Superresolution software manual

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This manual describes the use of the software application implementing the SR algorithms developed in [1, 2, 3, 4, 5] as well as other superresolution methods developed by the authors [6]. The application has been developed in MATLAB® (7.13/R2011b) including the graphic user interface (see figure 1).

The developed software:

- Allows the execution of SR methods in real and simulate modes.
- Evaluates the following SR methods:
  - Bicubic interpolation.
  - The TV prior based method proposed in [6].
  - The method described in the algorithm 3.1 of [1] which utilizes a SAR prior model.
  - The algorithm proposed in [2], with the $\ell 1$-norm of the horizontal and vertical gradients as the image prior model.
  - The method proposed in [3] based on a SAR and $\ell 1$-norm model combination with registration parameter estimation.
  - The method described in the work [4] which combines SAR and TV prior models with the estimation of the registration parameters.
  - The method proposed in [5], where a prior distribution based on a general combination of spatially adaptive or non-stationary image filters is used with the estimation of all parameters.

If you use this software to evaluate any of the described methods, please cite the corresponding papers. The papers can be downloaded for research purposed from `http://decsai.ugr.es/vip`.

- Saves the results (HR images and registration parameters).
- Allows the user to stop the execution at any time, with the possibility of saving all the estimated parameters as well as the estimated HR image.

We assume here that a digital camera captures a sequence of L low resolution images of size N pixels. In the spatial domain, the process to capture the k-th image, $\mathbf{y}_k$, can be expressed using matrix-vector notation, as

$$\mathbf{y}_k = \mathbf{A}\mathbf{H}_k\mathbf{C}(\mathbf{s}_k)\mathbf{x} + \mathbf{n}_k, \qquad (1)$$

where $\mathbf{x}$ represents a digitalization of the real scene with a resolution of PN pixels, with $P > 1$ representing the magnification factor, $\mathbf{C}(\mathbf{s}_k)$ is a $PN \times PN$ matrix representing the motion of the k-th image in the sequence with respect to the reference image, with $\mathbf{s}_k = (\theta_k, c_k, d_k)^T$ the motion parameters (rotation angle and horizontal and vertical displacement), $\mathbf{H}_k$ is a $PN \times PN$ matrix representing the blur, $\mathbf{A}$ is the $N \times PN$ integration and subsampling matrix and $\mathbf{n}_k$ represents the noise. This model is used in the software to simulate the low resolution observed images.

The simulated mode allows to evaluate the quality of the resulting HR images and the error in the estimated parameters for each method (see the experiment sections in chapters 4–6 of [1]). In contrast the real mode execution allows to run the methods with real datasets. This mode has been utilized in the real experiments in chapter 6 of [1].

Depending on the selected mode, and before running the selected method, the user has to provide the information required by the method. Additionally, if the simulated mode is selected, the user has to introduce the necessary information to generate the observed low resolution image set according to Eq. (1), that is, the original HR image, the number of observation to generate, the blur, the additive Gaussian noise variance and the subsampling factor. In real mode, the user has to provide the LR image set, the assumed, or previously estimated, blur and the desired upsampling factor.

Once the initial information has been filled in, the user has to choose the SR method and run it. Note that, when selecting any of the proposed methods that use model combination, it is also necessary to introduce the combination parameter (λ) in the range $[0, 1]$.

The user can intuitively navigate through the GUI and complete the initial information needed by the SR method. Also, the user can access the reconstructed HR image and registration parameters on each iteration, in case they were estimated.

The access and workflow through the developed GUI is detailed next.

1 Installation

The application does not need to be installed. To access the application just uncompress the provided package. The application was developed in MATLAB® version 7.13.0.564 (R2011b) and it has been tested to work only in this version.

2 User interaction with the application

The main steps to run the application are:

1. Start the application.

2. Select the (**Real** or **Simulated**).

3. Fill in the initial information.

4. Select the SR method to execute.

5. Execution monitoring and saving options.

Let us describe each step in details.

2.1 Running the application

To run the MATLAB® application, change your current directory to the application folder and run the program ***SuperResolutionv1.m***. In a few seconds the GUI depicted in figure 1 will appear.

The GUI is divided in the following interactive areas:

1. **Mode/Reset**: Allows the user to select between *simulated* or *real* execution mode and to reset the program.

2. **Low Resolution Image**: this area shows the utilized simulated or real observations depending on the current execution mode.

3. **High Resolution Image (Simulated Mode)**: Used only in simulated mode. It is utilized to load and previsualize the HR image from which the LR observations will be generated.

4. **LR Generator**: (Only active in simulated mode). This panel allows to introduce the required information to generate LR observations from the image loaded in the previous area.

5. **Super Resolution**: Allows to select the SR method to be applied to the LR observations.

6. **High Resolution Image**: This area displays the resulting HR image on each iteration. The reconstruction process can so be monitored.

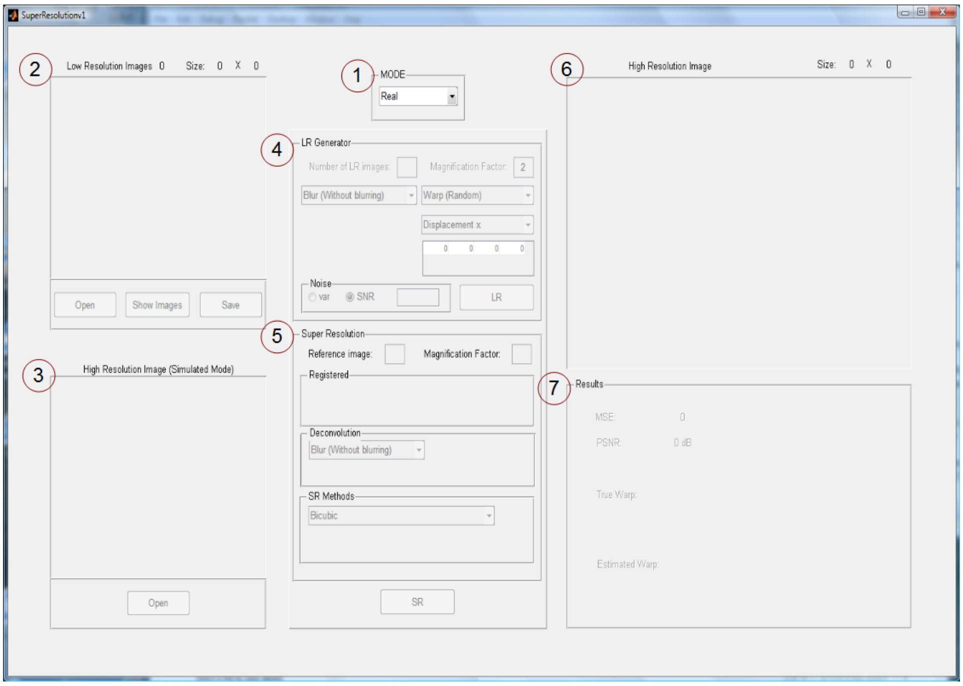


Figure 1: GUI appearance. Numbers 1 to 7 inside the red circles indicate the interface interaction areas.

7. **Results**: In simulated mode, this area shows error measures of the HR reconstruction and the value of the real and estimated parameters (if applicable). In real mode, it shows the estimated registration parameters.

The only GUI element active at the beginning is the area **Mode**. The user must then select one of the two available execution modes: real or simulated.

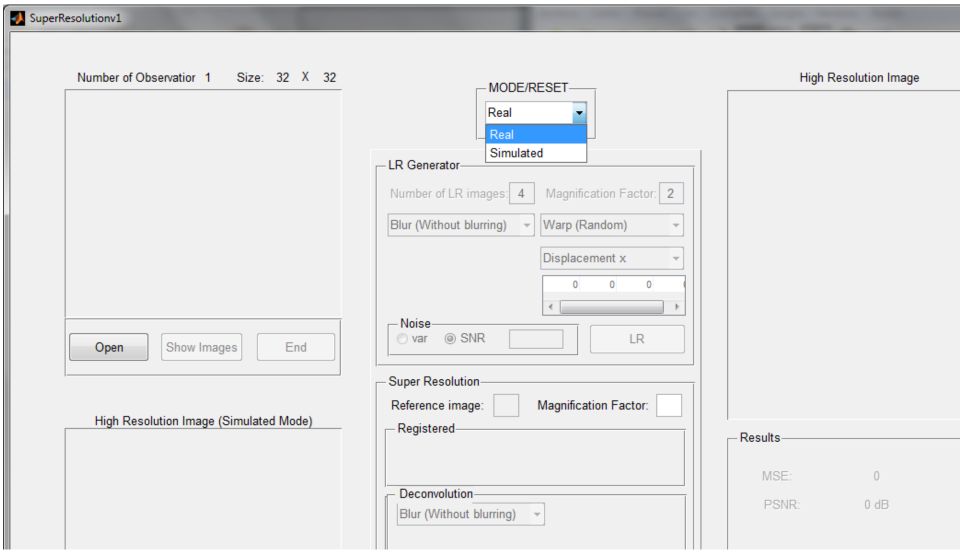
2.2 Execution Mode

The execution mode can be selected by clicking on the **MODE/RESET** pull-down menu (see figure 2). Note that the **Real** mode is chosen by default.

Depending on the selected mode, the GUI activates the fields where to provide the information needed to run the selected SR method.

Each execution mode is described in a separate section since the selected mode determines the application workflow.

Selecting the execution mode at any time involves resetting the application to the selected mode. All the loaded images and obtained results will be lost and all the parameters will be reset to their default values.



Number of Observatior 1 Size: 32 X 32

Number of LR images: 4 Magnification Factor: 2

MSE: 0

PSNR: 0 dB

Figure 2: GUI appearance when the area **MODE/RESET** is active.

2.2.1 Simulated Mode

When the simulated mode is selected, the **Open** button, in the area **High Resolution Image (Simulated Mode)**, is activated (see figure 3).

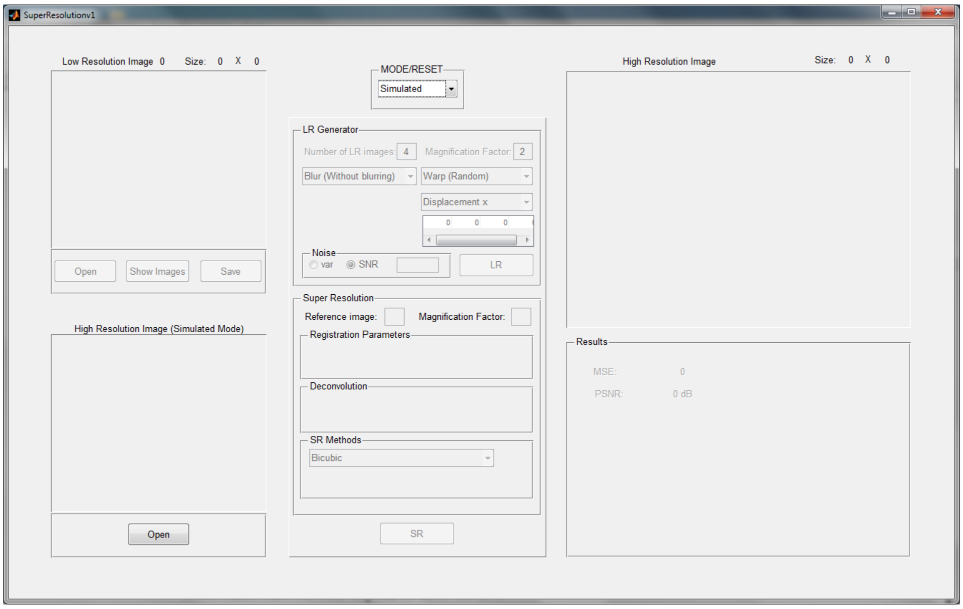
When the **Open** button is pressed, the file manager is launched, this allows to select the HR image to be used in the experiments, see figure 4. For instance, if we select the image *lenag80.png*, the image is displayed and the **LR Generator** panel becomes available (see figure 5). This panel shows all the required information needed to generate the LR images using Eq. (1).

All fields have been initialized to default values that can be modified at any time. The blurring function is defined by the selected kernel, as shown in figure 6. Note that, for each type of blur, the values of the blur matrix coefficients are requested by the application. They are initialized with a default value in order to facilitate the user input.

When the **Customized** option for the blur is selected, a new window is displayed in order to introduce the blur coefficients, see figure 7. Additionally one can select either the **Save** option to save the current kernel or **Load** to load a new one.

The registration parameters can be defined in three forms: **Warp (Random)**, **Customized** and **Example**, depending on whether you want to generate them randomly, introduce the parameter manually (rotation angle and vertical and horizontal displacements) for each observation or using the parameters in the experiments described in chapters 4–6 of [1], respectively (see figure 8).

Finally, the user must set the zero-mean Gaussian noise level, which



MODE/RESET: Simulated

Number of LR images: 4 Magnification Factor: 2

Blur (Without blurring)

Warp (Random)

Displacement x

0 0 0

SR Methods: Bicubic

MSE: 0

PSNR: 0 dB

Figure 3: GUI appearance when the area **Mode** is activated to **Simulated**. Note that the button **Open** is now active.

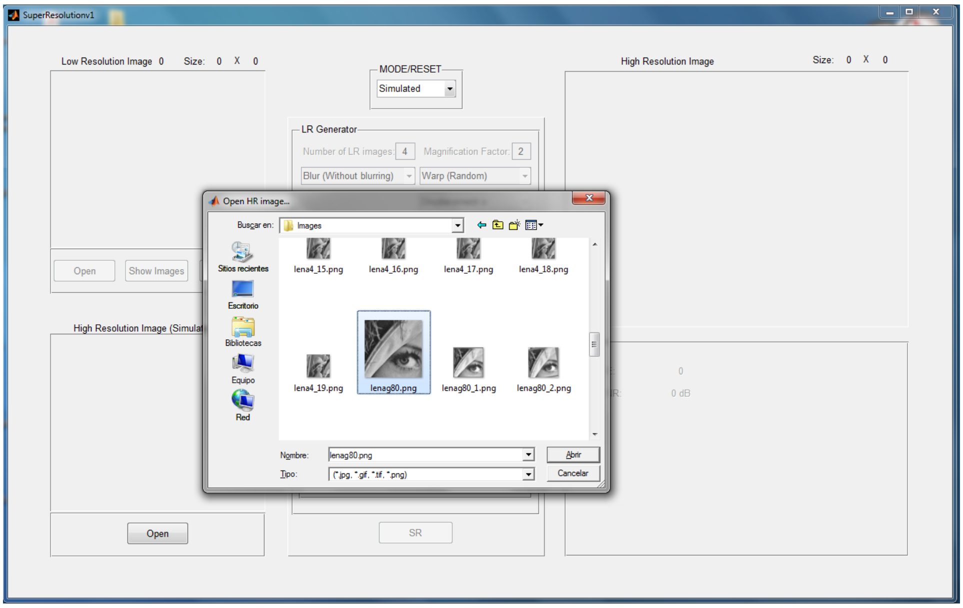
can be defined in two forms: introducing the noise variance or by setting the signal-to-noise ratio (SNR), both in exclusive buttons. Depending on the selected option, the numeric field allows to introduce either the noise variance or the SNR value. The SNR mode is active by default with a value of **30** dB.

The **LR** button is available once all the required information to generate the observations has been provided (see figure 9). Notice how the areas **Low Resolution Image** and **Super Resolution** have been activated. Now the **Low Resolution Image** area allows to save the generated observations. The observations are saved by typing a generic name in the file manager window. For instance, if the user generated 5 observations and set the generic name *lenag.png*, then the application creates the image files *lenag_1.png, lenag_2.png, lenag_3.png, lenag_4.png* y *lenag_5.png.*

Now we can apply the SR methods implemented in the software to the generated observations. Notice that **Reference image**, **Registration parameters** and **SR Methods** are the only areas enabled in simulated mode. The subarea **Registration parameters** allows the user to choose between using the true registration parameters or estimate them. True registration parameters are used by default.

The next step consists of selecting the desired SR method to execute as shown in figure 10.

At this point, there are 5 active areas: **Low Resolution Image**, **Mode**,



MODE/RESET: Simulated

Number of LR images: 4 Magnification Factor: 2

Blur (Without blurring) Warp (Random)

Buscar en: Images

Nombre: lenag80.png

Tipo: (*.jpg, *.gif, *.tif, *.png)

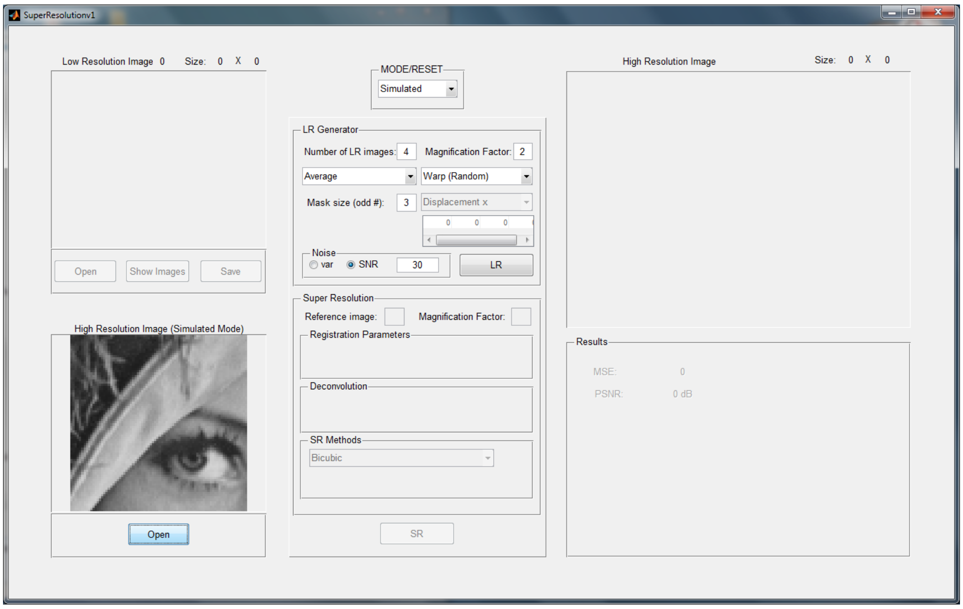
Figure 4: GUI appearance after clicking the **Open** button.

High Resolution Image (Simulated Mode), **LR Generator** and **Super Resolution**. That means that you can modify the fields of any of these areas, and generate new observations, with the possibility of saving the previous ones.

The selected SR method is executed by pressing the **SR** button. The areas **High Resolution Image** and **Results** are now enabled, as displayed in figure 11. On each iteration the HR reconstruction and its quality metrics are displayed. The execution can be stopped at any time by pressing the **Cancel** button. When the method stops, due to convergence or cancellation, the application shows the true registration parameters and, if applicable, the estimated ones (see figure 12).

Additionally the application allows the user to display the best reconstruction in the PSNR sense, by pressing the **Best Results** button, that could not coincide with the solution obtained in the last iteration, as seen in figure 13. If the button is pressed again, the HR reconstruction in the last iteration is shown. Both reconstructions can be saved pressing the **Save** button.

In order to request the file name to save the HR reconstruction, the file manager is launched. Let us point out that the application saves the HR reconstruction in the last iteration with the given name, the best reconstruction in the PSNR sense with the same name but ending in *Best* and it also saves a file with the same name but ending in -Dat.mat containing the estimated parameters in a data structure named *outopt* (see figure 14).



MODE/RESET: Simulated

Number of LR images: 4

Magnification Factor: 2

Average

Warp (Random)

Mask size (odd #): 3

Displacement x: 0 0 0

Noise: ○ var ● SNR 30

Magnification Factor:

SR Methods: Bicubic

MSE: 0

PSNR: 0 dB

Figure 5: GUI appearance after the initial HR image is loaded.

When any SR method using prior model combination is selected, the combination coefficient, λ, is shown as depicted in figure 15. The combination coefficient, in the range 0 to 1, is displayed on a new field. The default value 0, means that the algorithm is exclusively applying the SAR prior model.

When the SR method in [5] entitled **SR using Mix Filters** is selected, the window in figure 19 is presented. Pressing the **Editor** button, the figure 20 appears and you can define new filters and save them. Pressing the **New** button, the figure 21 appears and you can create a new list of filters in the *FilterDir* directory from previously created filter files. Care must be taken of selecting only filter files and not list of filters (those ending on *FilterList.mat*). Pressing the **Load** button you can load previously saved list of filters (as shown in figure 22). Filters and filter lists can be stored in the directory *FiltersDir*. When the filter list has been completed you must press the **Finish the Filter Selection to Mix** button, to, optionally, save the list and run the method.

2.2.2 Real Mode

The **Number of Observations** panel and **Open** button are activated on Real mode (see figure 16).

When pressing the **Open** button, the file manager is launched requesting for the first observed image file name. The rest of options (**Show Images**

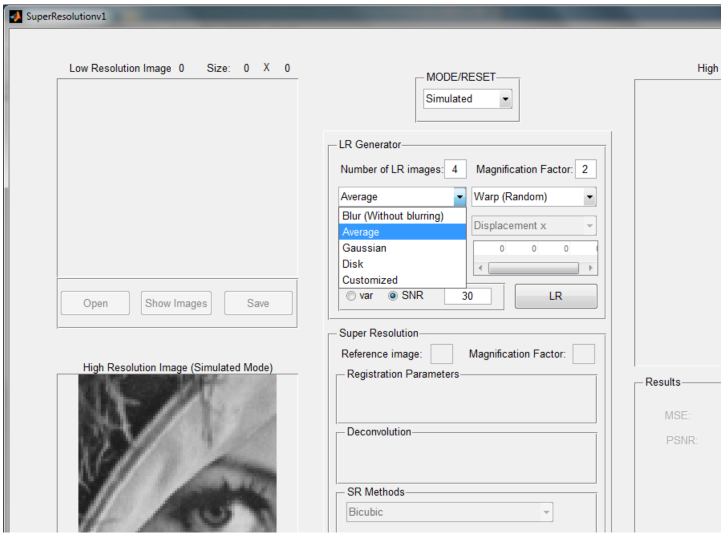


Figure 6: Blur kernel selection.

and **End**) are available once the first observation is introduced. Adding new observations is as simple as repeating the procedure until the last observation is opened and the **End** button is pressed. The user can also load all the observed images at once by selecting a .mat file containing a single variable of size (rows × columns × n. observations) that stores all the images.

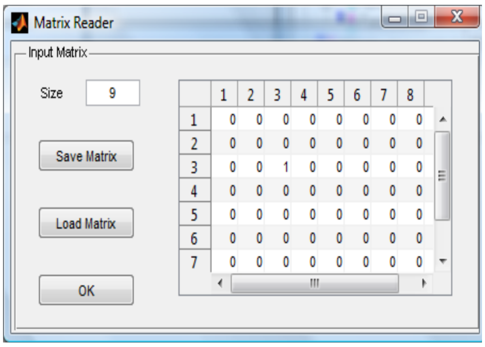
The **show images** button displays the set of images currently loaded.

When the **End** button is pressed, the **Super Resolution** panel is activated, allowing the user to set the magnification factor (set to 2 in each direction by default), and the blurring kernel (without blurring, by default) in the **Deconvolution** subpanel.

As for the simulated mode, the user selects the SR method and presses the **SR** button to run it. The appearance of the panels **High Resolution Image** and **Results** are shown in figure 17. Once the method has finished, the registration parameters are shown, accessing iteration number you can retrieve previous iterations reconstruction and the results can be saved by pressing the **Save** button, see figure 18.

3 Files output during the execution

The application displays the execution status in the GUI but it also saves *log* files in the directory **tempSR** which contains the information of all the parameters estimated in each iteration. An example of the content of this file, for the real mode execution depicted in figure 18, is shown in figure 23.



Size 9

	1	2	3	4	5	6	7	8	
1	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0
3	0	0	1	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0

Figure 7: This matrix allows the user to define the blur kernel in the **Customized** mode.

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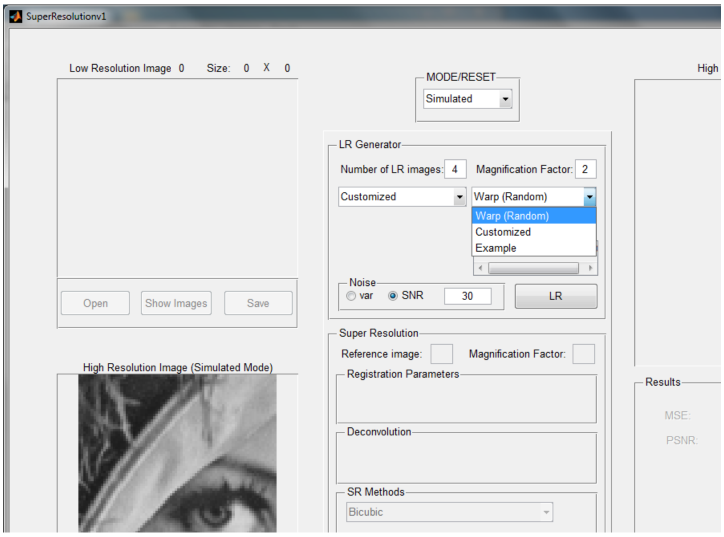
Note

Please report bugs to Rafael Molina (rms@decsai.ugr.es).

License

References

[1] S. Villena. *Superresolución y Reconstrucción Bayesiana de Imágenes a Partir de Imágenes de Baja Resolución Rotadas y Desplazadas. Com-*



MODE/RESET: Simulated

LR Generator

Number of LR images: 4 Magnification Factor: 2

Customized Warp (Random)

Noise ○ var ● SNR 30

Figure 8: Setting the warp

binación de Modelos. PhD thesis, Universidad de Granada, December 2011.

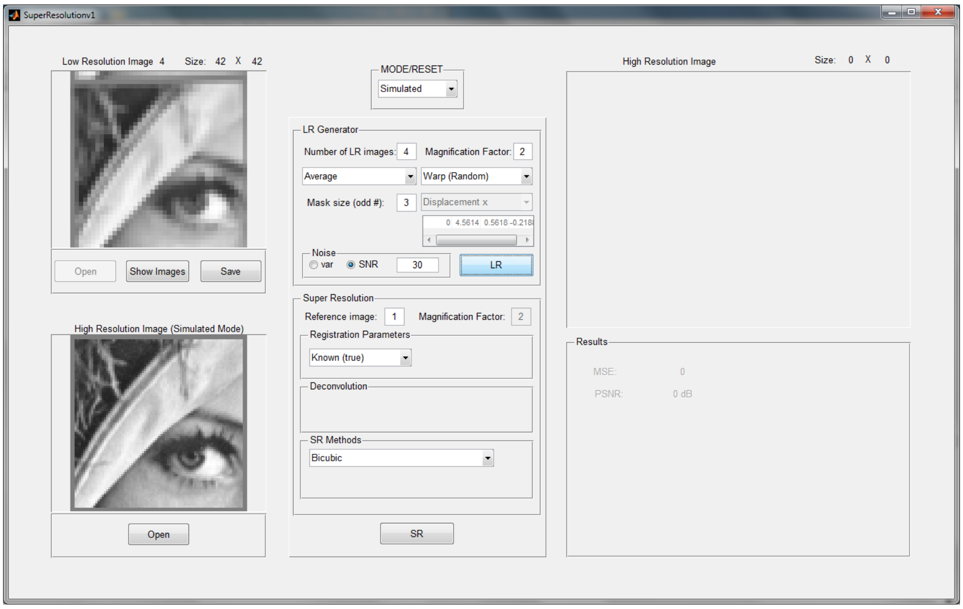
[2] S. Villena, M. Vega, R. Molina, and A. K. Katsaggelos. Bayesian super-resolution image reconstruction using an l1 prior. In *6th International Symposium on Image and Signal Processing and Analysis (ISPA 2009) Best paper award, Image Processing and Analysis Track*, pages 152–157, 2009.

[3] S. Villena, M. Vega, D. Babacan, R. Molina, and A. Katsaggelos. Bayesian combination of sparse and non sparse priors in image superresolution. *Submitted to Digital Signal Processing*, 2012.

[4] S. Villena, M. Vega, D. Babacan, R. Molina, and A. Katsaggelos. Using the Kullback-Leibler divergence to combine image priors in super-resolution image reconstruction. In *IEEE International Conference on Image Processing*, pages 809–812. Hong-Kong (China), September 2010.

[5] S. Villena, M. Vega, R. Molina, and A.K. Katsaggelos. A non-stationary image prior combination in super-resolution. *Digital Signal Processing*, 32:1–10, September 2014.

[6] S. D. Babacan, R. Molina, and A.K. Katsaggelos. Variational Bayesian super resolution. *IEEE Transactions on Image Processing*, 20(4):984–999, 2011.



MODE/RESET: Simulated

Number of LR images: 4 Magnification Factor: 2

Average | Warp (Random)

Mask size (odd #): 3 Displacement x

0 4.5614 0.5618 -0.218

Noise: ○ var ● SNR 30

Reference image: 1 Magnification Factor: 2

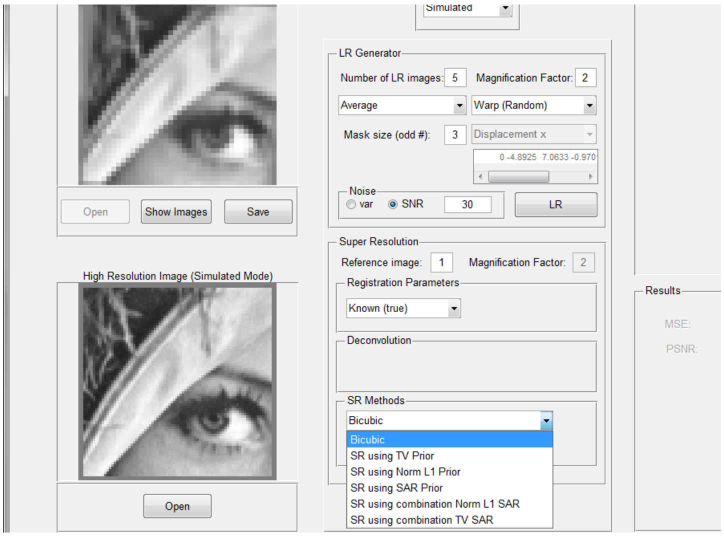
Registration Parameters: Known (true)

SR Methods: Bicubic

MSE: 0

PSNR: 0 dB

Figure 9: Observations generation



Number of LR images: 5 Magnification Factor: 2

Average | Warp (Random)

Mask size (odd #): 3 Displacement x

0 -4.8925 7.0633 -0.970

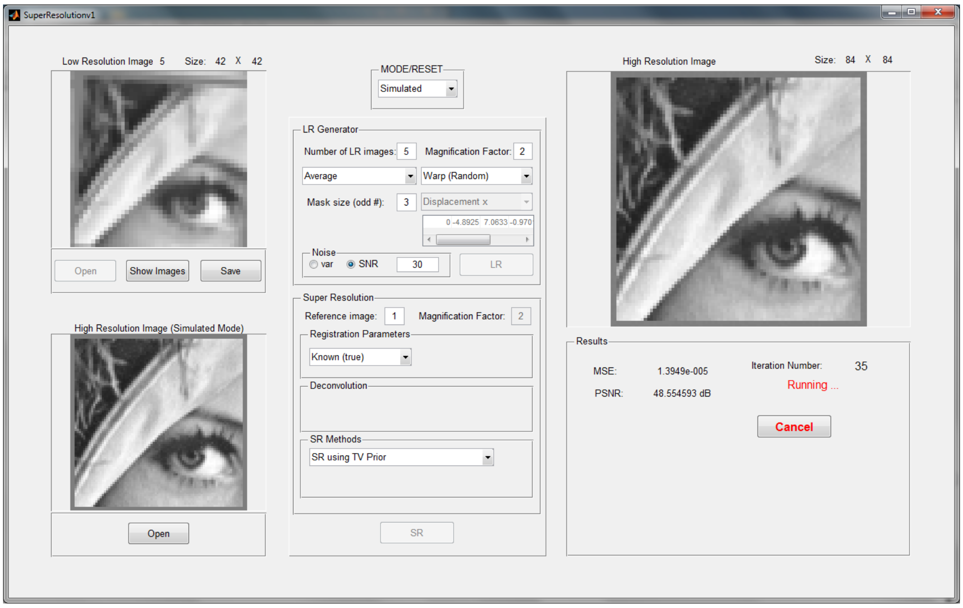
Noise: ○ var ● SNR 30

Reference image: 1 Magnification Factor: 2

Registration Parameters: Known (true)

SR Methods: Bicubic

Figure 10: Available SR methods.



Low Resolution Image 5 Size: 42 X 42

MODE/RESET: Simulated

High Resolution Image Size: 84 X 84

LR Generator

Number of LR images: 5 Magnification Factor: 2

Average Warp (Random)

Mask size (odd #): 3 Displacement x

0 -4.8925 7.0633 -0.970

Noise: ○ var ● SNR 30

Super Resolution

Reference image: 1 Magnification Factor: 2

Registration Parameters: Known (true)

Deconvolution

SR Methods: SR using TV Prior

High Resolution Image (Simulated Mode)

Results

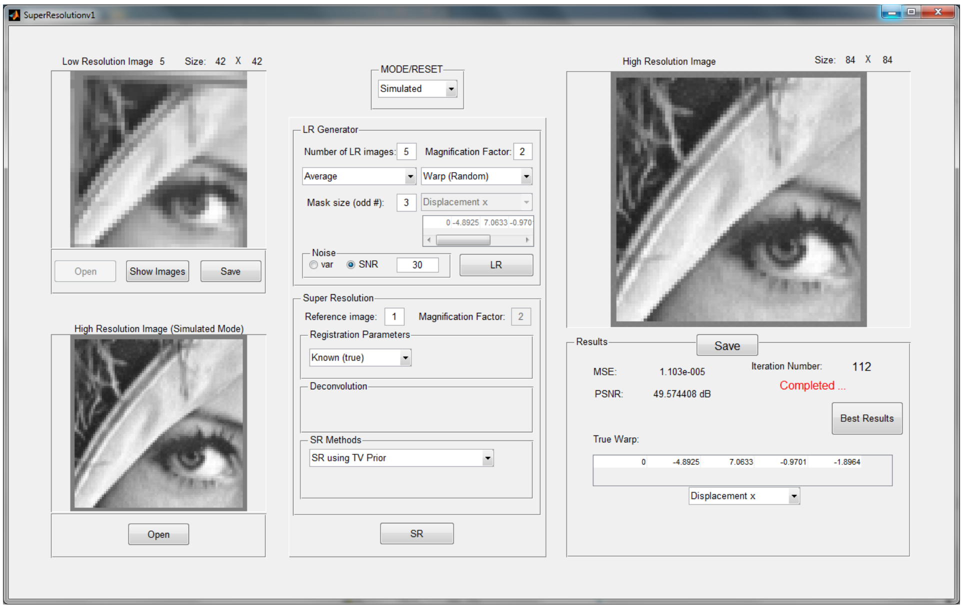
MSE: 1.3949e-005

PSNR: 48.554593 dB

Iteration Number: 35

Running ...

Figure 11: Running the SR method.



Low Resolution Image 5 Size: 42 X 42

MODE/RESET: Simulated

High Resolution Image Size: 84 X 84

LR Generator

Number of LR images: 5 Magnification Factor: 2

Average Warp (Random)

Mask size (odd #): 3 Displacement x

0 -4.8925 7.0633 -0.970

Noise: ○ var ● SNR 30

Super Resolution

Reference image: 1 Magnification Factor: 2

Registration Parameters: Known (true)

Deconvolution

SR Methods: SR using TV Prior

High Resolution Image (Simulated Mode)

Results

MSE: 1.103e-005

PSNR: 49.574408 dB

Iteration Number: 112

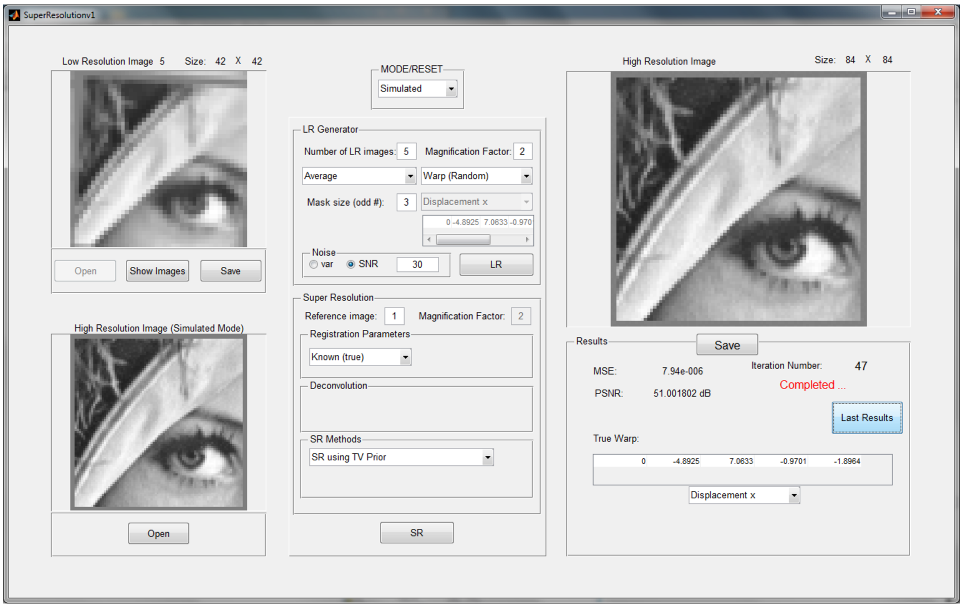
Completed ...

True Warp:

0 -4.8925 7.0633 -0.9701 -1.8964

Displacement x

Figure 12: Execution of the SR method finalized.



Low Resolution Image 5 Size: 42 X 42

MODE/RESET: Simulated

Number of LR images: 5 Magnification Factor: 2

Average

Warp (Random)

Mask size (odd #): 3

Displacement x

0 -4.8925 7.0633 -0.970

○ var ● SNR 30

Reference image: 1 Magnification Factor: 2

Known (true)

SR using TV Prior

High Resolution Image Size: 84 X 84

MSE: 7.94e-006

PSNR: 51.001802 dB

Iteration Number: 47

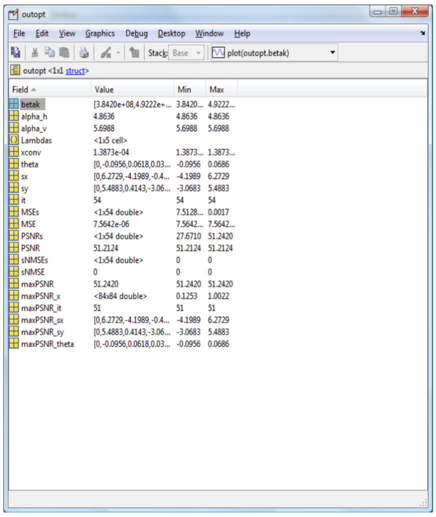
Completed ...

True Warp:

```
        0     -4.8925     7.0633     -0.9701     -1.8964
```

Displacement x

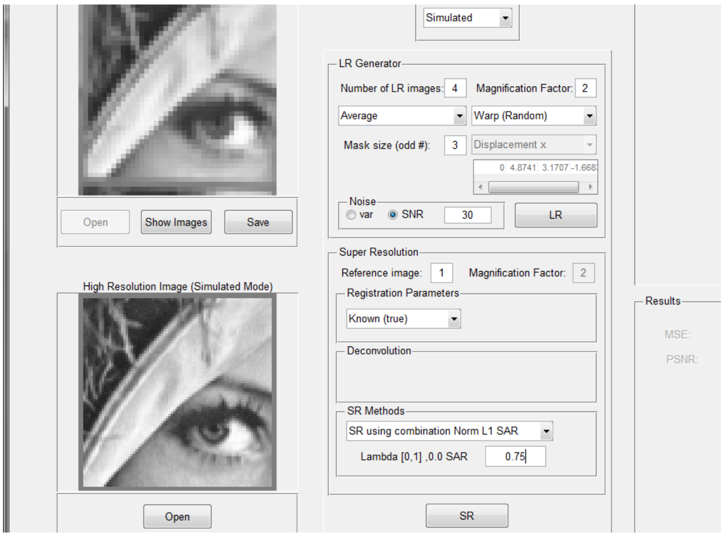
Figure 13: Display the best HR reconstruction.



outopt <1x1 struct>

Field	Value	Min	Max
betak	[3.8420e+08,4.9222e+...	3.8420...	4.9222...
alpha_h	4.8636	4.8636	4.8636
alpha_v	5.6988	5.6988	5.6988
Lambdas	<1x5 cell>		
xconv	1.3873e-04	1.3873...	1.3873...
theta	[0,-0.0956,0.0618,0.03...	-0.0956	0.0686
sx	[0,6.2729,-4.1989,-0.4...	-4.1989	6.2729
sy	[0,5.4883,0.4143,-3.06...	-3.0683	5.4883
it	54	54	54
MSEs	<1x54 double>	7.5128...	0.0017
MSE	7.5642e-06	7.5642...	7.5642...
PSNRs	<1x54 double>	27.6710	51.2420
PSNR	51.2124	51.2124	51.2124
sNMSEs	<1x54 double>	0	0
sNMSE	0	0	0
maxPSNR	51.2420	51.2420	51.2420
maxPSNR_x	<84x84 double>	0.1253	1.0022
maxPSNR_it	51	51	51
maxPSNR_sx	[0,6.2729,-4.1989,-0.4...	-4.1989	6.2729
maxPSNR_sy	[0,5.4883,0.4143,-3.06...	-3.0683	5.4883
maxPSNR_theta	[0,-0.0956,0.0618,0.03...	-0.0956	0.0686

Figure 14: Stored parameter in the structure *outopt* when saving the estimated HR image using the method in [2].



Simulated

Number of LR images: 4 Magnification Factor: 2

Average Warp (Random)

Mask size (odd #): 3 Displacement x

0 4.8741 3.1707 -1.668

○ var ● SNR 30

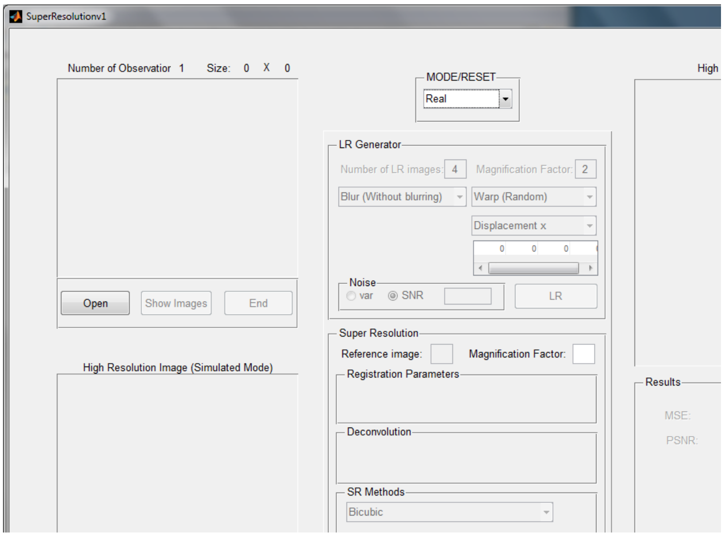
Reference image: 1 Magnification Factor: 2

Known (true)

SR using combination Norm L1 SAR

Lambda [0,1] ,0.0 SAR 0.75

Figure 15: Coefficient value for the prior model combination when method in [3] or [4] is selected.



Number of Observatior 1 Size: 0 X 0

Real

Number of LR images: 4 Magnification Factor: 2

Blur (Without blurring) Warp (Random)

Displacement x

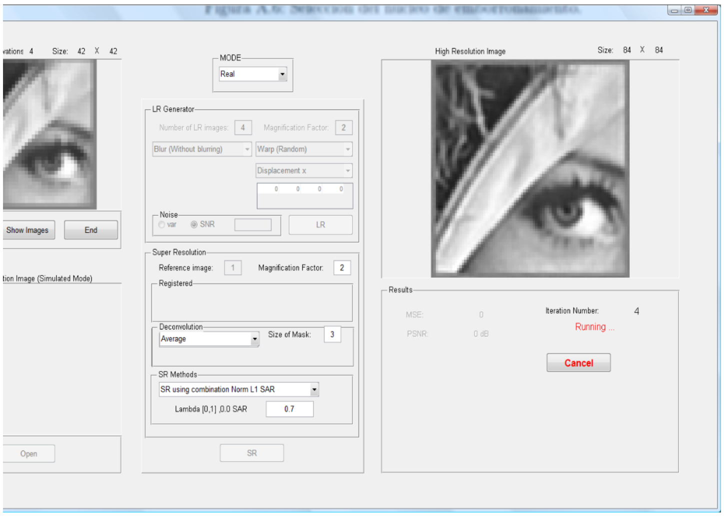
0 0 0

○ var ● SNR

Reference image: Magnification Factor:

Bicubic

Figure 16: **Real Mode**.



vations 4 Size: 42 X 42

MODE: Real

LR Generator
Number of LR images: 4 Magnification Factor: 2
Blur (Without blurring) Warp (Random)
Displacement x
0 0 0 0
Noise ○ var ● SNR

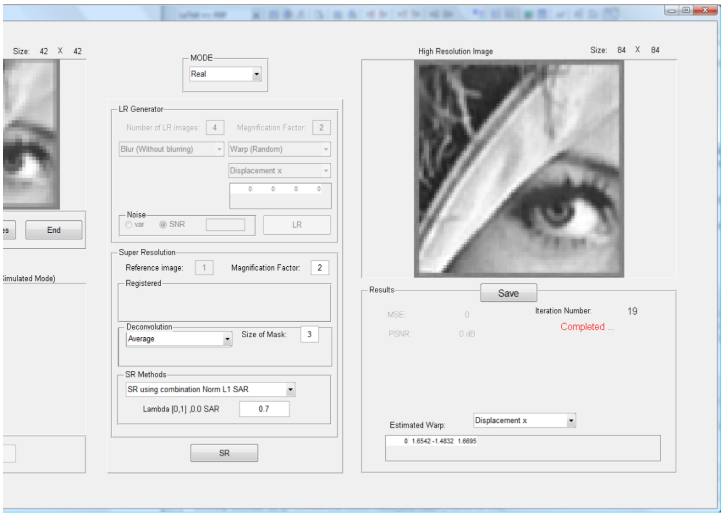
Super Resolution
Reference image: 1 Magnification Factor: 2
Registered
Deconvolution: Average Size of Mask: 3
SR Methods: SR using combination Norm L1 SAR
Lambda [0,1] ,0.0 SAR 0.7

High Resolution Image Size: 84 X 84

Results
MSE: 0
PSNR: 0 dB
Iteration Number: 4
Running ...

tion Image (Simulated Mode)

Figure 17: Execution of the method in [3] in **Real** mode with $\lambda = 0.7$.



Size: 42 X 42

MODE: Real

LR Generator
Number of LR images: 4 Magnification Factor: 2
Blur (Without blurring) Warp (Random)
Displacement x
0 0 0 0
Noise ○ var ● SNR

Super Resolution
Reference image: 1 Magnification Factor: 2
Registered
Deconvolution: Average Size of Mask: 3
SR Methods: SR using combination Norm L1 SAR
Lambda [0,1] ,0.0 SAR 0.7

High Resolution Image Size: 84 X 84

Results
MSE: 0
PSNR: 0 dB
Iteration Number: 19
Completed ...
Estimated Warp: Displacement x
0 1.6542 -1.4832 1.6695

imulated Mode)

Figure 18: End of execution of method in [3] in **Real** Mode with $\lambda = 0.7$ at iteration 19.

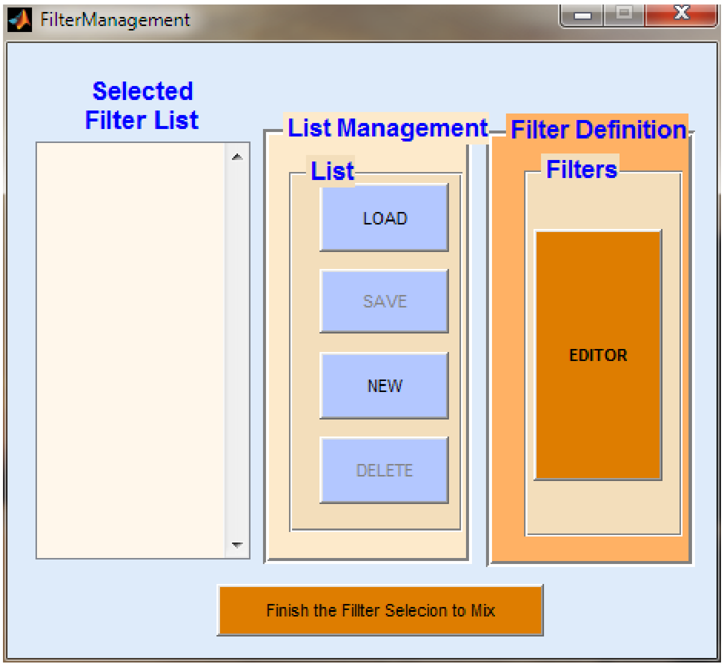


Figure 19: Starting execution of method in [5].

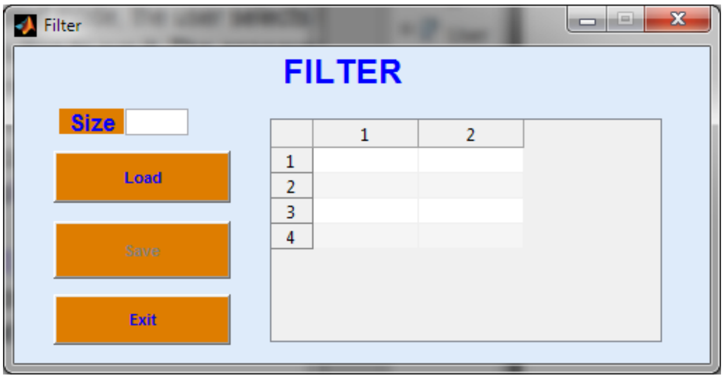
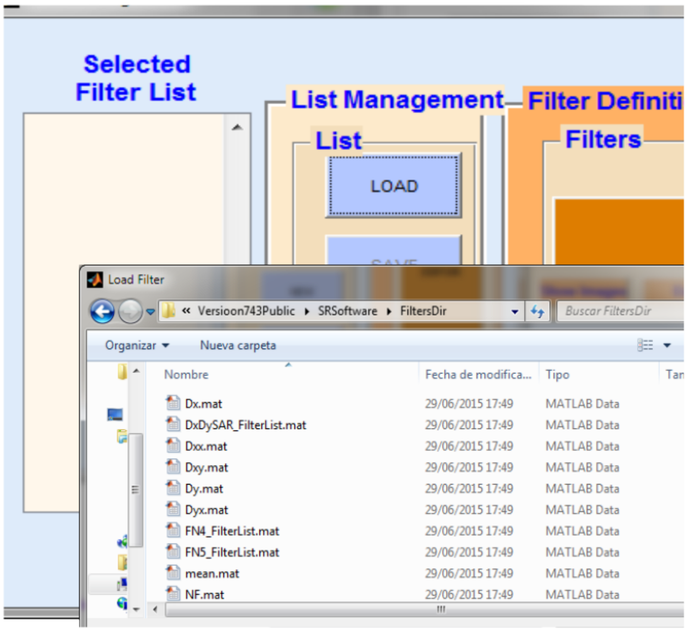
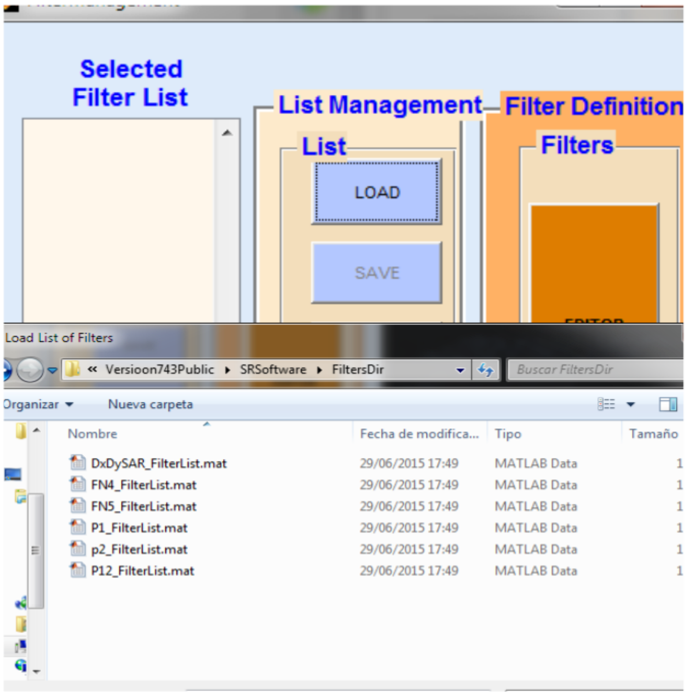


Figure 20: Definition of filter in execution of method in [5].



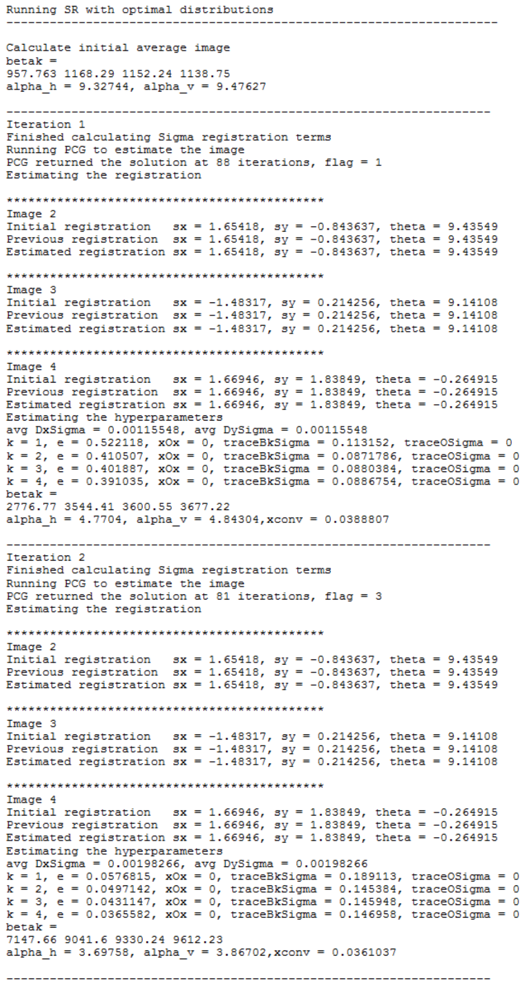
Nombre	Fecha de modifica...	Tipo	Tan
Dx.mat	29/06/2015 17:49	MATLAB Data	
DxDySAR_FilterList.mat	29/06/2015 17:49	MATLAB Data	
Dxx.mat	29/06/2015 17:49	MATLAB Data	
Dxy.mat	29/06/2015 17:49	MATLAB Data	
Dy.mat	29/06/2015 17:49	MATLAB Data	
Dyx.mat	29/06/2015 17:49	MATLAB Data	
FN4_FilterList.mat	29/06/2015 17:49	MATLAB Data	
FN5_FilterList.mat	29/06/2015 17:49	MATLAB Data	
mean.mat	29/06/2015 17:49	MATLAB Data	
NF.mat	29/06/2015 17:49	MATLAB Data	

Figure 21: Definition of filter in execution of method in [5].



Nombre	Fecha de modifica...	Tipo	Tamaño
DxDySAR_FilterList.mat	29/06/2015 17:49	MATLAB Data	1
FN4_FilterList.mat	29/06/2015 17:49	MATLAB Data	1
FN5_FilterList.mat	29/06/2015 17:49	MATLAB Data	1
P1_FilterList.mat	29/06/2015 17:49	MATLAB Data	1
p2_FilterList.mat	29/06/2015 17:49	MATLAB Data	1
P12_FilterList.mat	29/06/2015 17:49	MATLAB Data	1

Figure 22: Load a list of filter in execution of method in [5].



```
Running SR with optimal distributions
--------------------------------------------------------------------

Calculate initial average image
betak =
957.763 1168.29 1152.24 1138.75
alpha_h = 9.32744, alpha_v = 9.47627

-------------------------------------------------------------------
Iteration 1
Finished calculating Sigma registration terms
Running PCG to estimate the image
PCG returned the solution at 88 iterations, flag = 1
Estimating the registration

********************************************
Image 2
Initial registration   sx = 1.65418, sy = -0.843637, theta = 9.43549
Previous registration  sx = 1.65418, sy = -0.843637, theta = 9.43549
Estimated registration sx = 1.65418, sy = -0.843637, theta = 9.43549

********************************************
Image 3
Initial registration   sx = -1.48317, sy = 0.214256, theta = 9.14108
Previous registration  sx = -1.48317, sy = 0.214256, theta = 9.14108
Estimated registration sx = -1.48317, sy = 0.214256, theta = 9.14108

********************************************
Image 4
Initial registration   sx = 1.66946, sy = 1.83849, theta = -0.264915
Previous registration  sx = 1.66946, sy = 1.83849, theta = -0.264915
Estimated registration sx = 1.66946, sy = 1.83849, theta = -0.264915
Estimating the hyperparameters
avg DxSigma = 0.00115548, avg DySigma = 0.00115548
k = 1, e = 0.522118, xOx = 0, traceBkSigma = 0.113152, traceOSigma = 0
k = 2, e = 0.410507, xOx = 0, traceBkSigma = 0.0871786, traceOSigma = 0
k = 3, e = 0.401887, xOx = 0, traceBkSigma = 0.0880384, traceOSigma = 0
k = 4, e = 0.391035, xOx = 0, traceBkSigma = 0.0886754, traceOSigma = 0
betak =
2776.77 3544.41 3600.55 3677.22
alpha_h = 4.7704, alpha_v = 4.84304,xconv = 0.0388807

-------------------------------------------------------------------
Iteration 2
Finished calculating Sigma registration terms
Running PCG to estimate the image
PCG returned the solution at 81 iterations, flag = 3
Estimating the registration

********************************************
Image 2
Initial registration   sx = 1.65418, sy = -0.843637, theta = 9.43549
Previous registration  sx = 1.65418, sy = -0.843637, theta = 9.43549
Estimated registration sx = 1.65418, sy = -0.843637, theta = 9.43549

********************************************
Image 3
Initial registration   sx = -1.48317, sy = 0.214256, theta = 9.14108
Previous registration  sx = -1.48317, sy = 0.214256, theta = 9.14108
Estimated registration sx = -1.48317, sy = 0.214256, theta = 9.14108

********************************************
Image 4
Initial registration   sx = 1.66946, sy = 1.83849, theta = -0.264915
Previous registration  sx = 1.66946, sy = 1.83849, theta = -0.264915
Estimated registration sx = 1.66946, sy = 1.83849, theta = -0.264915
Estimating the hyperparameters
avg DxSigma = 0.00198266, avg DySigma = 0.00198266
k = 1, e = 0.0576815, xOx = 0, traceBkSigma = 0.189113, traceOSigma = 0
k = 2, e = 0.0497142, xOx = 0, traceBkSigma = 0.145384, traceOSigma = 0
k = 3, e = 0.0431147, xOx = 0, traceBkSigma = 0.145948, traceOSigma = 0
k = 4, e = 0.0365582, xOx = 0, traceBkSigma = 0.146958, traceOSigma = 0
betak =
7147.66 9041.6 9330.24 9612.23
alpha_h = 3.69758, alpha_v = 3.86702,xconv = 0.0361037

-------------------------------------------------------------------
```

Figure 23: Content of the log file after running the method in [3] in real mode with $\lambda = 0.7$ in iteration 2.