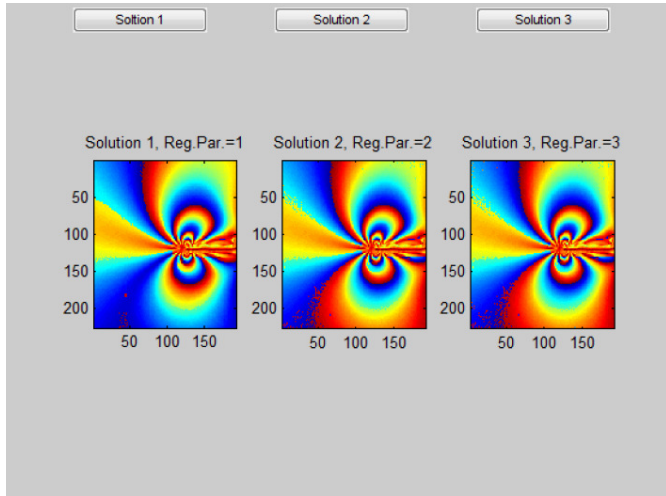
The Window Size is also dependent on the noise, resolution, and fringe density; with more noise and lower fringe density, the Window Size should be larger. Typical values are between 2 and 7 (approx.).

The Partial Differential Length has the same dependence on the noise and the fringe density as the Window Size, and the possible value also lies between 2 and 7 (approx.).

For each of the parameters there is normally a range of valid values and this range may be more or less restricted depending on the nature of the data. In particular, data or areas within the data with low fringe density may introduce noise that the effect of which can be reduced with lower values of the Regularization Parameter; but low values of this parameter may introduce errors because of the lack of recognition of the abrupt phase-changes in the relative retardation (necessary for removal of the ambiguity problem). In this case the user has to play with all the parameters, and the use of URP-mask can be very helpful.

The regularization process is then performed by pressing the 'Regularization' button. After the processing (this may take a long time depending on the data size) three different solutions are shown using three different Regularization Parameters: the value introduced by the user, L_u ,

(L_u +1) and (L_u +2). The user has to select the correct one (see Fig. 6) by clicking on the corresponding 'Solution 1, 2 or 3' button. In the example shown in Fig. 6, solutions 2 and 3 are correct; and by pressing 'Solution 2', the corresponding image is displayed in the main window as shown in Fig. 7 in gray scale.



.Fig. 6. Three possible solutions for the wrapped relative retardation using three different regularization parameters. The user has to select the correct one (in this case solution 2 and 3 are both correct).

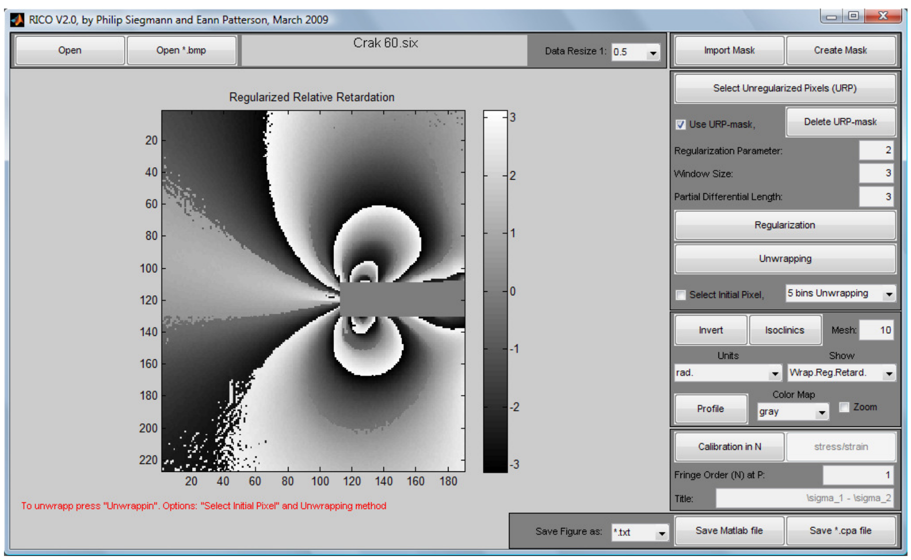


Fig. 7. The selected regularized relative retardation (here shown in grey scale) is wrapped.

Unwrapping process

The relative retardation is periodic or wrapped and must be unwrapped to generate a continuous map of isochromatic fringe order. This process is performed when the 'Unwrapping' button is pressed. The process can be performed completely automatically with the seed point being selected as the pixel having the highest quality. To select the seed point manually (for both, regularization and unwrapping) tick the box 'Select Initial Pixel' and a temporary window will appear after pressing ‘Unwrapping’. In this window the quality map is displayed in grey scale for each pixel, darker pixels have a lower quality value.

For more accurate but slower unwrapping the quality map can be divided into a large number of partitions by using the drop-down menu under the ‘Unwrapping’ button:

Select ‘5 bins Unwrapping’ for a faster unwrapping, for more precise but slower unwrapping select ‘10 or 100 bins Unwrapping’. The respective quality maps can be seen when the option of ‘Select Initial Pixel’ is activated. For noisier data, more bins should be considered for the unwrapping.

The unwrapped (continuous) map of isochromatic fringe order is displayed in the figure in the main window at the end the process (see Fig. 8(a)).

There is some ambiguity in the selection of the initial pixels for the regularization process and hence in the solution for the isochromatic fringe order, such that the resultant map maybe inverted – simply press the ‘Invert’ button to reverse the distribution (see Fig. 8).

(a) (b)

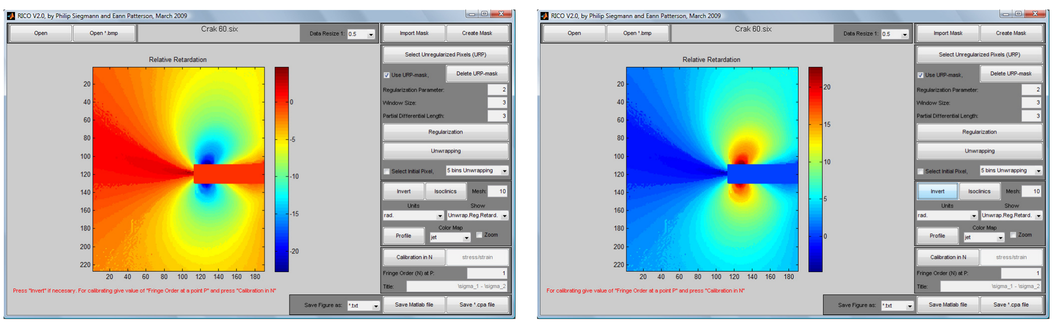


Fig. 8. (a) Unwrapped relative retardation, (b) Inverted unwrapped relative retardation.

Calibration

The unwrapped isochromatic phase map require calibration. Enter the value of the fringe order you intend to use for calibration in the box in the dark grey zone in the bottom right corner of the main window ‘Fringe Order (N) at P:’. The use of half order or integer fringes is recommended (default is 1). Then, press the ‘Calibration in N’ button and a temporary window will appear with a display of ¼ order contours as shown in Fig. 9. Select a point on an appropriate contour with the mouse and right click. To assist in the selection of the calibration point it is recommended to display also the ‘Intensity Image #1’ in the main window using the drop down menu ‘Show’. The calibrated isochromatic fringe map is shown in Fig. 10. The calibration process can be performed as many times as necessary.

Subsequently a map of maximum shear stress or strain (i.e. difference in principal values) can be generated by performing a further calibration. Again enter the value of the stress or strain metric in the same box now called 'Stress/strain at P:', but also type in the title with the appropriate units in the box below called 'Title:', then press the 'Calib. Stress/strain' button and select the point at which the stress or strain is known. This might be the same or a different point to the one used for the fringe order calibration.

Once the calibration has been completed, the 'Units' of the figure shown cannot be changed. The calibration is lost when a figure is selected by using the drop down menu 'Show', or when the unwrapping or regularization is performed afresh.

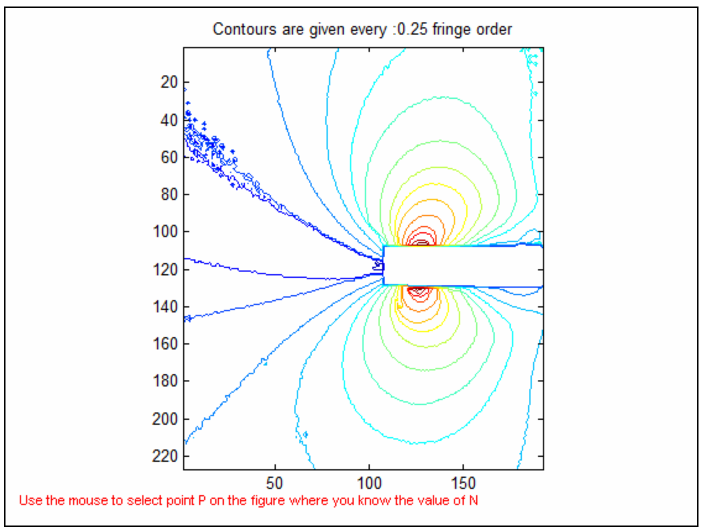


Fig. 9. Temporary window with a display of ¼ order contours.

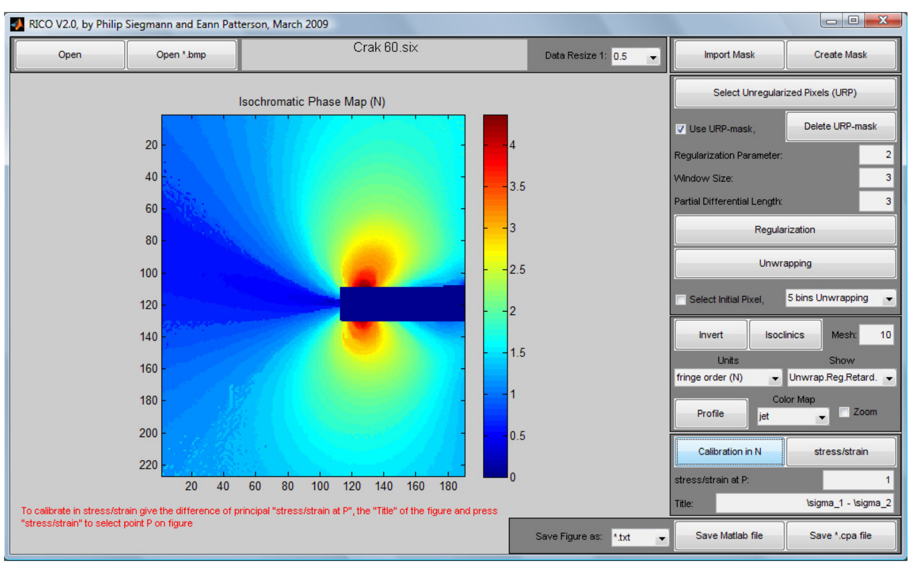


Fig. 10.Calibrated isochromatic fringe map.

Isoclinic Vector field

By pressing the "Isoclincs" button, the vector field of the principal stress differences are shown at a mesh of pixels on the current figure as shown in Fig. 11. The mesh size can be selected by giving the amount of pixels in x or y direction in "Mesh: …", the default value is 11. The shown vector field can be removed by pressing the "Visible off" button that appears on the top right of the figure.

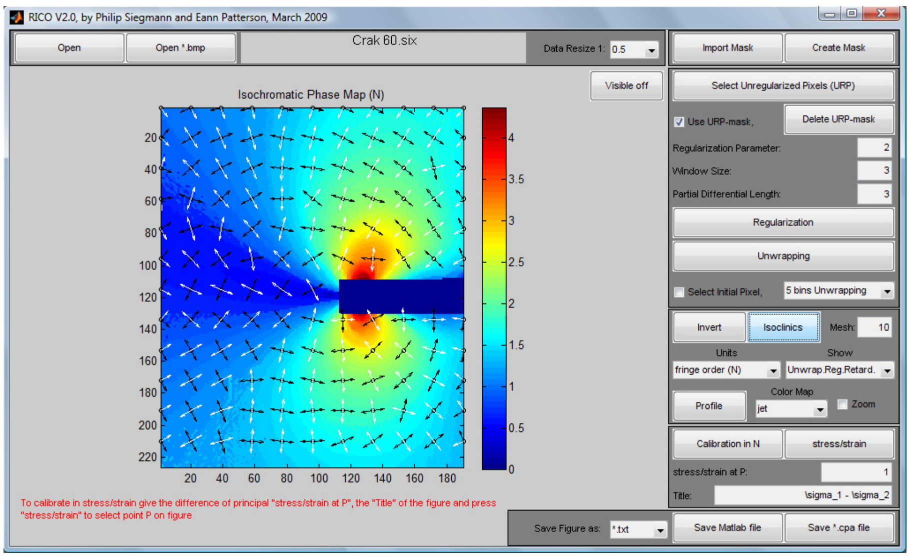


Fig. 11. Isoclinic Vector Field displayed on the Isochromatic Phase Map

Profile Display

Profiles across the data displayed in the figure can be obtained by pressing the 'Profile' button and then left clicking on a start point in the map followed by a left click of the end point of the desired profile followed by pressing the 'Enter' key. As Shown in Fig. 12, a window is displayed with the plot of the data as a function of pixel location along the profile. This profile can also be saved as image or as data in a '.txt' format with three columns: x-position, y-position and z-profile high by pressing the corresponding buttons on the profile widow.

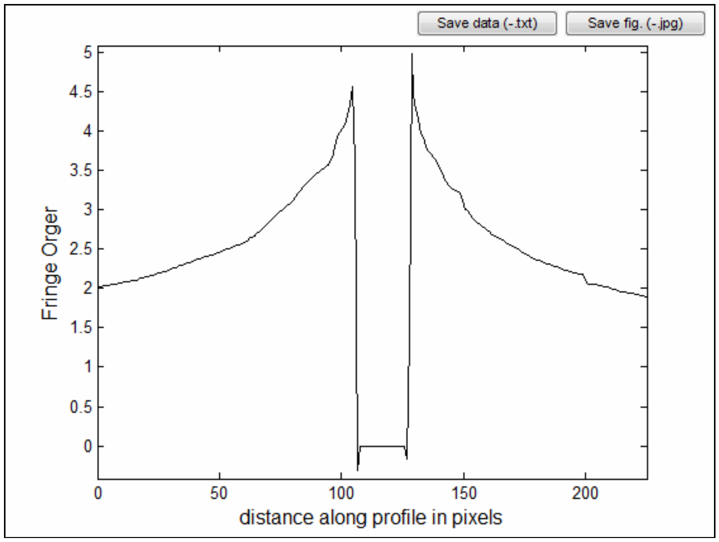


Fig. 12. Display of the profile window.

Image Display

The map displayed in the figure can be selected (if available) using the drop-down menu marked 'Show' right to the 'Profile' button. Similarly, the units of the data can be changed using the adjacent drop-down menu marked 'Units'. The maps that can be displayed are: 'Intensity Image #1', 'Unregularized Relative Retardation #1', 'Unregularized Relative Retardation #2', 'Quality Map' used for the regularization, 'Wrapped Regularized Retardation', 'Unwrapped Regularized Retardation' and the 'Isoclinics'. The 'Unwrapped Regularized Retardation' is not calibrated, and the Isoclinics may be regularized or not depending on whether the regularization has been done or not.

If any of these maps are displayed, the calibration is removed and a new calibration has to be performed.

The colour scheme for the figure can be selected using the drop-down menu marked 'Color Map'.

Saving data

Once a file has been opened the data displayed in the figure in the main window can be saved using the drop-down menu 'Save current figure as: *.txt, *.eps, *.tif, *.jpg'. After selecting the appropriate file format use the drop-down menu to the left of the button.

If '*.txt' is selected, the data in the current figure is saved in matrix format as an 'ascii' file, with the same size as the figure.

If '*.eps,' '*.tif', or '*.jpg' is selected, the image (including the colour bar and title) shown in the main window is saved.

The button 'Save *.cpa file' does not save the processed image, only the six phase shifted images, the mask and the URP-mask (if created).

Use 'Save Matlab file' to save the following data into a matlab file: The unwrapped and calibrated regularized isochromatic fringe map (delta) if it has been calibrated (if not the units are in rad.), the wrapped regularized relative retardation in rad. (deltaw), the intensity image #1 (i1) and the mask (mask). This can be done only if the unwrapping has been performed.

The file 'savemat', is a '.m' file an can be opened and changed by the user so that the desired data to be saved when using the 'Save Matlab file' button can be changed (use the matlab help support to know how to use the 'save' command).

References

[1] Siegmann P., Beckman D. and Patterson E.A. A robust approach to demodulate and unwrapping phase-stepped photoelastic data," Exp. Mech. 45(3), pp. 278-289, 2005.

[2] Siegmann P., Díaz-Garrido F., and Patterson E.A. Robust approach to regularize an isochromatic fringe map," Applied Optics, 48(22), pp. E24-E34, 2009.

[3] Patterson E.A. and Wang Z.F.. Towards Full-field Automated Photoelastic Analysis of Complex Components. Strain, 27, pp.49–56, 1991.

APPENDIX

Experimentally acquisition of the photoelastic data

The photoelastic data processed with RICO are the six phase stepped images used in the algorithm of Patterson and Wang [3] obtained with a circular polariscope with the following orientation of the fast axis with respect to the x-axis (e.g.): Polarizer at -π/4 rad., 1st Quarter-wave plate at π/2 rad., and

Image Nr.	2nd Quarter-wave plate	Analyzer	Light intensity
1*	0	π/4	$i_1 = i_m - i_v \cos\delta$
2	0	-π/4	$i_2 = i_m + i_v \cos\delta$
3	0	0	$i_3 = i_m - i_v \sin\delta \sin 2\theta$
4	π/4	π/4	$i_4 = i_m + i_v \cos\delta \sin 2\theta$
5	π/2	π/2	$i_5 = i_m + i_v \sin\delta \sin 2\theta$
6	3π/4	3π/4	$i_6 = i_m - i_v \cos\delta \sin 2\theta$

*: Dark field fringe pattern

The photoelastic data to be processed with RICO should be as good as possible. Special attention should be given to the following points:

1. Illumination conditions: The maximum range of intensity levels but without saturation should be used.
2. Image acquisition: There should be no changes in the relative position of the sample and the image acquisition system while capturing the six images, and no change in any of the image acquisition parameters (focal length, exposure time, gain level, aperture,…), and the response of the image acquisition system has to be linear with the light intensity (be careful by using CMOS cameras).
3. Ensure the correct arrangement of the polariscope for each of the six images as well as the order in which they are taken.

How to create a mask for RICO

Good photoelastic data has well-defined black and white fringe patterns in the dark and light fringe pattern. This is important because the quality map used for the regularization process has twice as many fringes as the dark field fringe pattern [2]. An example of quality map in grey scale is shown in Fig. 12 for a fatigue crack in a CT specimen. The pixels with high quality value correspond to white fringes while the black fringes correspond to low quality pixels. For a correct regularization process the white fringes should not overlap or come together, thus, there should be a black fringe between each white one, and this is normally the case for good photoelastic data. There are two main instances when the white fringes are overlapped or come together: (i) when the fringe density is too high for the camera resolution; (ii) when the stress or strain distribution is not constant along the light path. In these zones, pixels have to be removed or masked out from the regularization processing.

In Fig. 13 (a) we can appreciate a white area in front of the crack tip and the crack flanks corresponding to the plastic deformation, there the fringes are not well-defined, and also some areas where the fringes come together. These areas have to be masked out. The mask used is shown in Fig. 13 (b).

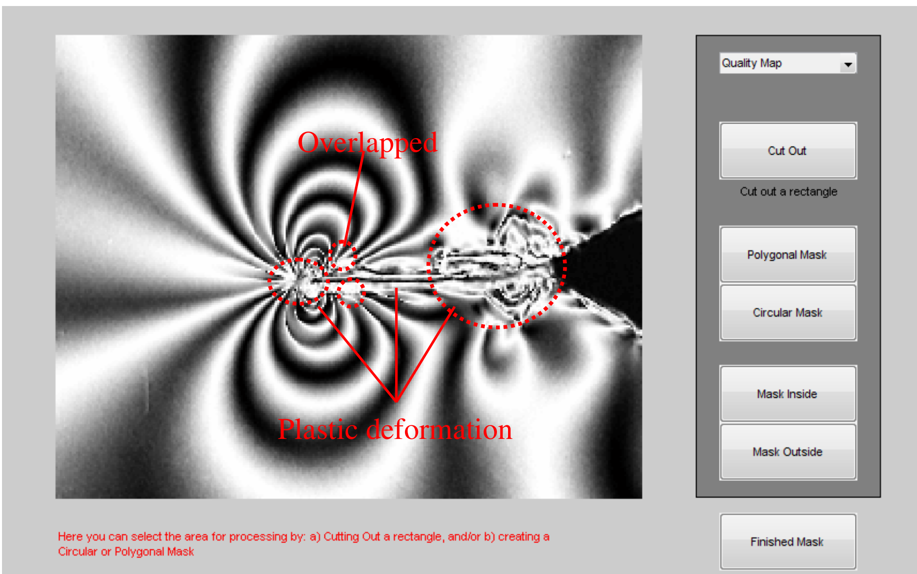


Fig. 13(a) Quality map with areas where the high quality pixels (white fringes) join, causing errors in the regularization process.

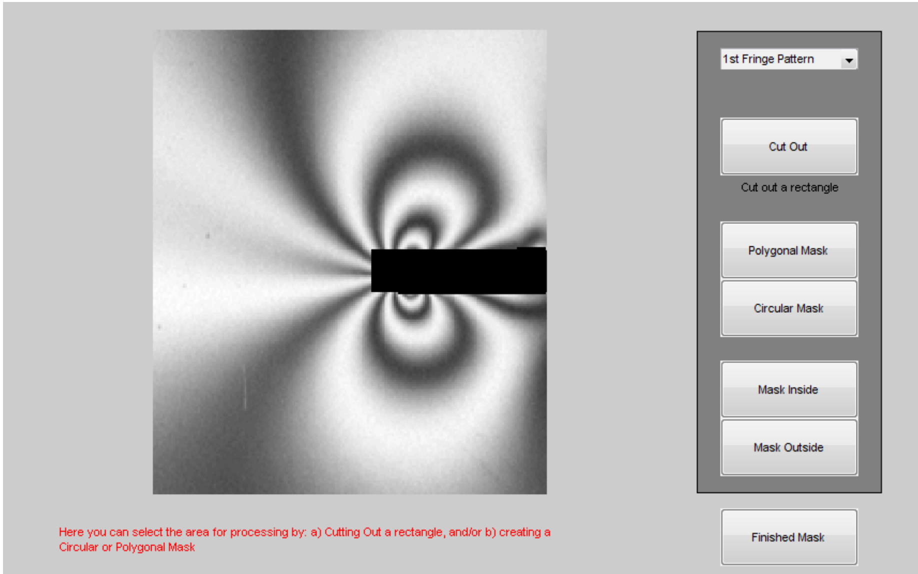


Fig. 13 (b). Mask used to remove the problematic areas that may cause errors in the regularization process.

The 'Unregularized Pixels Mask' (URP-mask)

The URP-mask has two functions: One is to increase the processing speed, and the other one is to help the user to deal with complicate data which are difficult or impossible to process 'automatically'.

The URP-mask defines the areas of pixels which are not processed in the regularization process. This means that their value is taken from one of the two possible solutions for the ambiguous relative retardations ($\delta^{+}_{a,w}$ or $\delta^{-}_{a,w}$), see [2]. In RICO the value in 'Relative Retardation #1' will always be used. An example of how to define an URP-mask is shown in Fig. 14. In selecting these areas, the user has to follow carefully the correct slope which has to be continuous with the expected solution. This means that the user has to have some knowledge of the stress distribution.

How to select these areas and create the URP-mask:

- After pressing the 'Select Unregularized Pixels' button, a new window as shown in Fig. 13 is opened. Different images can be used on which the areas that define the URP-mask can be drawn. At the beginning it is recommended to use the ambiguous relative retardation 'Relative Retardation #1'.
- Press on 'Polygonal Mask' and click with the mouse on the figure at points along the boundary of the area to be used within the URP-mask as shown in Fig. 14(a).

- The slope selected by user may be inverted relative to the expected behaviour of the relative retardation. This is OK because after the regularization process the obtained unambiguous relative retardation can be inverted.
- The selected areas don't need to be perfectly delimited because the actual boundaries are automatically detected in the regularization process. An example of URP-mask is shown in Fig. 14, where in (a) the area around the zero fringe order has been selected. And the areas selected in (b), (c) and (d) follow the same slope as the first one (downhill in this case).
- After each selecting each area press 'Mask Inside'. The user can repeat the process for delimiting more areas belonging to the URP-mask. For Example see Fig. 13(b) and (c). Press 'Finished Mask' when the URP-mask is finished.
- Active the check-box 'Use URP-mask' to use the URP-mask in the regularization process.
- The existing URP-mask can be deleted if you want to replace it with a new one by pressing the 'Delete URP-mask' button.
- Finally, the URP-mask together with the mask and the six phase shifted images can be saved in the '*.cpa' format by pressing on 'Save *.cpa file'.

For the example shown in Figure 14, the unambiguous relative retardation obtained is shown in Figure 15. Using the URP-mask it is easier to select appropriate regularization parameters.

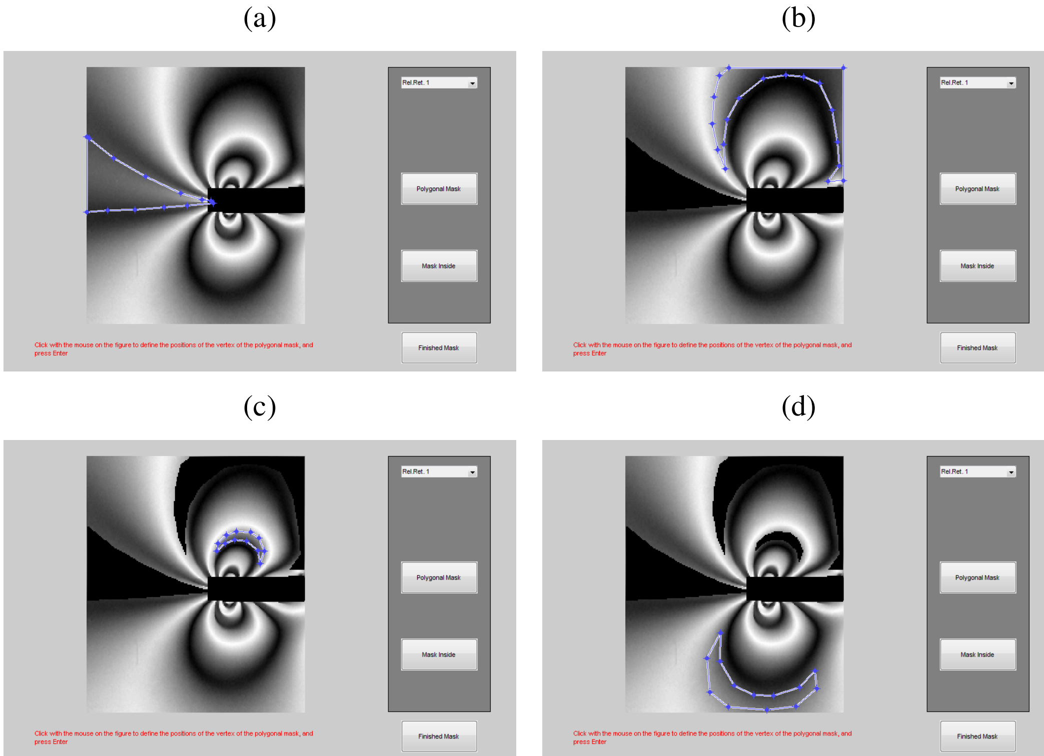


Fig. 14. Example of manually selected areas to create an URP-mask.

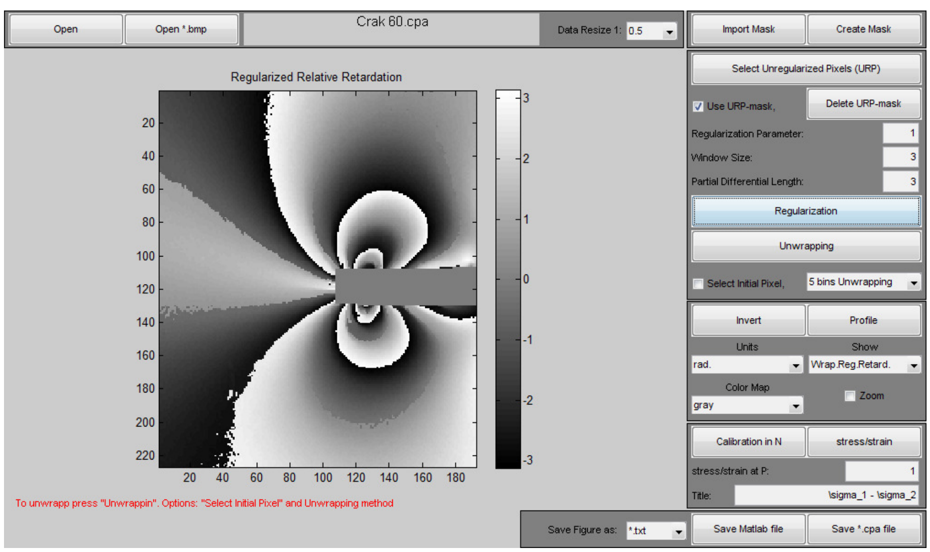


Fig. 15. The wrapped unambiguous relative retardation obtained using the URP-mask shown in Fig. 14.

List of all the files and sub-files used in RICO V2.0

RICO (main file)

- ricobuttons
- loadped
    - WrappedIsochromatic
- loadsixbmp
    - WrappedIsochromatic
- loadmask
- createmask
    - figtomask
    - cutout
    - polygmask
    - circmask
    - insidemask
    - outsidemask
    - okmask
- NRP
    - figtoNRPmask
    - polygNRPmask
    - insideNRPmask
    - okNRPmask
- DeleteNRPmask
- Regularization
- Unwrappretardation
    - PhaseDerVar
    - insertmatrix
    - QGU
        - contorno
        - unwrapped_neighdbors
- signinvert
- showprofile_save
    - saveprofilefig
    - saveprofiledata
- showisoc
- visibleoffisoc
- changeunit
- showfig
- colorfig
- setzoom
- calibpen
- calibpes
- savefig
- savemat
- savecpa