ImagesToLARModel, a tool for creation of three-dimensional models from a stack of images

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Abstract

Here we will present a software for creating a three-dimensional model from a stack of images. This can be useful because of the simplicity of these type of representations. In particular a scope of use can be offered by medicine, where there is an enormous number of images but with very complex two-dimensional representations.

This work will use the LAR representation ([CL13]) with the Julia language, because of its simplicity, showing how it can be used for quickly process image data.

Contents

1 Introduction

This work has the aim to transform a two-dimensional representation of a model (based on a stack of images) into a three-dimensional representation based on the LAR schema. In particular, it will produce a single obj model which can be viewed with standard graphics softwares.

In the past were developed other softwares using same principles (see [PDFJ15]). However, they were optimized for speed and cannot be able to accept huge amounts of data. With the rise of the big data era, we now have more and more data available for research purposes, so softwares must be able to deal with them. A typical hardware environment is based on a cluster of computers where computation can be distributed among a lot of different processes. However, as stated by *Amdahl's law*, the speedup of a program using multiple processors is limited by the time needed for the sequential fraction of the program. So use of parallel techniques for dealing with big data is not important for time performance gain but for memory space gain. In fact, our biggest problem is lack of memory, due to model sizes. As a consequence, every parts of this software is written with the clear objective of minimizing memory usage at the cost of losing something in terms of time performance. So, for example, images will be converted in blocks determined by a grid size (see section 5) among different processes and different machines of the cluster
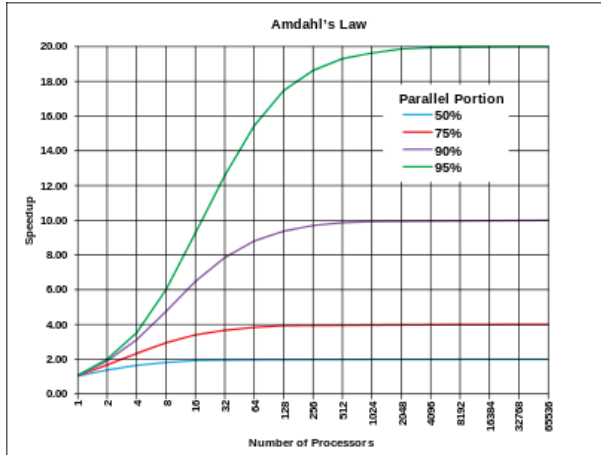

Figure 1: Amdahl's law

3

1.1 Why Julia

Ricordare che precedenti versioni erano in python
Semplicita
Efficienza
Capacita di realizzare programmi paralleli con poco sforzo

2 Software structure

2.1 Julia packages

This software will be distributed as a Julia Package. For the actual release (Julia 0.4) a package is a simple git project with the structure showed in figure 2
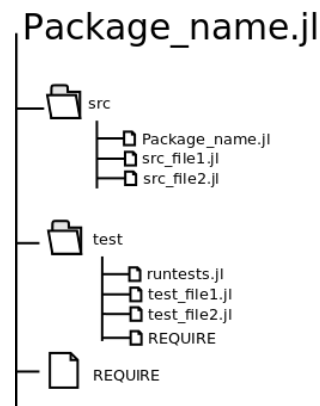

Figure 2: Julia module structure

Source code must be in folder `src`, while in `test` folder there are module tests with a `runtests.jl` for executing them and with a `REQUIRE` file for specifying tests dependencies. For listing dependencies for the entire project, there is another REQUIRE file in main folder. As an example in figure 3 there is the REQUIRE file for `ImagesToLARModel.jl`.

After creating this structure for a project it can be pushed on a git repository and installed on Julia systems. The usual installation procedure use this syntax:

```
Pkg.add("Package-name")
```

This will check for that package in METADATA.jl repository on github where there are all official Julia package. However it is also possible to install an unofficial package (on a public git repository) using this sintax:

julia 0.3
JSON
Logging
PyCall
Images
Colors

Figure 3: REQUIRE contents for `ImagesToLARModel.jl`

```
Pkg.clone("git://repository-address.git")
```

This will install the package on your system with all the dependencies listed in RE-QUIRE file.

2.2 Architecture of ImagesToLARModel

In previous section we have seen how to create a Julia package for distribute our application. Now we focus on the structure of our application. In `src` folder we can find the following modules:

ImagesToLARModel.jl: main module for the software, it takes input parameters and start images conversion

ImagesConvertion.jl: it is called by `ImagesToLARModel.jl` module and controls the entire conversion process calling all other modules

GenerateBorderMatrix.jl: it generates the boundary operator for grid specified in input, saving it in a JSON file

PngStack2Array3dJulia.jl: it is responsible of images loading and conversion into computable data

Lar2Julia.jl: it contains a small subset of LAR functions written in Julia language

LARUtils.jl: it contains utility functions for manipulation of LAR models

Model2Obj.jl: it contains function that manipulates obj files

larcc.py: python larcc module for boundary computation. In next releases of the software it will be rewritten in Julia language

In figure 4 there is a simple schema of dependencies between modules.

Next sections of this document will explain in details all these modules showing also the code involved in conversion
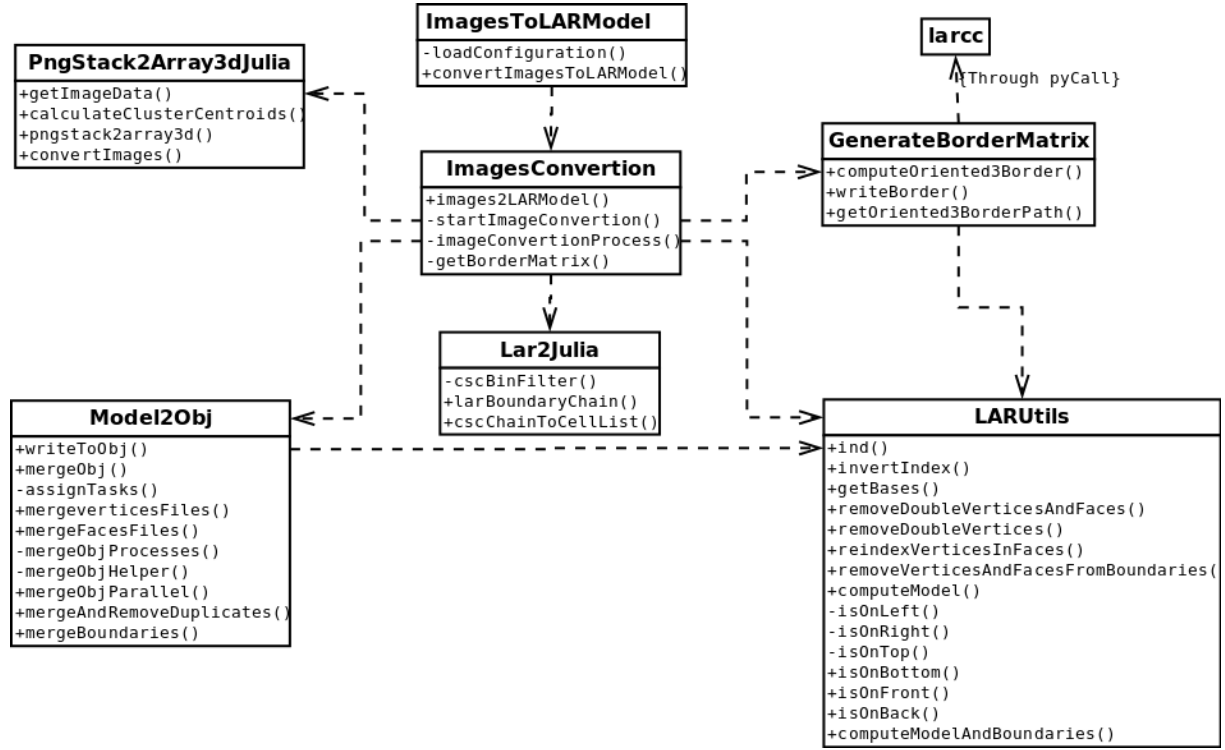
Figure 4: Schema of module dependencies of ImagesToLARModel

3   ImagesToLARModel

This is the main module for the application; it takes the input data and start conversion calling `ImagesConvertion.jl`.

3.1   Calling modules

As we have already said, this first module has the responsibility of starting the conversion calling all other modules in the package. In Julia calling modules requires that they are in a path specified by `LOAD PATH` array. So at the beginning of this module we need to add this line:

⟨ *update load path* 6 ⟩ ≡

```
    push!(LOAD_PATH, Pkg.dir("ImagesToLARModel/src"))
    ◇
```

Fragment referenced in 23a.

`Pkg.dir()` function gives us the path of the Julia installation, so `Pkg.dir("ImagesToLARModel/src")` returns "⟨*Julia − path*⟩/*ImagesToLARModel/src*"

After this line we can now import all modules defined here and export public functions:

⟨ *modules import ImagesToLARModel* 7a ⟩ ≡

```
import JSON
import ImagesConvertion

using Logging

export convertImagesToLARModel
```

◇

Fragment referenced in 23a.

3.2   Input loading

Images conversion takes several parameters:

- inputDirectory: The path of the directory containing the stack of images

- outputDirectory: The path of the directory containing the output

- bestImage: Image chosen for centroid computation (see section 4)

- nx, ny, nz: Sizes of the grid chosen for image segmentation (see section 4)

- DEBUG_LEVEL: Debug level for Julia logger

- parallelMerge (experimental): Choose between sequential or parallel merge of files (see section 9)

Because of their number it has been realized a function for simply loading them from a JSON configuration file; this is the code:

⟨ *load JSON configuration* 7b ⟩ ≡

```
function loadConfiguration(configurationFile)
  """
  load parameters from JSON file

  configurationFile: Path of the configuration file
  """
```

```
      configuration = JSON.parse(configurationFile)

      DEBUG_LEVELS = [DEBUG, INFO, WARNING, ERROR, CRITICAL]

      parallelMerge = false
      try
        if configuration["parallelMerge"] == "true"
          parallelMerge = true
        else
          parallelMerge = false
        end
      catch
      end

      return configuration["inputDirectory"], configuration["outputDirectory"],
             configuration["bestImage"],
             configuration["nx"], configuration["ny"], configuration["nz"],
             DEBUG_LEVELS[configuration["DEBUG_LEVEL"]],
             parallelMerge

    end
    ◇
```

Fragment referenced in 23a.

A valid JSON file has the following structure:

{
  "inputDirectory": "Path of the input directory",
  "outputDirectory": "Path of the output directory",
  "bestImage": "Name of the best image (with extension) ",
  "nx": x grid size,
  "ny": y grid size,
  "nz": border z,
  "DEBUG_LEVEL": julia Logging level (can be a number from 1 to 5)
  "parallelMerge": "true" or "false"
}

For example, we can write:

{
  "inputDirectory": "/home/juser/IMAGES/"

"outputDirectory": "/home/juser/OUTPUT/",
"bestImage": "0009.tiff",
"nx": 2,
"ny": 2,
"nz": 2,
"DEBUG_LEVEL": 2
}

As we can see, in a valid JSON configuration file DEBUG_LEVEL can be a number from 1 to 5. Instead, when we explicitly define parameters, DEBUG_LEVEL can only be one of the following Julia constants:

- DEBUG

- INFO

- WARNING

- ERROR

- CRITICAL

3.3   Starting conversion

As we have already said, this module has the only responsibility to collect data input and starts other modules. These are the functions that start the process and the only exposed to the application users:

⟨ *Start conversion from JSON file* 9 ⟩ ≡

```
    function convertImagesToLARModel(configurationFile)
      """
      Start convertion of a stack of images into a 3D model
      loading parameters from a JSON configuration file

      configurationFile: Path of the configuration file
      """
      inputDirectory, outputDirectory, bestImage, nx, ny, nz,
          DEBUG_LEVEL, parallelMerge = loadConfiguration(open(configurationFile))
      convertImagesToLARModel(inputDirectory, outputDirectory, bestImage,
                            nx, ny, nz, DEBUG_LEVEL, parallelMerge)
    end
    ◇
```

Fragment referenced in 23a.

⟨ *Start manual conversion* 10 ⟩ ≡

```
function convertImagesToLARModel(inputDirectory, outputDirectory, bestImage,
                                 nx, ny, nz, DEBUG_LEVEL = INFO, parallelMerge = false)
    """
    Start convertion of a stack of images into a 3D model

    inputDirectory: Directory containing the stack of images
    outputDirectory: Directory containing the output
    bestImage: Image chosen for centroids computation
    nx, ny, nz: Border dimensions (Possibly the biggest power of two of images dimensions)
    DEBUG_LEVEL: Debug level for Julia logger. It can be one of the following:
        - DEBUG
        - INFO
        - WARNING
        - ERROR
        - CRITICAL
    """
    # Create output directory
    try
      mkpath(outputDirectory)
    catch
    end

    Logging.configure(level=DEBUG_LEVEL)
    ImagesConvertion.images2LARModel(nx, ny, nz, bestImage,
            inputDirectory, outputDirectory, parallelMerge)
end
```
◇

Fragment referenced in 23a.

4   PngStack2Array3dJulia

This module has the responsibility of convert a png image into an array of values that will
be passed to other modules

4.1   Module imports

These are modules needed for this part of the package and the public functions exported

⟨ *modules import PngStack2Array3dJulia* 11a ⟩ ≡

```
using Images # For loading png images
using Colors # For grayscale images
using PyCall # For including python clustering
using Logging
@pyimport scipy.ndimage as ndimage
@pyimport scipy.cluster.vq as cluster

NOISE_SHAPE_DETECT=10

export calculateClusterCentroids, pngstack2array3d, getImageData, convertImages
```
◇

Fragment referenced in 53.

We need `Images` and `Colors` packages for manipulating png images and `PyCall` for using Python functions for clustering and filtering images. As a consequence, we need a python environment with `scipy` to be able to run the package

4.2   Convert input to png

First thing to do in our program is getting our input folder and convert the stack of images into png format. This process lets us to avoid managing an enormous variety of formats during computation, simplifying code used for transformation.

Convertion needs the following parameters:

- inputPath: path of the folder containing the original images

- outputPath: path where we will save png images

- bestImage: name of the image chosen for centroids computing (see section 4.4)

After conversion *outputPath* will contain our png images and the function will return the new name chosen for the best image.

Now we can examine single parts of conversion process. First of all we need to specify a new name for images, keeping the right order between them; so we need to define a prefix based on number of images:

⟨ *Define string prefix* 11b ⟩ ≡

```
imageFiles = readdir(inputPath)
numberOfImages = length(imageFiles)
outputPrefix = ""
for i in 1: length(string(numberOfImages)) - 1
  outputPrefix = string(outputPrefix,"0")
end ◇
```

Fragment referenced in 14.

Next we need to open the single image doing the following operations:

1. Open images using `Images` library (which relies on `ImageMagick`) and save them in greyscale png format

2. if one or both dimensions of the image are odd we need to remove one row (or column) of pixels to make it even. This will be more clear when we will introduce the grid for parallel computation (see section 5)

⟨ *Greyscale conversion* 12a ⟩ ≡
```
rgb_img = convert(Image{ColorTypes.RGB}, img)
gray_img = convert(Image{ColorTypes.Gray}, rgb_img) ◇
```

Fragment referenced in 14.

As we can see, we first need to convert image to RGB and then reconverting to greyscale. Without the RGB conversion these rows will return a stackoverflow error due to the presence of alpha channel

⟨ *Image resizing* 12b ⟩ ≡
```
# resizing images if they do not have even dimensions
dim = size(img)
if(dim[1] % 2 != 0)
  debug("Image has odd x; resizing")
  xrange = 1: dim[1] - 1
else
  xrange = 1: dim[1]
end

if(dim[2] % 2 != 0)
  debug("Image has odd y; resizing")
  yrange = 1: dim[2] - 1
```

```
      else
        yrange = 1: dim[2]
      end

      img = subim(gray_img, xrange, yrange) ◇
```

Fragment referenced in 14.

Next we just have to search for the best image and add one image if they are odd (for same
reasons we need even image dimensions)

⟨ *Search for best image* 13a ⟩ ≡
```
      # Searching the best image
      if(imageFile == bestImage)
        newBestImage = string(outputPrefix[length(string(imageNumber)):end],
                               imageNumber,".png")
      end
      imageNumber += 1 ◇
```

Fragment referenced in 14.

⟨ *Add one image* 13b ⟩ ≡
```
      # Adding another image if they are odd
      if(numberOfImages % 2 != 0)
        debug("Odd images, adding one")
        imageWidth, imageHeight = getImageData(string(outputPath, "/", newBestImage))

        if(imageWidth % 2 != 0)
          imageWidth -= 1
        end

        if(imageHeight % 2 != 0)
          imageHeight -= 1
        end

        imArray = zeros(Uint8, (imageWidth, imageHeight))
        img = grayim(imArray)
        outputFilename = string(outputPath, "/",
                         outputPrefix[length(string(imageNumber)):end], imageNumber,".png")
        imwrite(img, outputFilename)
      end ◇
```

13

Fragment referenced in 14.

Finally this is the code for the entire function:

⟨ *Convert to png* 14 ⟩ ≡

```
function convertImages(inputPath, outputPath, bestImage)
  """
  Get all images contained in inputPath directory
  saving them in outputPath directory in png format.
  If images have one of two odd dimensions, they will be resized
  and if folder contains an odd number of images another one will be
  added

  inputPath: Directory containing input images
  outputPath: Temporary directory containing png images
  bestImage: Image chosen for centroids computation

  Returns the new name for the best image
  """

  ⟨ Define string prefix 11b ⟩

  newBestImage = ""
  imageNumber = 0
  for imageFile in imageFiles
    img = imread(string(inputPath, imageFile))
    ⟨ Greyscale conversion 12a ⟩
    ⟨ Image resizing 12b ⟩
    outputFilename = string(outputPath, outputPrefix[length(string(imageNumber)):end],
                            imageNumber,".png")
    imwrite(img, outputFilename)

    ⟨ Search for best image 13a ⟩

  end

  ⟨ Add one image 13b ⟩

  return newBestImage
end
```
◇

Fragment referenced in 53.

4.3 Getting data from a png

Now we need to load information data from png images. In particular we are interested in getting width and height of an image. As stated in [W3C] document, a standard PNG file contains a *signature* followed by a sequence of *chunks* (each one with a specific type).

The signature always contain the following values:

137 80 78 71 13 10 26 10

This signature indicates that the remainder of the datastream contains a single PNG image, consisting of a series of chunks beginning with an `IHDR` chunk and ending with an `IEND` chunk. Every chunk is preceded by four bytes indicating its length.

As we are interested in width and height we need to parse the `IHDR` chunk. It is the first chunk in PNG datastream and its type field contains the decimal values:

73 72 68 82

The header also contains:

Width	4 bytes
Height	4 bytes
Bit depth	1 bytes
Color type	1 byte
Compression method	1 byte
Filter method	1 byte
Interlace method	1 byte

So for reading width and height we need first 24 bytes; the first eight contain the signature, then we have four bytes for length, four bytes for the type field and eight bytes for information we are interested in. This is the code:

⟨ *Get image data* 15 ⟩ ≡

```
function getImageData(imageFile)
  """
  Get width and height from a png image
  """

  input = open(imageFile, "r")
  data = readbytes(input, 24)

  if (convert(Array{Int},data[1:8]) != reshape([137 80 78 71 13 10 26 10],8))
    error("This is not a valid png image")
  end
```

15

```
      w = data[17:20]
      h = data[21:24]

      width = reinterpret(Int32, reverse(w))[1]
      height = reinterpret(Int32, reverse(h))[1]

      close(input)

      return width, height
    end
    ◇
```

Fragment referenced in 53.

4.4 Centroids computation

As we have seen above, this package uses greyscale images for conversion into three-dimensional models and for next steps we need binary images so we can distinguish between the background and the model we want to represent. We can use clustering techniques for obtaining this result. First step is centroids calculation from a chosen image (this choice must be made from the user, because we cannot knowing in advance what is the best image for finding clusters). Moreover we compute these centroids only for an image and then reuse them when we want to cluster all other images, saving processing time.
Actually we need only two centroids, because next steps should only recognize between background and foreground pixels. This is the code used for centroid computation:

⟨ *Centroid computation* 16 ⟩ ≡

```
    function calculateClusterCentroids(path, image, numberOfClusters = 2)
      """
      Loads an image and calculate cluster centroids for segmentation

      path: Path of the image folder
      image: name of the image
      numberOfClusters: number of desidered clusters
      """
      imageFilename = string(path, image)

      img = imread(imageFilename) # Open png image with Julia Package

      imArray = raw(img)

      imageWidth = size(imArray)[1]
```

16

```
    imageHeight = size(imArray)[2]

    # Getting pixel values and saving them with another shape
    image3d = Array(Array{Uint8,2}, 0)

    # Inserting page on another list and reshaping
    push!(image3d, imArray)
    pixel = reshape(image3d[1], (imageWidth * imageHeight), 1)

    centroids,_ = cluster.kmeans(pixel, numberOfClusters)

    return centroids

end
◇
```

Fragment referenced in 53.

4.5   Transform pixels to three-dimensional array

Now we can study the most important part of this module, where images are converted into data usable by other modules for the creation of the three-dimensional model. The basic concept consists in transforming every single pixel in an integer value representing color, and then clustering them all using centroids computed earlier. So, we can obtain a matrix containing only two values (the two centroids) representing background and foreground of the image.
Now we will follow the code. This function uses four parameters

- path: Path of the images directory

- minSlice: First image to read

- maxSlice: Last image to read

- centroids: Array containing centroids for clustering

For every image we want to transform in the interval [minSlice, maxSlice) we have to read it from disk and save pixel informations into a multidimensional Array:

⟨ *Read raw data* 17 ⟩ ≡
```
    img = imread(imageFilename) # Open png image with Julia Package
    imArray = raw(img) # Putting pixel values into RAW 3d array ◇
```
Fragment referenced in 20.

The `Images.jl raw` function, get all pixel values saving them in an Array. In Figure 7 we can see how the array will be like for a sample greyscale image.
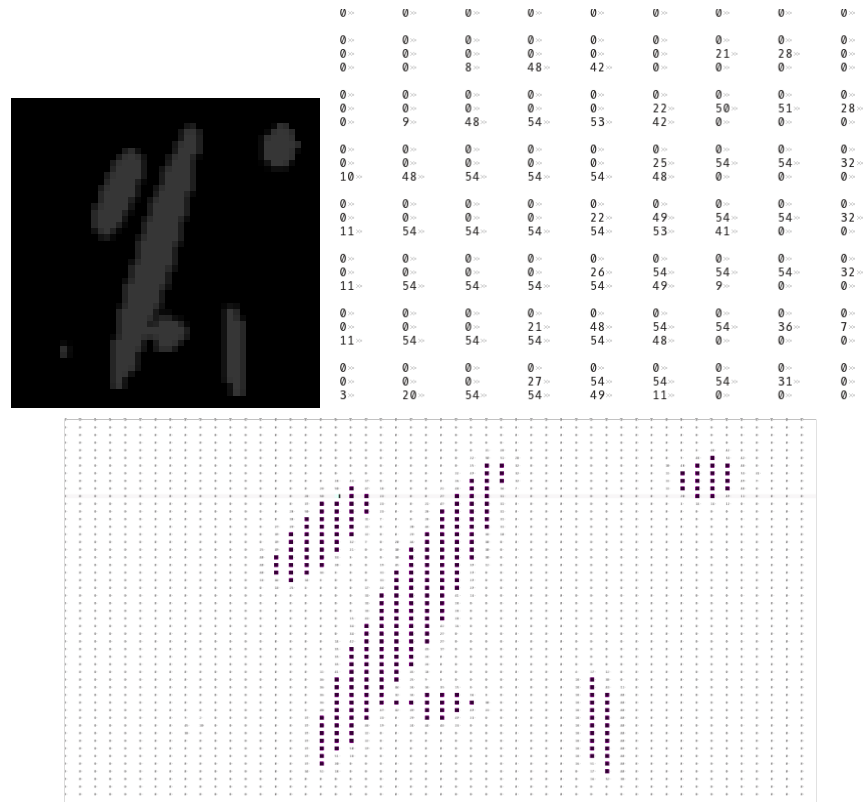

Figure 5: Reading raw data from image. (a) Original greyscale image (b) A view of raw data array (c) The entire raw data array with main color highlighted

Next we have to reduce noise on the image. The better choice is using a *median filter* from package `scipy.ndimage` because it preserves better the edges of the image:

⟨ *Reduce noise* 18 ⟩ ≡
```
    # Denoising
    image3d[page] = ndimage.median_filter(image3d[page], NOISE_SHAPE_DETECT) ◇
```
Fragment referenced in 20.

Where image3d is an array containing all raw data from images

Finally we have to compute clusters (using `scipy`) obtaining images with only two values:

⟨ *Clustering images* 19 ⟩ ≡

```
# Image Quantization
debug("page = ", page)
debug("image3d[page] dimensions: ", size(image3d[page])[1], "\t", size(image3d[page])[2])
pixel = reshape(image3d[page], size(image3d[page])[1] * size(image3d[page])[2] , 1)
qnt,_ = cluster.vq(pixel,centroids)

# Reshaping quantization result
centers_idx = reshape(qnt, size(image3d[page],1), size(image3d[page],2))
#centers_idx = reshape(qnt, size(image3d[page]))

# Inserting quantized values into 3d image array
tmp = Array(Uint8, size(image3d[page],1), size(image3d[page],2))

for j in 1:size(image3d[1],2)
  for i in 1:size(image3d[1],1)
    tmp[i,j] = centroids[centers_idx[i,j] + 1]
  end
end

image3d[page] = tmp ◇
```
Fragment referenced in 20.

Figure 6: Image transformation. (a) Original greyscale image (b) Denoised image (c) Two-colors image

This is the complete code:

⟨ *Pixel transformation* 20 ⟩ ≡

```
    function pngstack2array3d(path, minSlice, maxSlice, centroids)
      """
      Import a stack of PNG images into a 3d array

      path: path of images directory
      minSlice and maxSlice: number of first and last slice
      centroids: centroids for image segmentation
      """

      # image3d contains all images values
      image3d = Array(Array{Uint8,2}, 0)

      debug("maxSlice = ", maxSlice, " minSlice = ", minSlice)
      files = readdir(path)

      for slice in minSlice : (maxSlice - 1)
        debug("slice = ", slice)
        imageFilename = string(path, files[slice + 1])
        debug("image name: ", imageFilename)
```
        ⟨ *Read raw data* 17 ⟩
```
        debug("imArray size: ", size(imArray))

        # Inserting page on another list and reshaping
        push!(image3d, imArray)

      end

      # Removing noise using a median filter and quantization
      for page in 1:length(image3d)
```

        ⟨ *Reduce noise* 18 ⟩

        ⟨ *Clustering images* 19 ⟩

```
      end

      return image3d
    end
```
◇

Fragment referenced in 53.

5 ImagesConvertion

Now we will study the most important module for this package: `ImagesConvertion`. It has the responsibility of doing the entire conversion process delegating tasks to the other modules.

5.1 General algorithm

Now we will examine, in a general way, the algorithm used for convertion from a two-dimensional to a three-dimensional representation of our biomedical models.
We have already seen in section 4 how to get information from a png image, obtaining arrays with only two values; one for the **background** color and one for **foreground** color. This is only the first step of the complete conversion process.

Now we focus only on a single image of the stack. Our two-dimensional representation, consists of pixels of two different colors (where only the one associated with foreground is significant); so we can obtain a three-dimensional representation simply replacing every foreground pixel with a small cube. Focusing on the entire stack of images, the full three-dimensional representation can be obtained simply overlapping all the image representations

This algorithm is very simple, however we does not considered problems concerning lack of memory. In fact, we could have images so big that we cannot build these models entirely in memory; moreover they would require a lot of CPU time for computation. A good solution to these problems consists in taking our representation based on images and divide according to a **grid**.

So, instead of converting the entire model with a unique process, we can subdivide the input among a lot of processes, where every process will execute the conversion process on a small number of **blocks** according to the grid subdivision.

Summing up we can define the following terms, which will be used in next parts of this documentation:

- **Grid:** It is the subdivision of the entire stack of images, with sizes defined by the user. They should be powers of two (for increasing performance during border matrix computation which we will see in section 6)

- **Block:** It is a single cell of the grid

- **xBlock:** It is the x-coordinate of a block

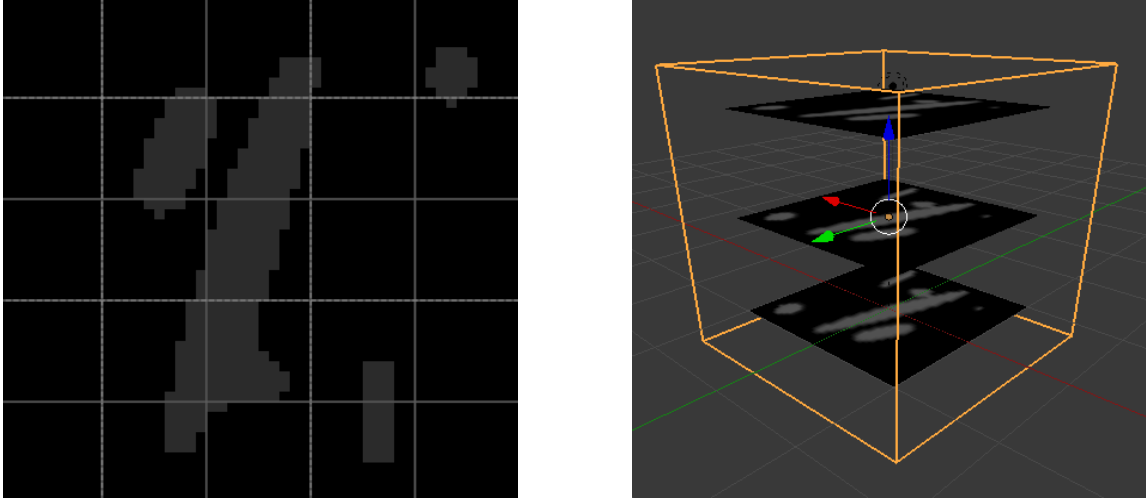- **yBlock:** It is the y-coordinate of a block

Figure 7: The grid used for parallel computation (a) 2D grid on a single image (b) 3D grid for the stack of images

- **zBlock:** It is the z-coordinate of a block

xBlock and *yBlock* are defined on a single image, while *zBlock* is defined on different images; in the code it will often be replaced by terms **StartImage** and **EndImage**, which indicate the first image and the last image of that block respectively.

In next subsections we will examine the conversion algorithm in detail, showing what happens for every block of the grid.

5.2 Module imports

These are modules needed for this part of the package and the public functions exported

⟨ *modules import ImagesConvertion* 22 ⟩ ≡

◇

Fragment never referenced.

6   GenerateBorderMatrix

7   Lar2Julia

8   LARUtils

9   Model2Obj

10   Exporting the library

ImagesToLARModel

`"src/ImagesToLARModel.jl" 23a≡`

```
module ImagesToLARModel

⟨ update load path 6 ⟩

⟨ modules import ImagesToLARModel 7a ⟩
⟨ load JSON configuration 7b ⟩
⟨ Start conversion from JSON file 9 ⟩
⟨ Start manual conversion 10 ⟩
end
◇
```

ImagesConvertion

`"src/ImagesConvertion.jl" 23b≡`

```
module ImagesConvertion

import GenerateBorderMatrix
import PngStack2Array3dJulia
import Lar2Julia
import Model2Obj
import LARUtils

import JSON

using PyCall
@pyimport scipy.sparse as Pysparse

using Logging
```

```
export images2LARModel

"""
This is main module for converting a stack
of images into a 3d model
"""

function images2LARModel(nx, ny, nz, bestImage, inputDirectory, outputDirectory, parallelMerge)
  """
  Convert a stack of images into a 3d model
  """

  info("Starting model creation")

  numberOfClusters = 2 # Number of clusters for
                       # images segmentation

  info("Moving images into temp directory")
  try
    mkdir(string(outputDirectory, "TEMP"))
  catch
  end

  tempDirectory = string(outputDirectory,"TEMP/")

  newBestImage = PngStack2Array3dJulia.convertImages(inputDirectory, tempDirectory, bestImage)

  imageWidth, imageHeight = PngStack2Array3dJulia.getImageData(string(tempDirectory,newBestImage))
  imageDepth = length(readdir(tempDirectory))

  # Computing border matrix
  info("Computing border matrix")
  try
    mkdir(string(outputDirectory, "BORDERS"))
  catch
  end
  borderFilename = GenerateBorderMatrix.getOriented3BorderPath(string(outputDirectory, "BORDERS"

  # Starting images convertion and border computation
  info("Starting images convertion")
  startImageConvertion(tempDirectory, newBestImage, outputDirectory, borderFilename,
                       imageHeight, imageWidth, imageDepth,
                       nx, ny, nz,
                       numberOfClusters, parallelMerge)
```

```
end

function startImageConvertion(sliceDirectory, bestImage, outputDirectory, borderFilename,
                              imageHeight, imageWidth, imageDepth,
                              imageDx, imageDy, imageDz,
                              numberOfClusters, parallelMerge)
  """
  Support function for converting a stack of images into a model

  sliceDirectory: directory containing the image stack
  imageForCentroids: image chosen for centroid computation
  """

  # Create clusters for image segmentation
  info("Computing image centroids")
  debug("Best image = ", bestImage)
  centroidsCalc = PngStack2Array3dJulia.calculateClusterCentroids(sliceDirectory, bestImage, n
  debug(string("centroids = ", centroidsCalc))

  try
    mkdir(string(outputDirectory, "BORDERS"))
  catch
  end
  debug(string("Opening border file: ", "border_", imageDx, "-", imageDy, "-", imageDz, ".json
  boundaryMat = getBorderMatrix(string(outputDirectory,"BORDERS/","border_", imageDx, "-",
                                       imageDy, "-", imageDz, ".json"))
  beginImageStack = 0
  endImage = beginImageStack

  info("Converting images into a 3d model")
  tasks = Array(RemoteRef, 0)
  for zBlock in 0:(imageDepth / imageDz - 1)
    startImage = endImage
    endImage = startImage + imageDz
    info("StartImage = ", startImage)
    info("endImage = ", endImage)

    task = @spawn imageConvertionProcess(sliceDirectory, outputDirectory,
                            beginImageStack, startImage, endImage,
                            imageDx, imageDy, imageDz,
                            imageHeight, imageWidth,
                            centroidsCalc, boundaryMat)

    push!(tasks, task)
  end
```

```
  # Waiting for tasks completion
  for task in tasks
    wait(task)
  end

  info("Merging boundaries")
  # Merge Boundaries files
  Model2Obj.mergeBoundaries(string(outputDirectory, "MODELS"),
                            imageHeight, imageWidth, imageDepth,
                            imageDx, imageDy, imageDz)

  info("Merging obj models")
  if parallelMerge
    Model2Obj.mergeObjParallel(string(outputDirectory, "MODELS"))
  else
    Model2Obj.mergeObj(string(outputDirectory, "MODELS"))
  end

end

function imageConvertionProcess(sliceDirectory, outputDirectory,
                               beginImageStack, startImage, endImage,
                               imageDx, imageDy, imageDz,
                               imageHeight, imageWidth,
                               centroids, boundaryMat)
  """
  Support function for converting a stack of image on a single
  independent process
  """

  info("Transforming png data into 3d array")
  theImage = PngStack2Array3dJulia.pngstack2array3d(sliceDirectory, startImage, endImage, cent

  centroidsSorted = sort(vec(reshape(centroids, 1, 2)))
  foreground = centroidsSorted[2]
  background = centroidsSorted[1]
  debug(string("background = ", background, " foreground = ", foreground))

  for xBlock in 0:(imageHeight / imageDx - 1)
    for yBlock in 0:(imageWidth / imageDy - 1)
      yStart = xBlock * imageDx
      xStart = yBlock * imageDy
      #xEnd = xStart + imageDx
      #yEnd = yStart + imageDy
      xEnd = xStart + imageDy
      yEnd = yStart + imageDx
```

```
debug("**********")
debug(string("xStart = ", xStart, " xEnd = ", xEnd))
debug(string("yStart = ", yStart, " yEnd = ", yEnd))
debug("theImage dimensions: ", size(theImage)[1], " ", size(theImage[1])[1], " ", size(t

# Getting a slice of theImage array

image = Array(Uint8, (convert(Int, length(theImage)), convert(Int, xEnd - xStart), conve
debug("image size: ", size(image))
for z in 1:length(theImage)
  for x in 1 : (xEnd - xStart)
    for y in 1 : (yEnd - yStart)
      image[z, x, y] = theImage[z][x + xStart, y + yStart]
    end
  end
end

nz, nx, ny = size(image)
chains3D = Array(Uint8, 0)
zStart = startImage - beginImageStack
for y in 0:(nx - 1)
  for x in 0:(ny - 1)
    for z in 0:(nz - 1)
      if(image[z + 1, x + 1, y + 1] == foreground)
        push!(chains3D, y + ny * (x + nx * z))
      end
    end
  end
end

if(length(chains3D) != 0)
  # Computing boundary chain
  debug("chains3d = ", chains3D)
  debug("Computing boundary chain")
  objectBoundaryChain = Lar2Julia.larBoundaryChain(boundaryMat, chains3D)
  debug("Converting models into obj")
  try
    mkdir(string(outputDirectory, "MODELS"))
  catch
  end
  # IMPORTANT: inverting xStart and yStart for obtaining correct rotation of the model
  models = LARUtils.computeModelAndBoundaries(imageDx, imageDy, imageDz, yStart, xStart,

  V, FV = models[1][1] # inside model
  V_left, FV_left = models[2][1]
  V_right, FV_right = models[3][1] # right boundary
```

```
            V_top, FV_top = models[4][1] # top boundary
            V_bottom, FV_bottom = models[5][1] # bottom boundary
            V_front, FV_front = models[6][1] # front boundary
            V_back, FV_back = models[7][1] # back boundary

            # Writing all models on disk
            model_outputFilename = string(outputDirectory, "MODELS/model_output_", xBlock, "-", yB]
            Model2Obj.writeToObj(V, FV, model_outputFilename)

            left_outputFilename = string(outputDirectory, "MODELS/left_output_", xBlock, "-", yBloc
            Model2Obj.writeToObj(V_left, FV_left, left_outputFilename)

            right_outputFilename = string(outputDirectory, "MODELS/right_output_", xBlock, "-", yB]
            Model2Obj.writeToObj(V_right, FV_right, right_outputFilename)

            top_outputFilename = string(outputDirectory, "MODELS/top_output_", xBlock, "-", yBlock
            Model2Obj.writeToObj(V_top, FV_top, top_outputFilename)

            bottom_outputFilename = string(outputDirectory, "MODELS/bottom_output_", xBlock, "-", y
            Model2Obj.writeToObj(V_bottom, FV_bottom, bottom_outputFilename)

            front_outputFilename = string(outputDirectory, "MODELS/front_output_", xBlock, "-", yB]
            Model2Obj.writeToObj(V_front, FV_front, front_outputFilename)

            back_outputFilename = string(outputDirectory, "MODELS/back_output_", xBlock, "-", yBloc
            Model2Obj.writeToObj(V_back, FV_back, back_outputFilename)
        else
          debug("Model is empty")
        end
      end
    end
end

function getBorderMatrix(borderFilename)
  """
  TO REMOVE WHEN PORTING OF LARCC IN JULIA IS COMPLETED

  Get the border matrix from json file and convert it in
  CSC format
  """
  # Loading borderMatrix from json file
  borderData = JSON.parsefile(borderFilename)
  row = Array(Int64, length(borderData["ROW"]))
  col = Array(Int64, length(borderData["COL"]))
  data = Array(Int64, length(borderData["DATA"]))
```

```julia
    for i in 1: length(borderData["ROW"])
      row[i] = borderData["ROW"][i]
    end

    for i in 1: length(borderData["COL"])
      col[i] = borderData["COL"][i]
    end

    for i in 1: length(borderData["DATA"])
      data[i] = borderData["DATA"][i]
    end

    # Converting csr matrix to csc
    csrBorderMatrix = Pysparse.csr_matrix((data,col,row), shape=(borderData["ROWCOUNT"],borderDa
    denseMatrix = pycall(csrBorderMatrix["toarray"],PyAny)

    cscBoundaryMat = sparse(denseMatrix)

    return cscBoundaryMat

  end
  end
  ◇
```

GenerateBorderMatrix

"src/GenerateBorderMatrix.jl" 29≡

```julia
    module GenerateBorderMatrix

    type MatrixObject
      ROWCOUNT
      COLCOUNT
      ROW
      COL
      DATA
    end


    export computeOriented3Border, writeBorder, getOriented3BorderPath

    import LARUtils
    using PyCall
```

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```
import JSON

@pyimport sys
unshift!(PyVector(pyimport("sys")["path"]), "") # Search for python modules in folder
# Search for python modules in package folder
unshift!(PyVector(pyimport("sys")["path"]), Pkg.dir("ImagesToLARModel/src"))
@pyimport larcc # Importing larcc from local folder

# Compute the 3-border operator
function computeOriented3Border(nx, ny, nz)
  """
  Compute the 3-border matrix using a modified
  version of larcc
  """
  V, bases = LARUtils.getBases(nx, ny, nz)
  boundaryMat = larcc.signedCellularBoundary(V, bases)
  return boundaryMat

end

function writeBorder(boundaryMatrix, outputFile)
  """
  Write 3-border matrix on json file

  boundaryMatrix: matrix to write on file
  outputFile: path of the outputFile
  """

  rowcount = boundaryMatrix[:shape][1]
  colcount = boundaryMatrix[:shape][2]

  row = boundaryMatrix[:indptr]
  col = boundaryMatrix[:indices]
  data = boundaryMatrix[:data]

  # Writing informations on file
  outfile = open(outputFile, "w")

  matrixObj = MatrixObject(rowcount, colcount, row, col, data)
  JSON.print(outfile, matrixObj)
  close(outfile)

end

function getOriented3BorderPath(borderPath, nx, ny, nz)
  """
```

```
        Try reading 3-border matrix from file. If it fails matrix
        is computed and saved on disk in JSON format

        borderPath: path of border directory
        nx, ny, nz: image dimensions
        """

        filename = string(borderPath,"/border_", nx, "-", ny, "-", nz, ".json")
        if !isfile(filename)
          border = computeOriented3Border(nx, ny, nz)
          writeBorder(border, filename)
        end
        return filename

    end
    end
    ◇
```

Lar2Julia

"src/Lar2Julia.jl" 31≡

```
    module Lar2Julia

    export larBoundaryChain, cscChainToCellList

    import JSON

    using Logging

    function larBoundaryChain(cscBoundaryMat, brcCellList)
        """
        Compute boundary chains
        """

        # Computing boundary chains
        n = size(cscBoundaryMat)[1]
        m = size(cscBoundaryMat)[2]

        debug("Boundary matrix size: ", n, "\t", m)

        data = ones(Int64, length(brcCellList))

        i = Array(Int64, length(brcCellList))
```

```
  for k in 1:length(brcCellList)
    i[k] = brcCellList[k] + 1
  end

  j = ones(Int64, length(brcCellList))

  debug("cscChain rows length: ", length(i))
  debug("cscChain columns length: ", length(j))
  debug("cscChain data length: ", length(brcCellList))

  debug("rows ", i)
  debug("columns ", j)
  debug("data ", data)

  cscChain = sparse(i, j, data, m, 1)
  cscmat = cscBoundaryMat * cscChain
  out = cscBinFilter(cscmat)
  return out
end

function cscBinFilter(CSCm)
  k = 1
  data = nonzeros(CSCm)
  sgArray = copysign(1, data)

  while k <= nnz(CSCm)
    if data[k] % 2 == 1 || data[k] % 2 == -1
      data[k] = 1 * sgArray[k]
    else
      data[k] = 0
    end
    k += 1
  end

  return CSCm
end

function cscChainToCellList(CSCm)
  """
  Get a csc containing a chain and returns
  the cell list of the "+1" oriented faces
  """
  data = nonzeros(CSCm)
  # Now I need to remove zero element (problem with Julia nonzeros)
  nonzeroData = Array(Int64, 0)
  for n in data
```

```
        if n != 0
          push!(nonzeroData, n)
        end
      end
    end

    cellList = Array(Int64,0)
    for (k, theRow) in enumerate(findn(CSCm)[1])
      if nonzeroData[k] == 1
        push!(cellList, theRow)
      end
    end
    return cellList
  end
  end
  ◇
```

LARUtils

"src/LARUtils.jl" 33≡

```
    module LARUtils

    using Logging

    export ind, invertIndex, getBases, removeDoubleVerticesAndFaces, computeModel, computeModelAndl

    function ind(x, y, z, nx, ny)
        """
        Transform coordinates into linearized matrix indexes
        """
        return x + (nx + 1) * (y + (ny + 1) * (z))
      end


    function invertIndex(nx,ny,nz)
      """
      Invert indexes
      """
      nx, ny, nz = nx + 1, ny + 1, nz + 1
      function invertIndex0(offset)
          a0, b0 = trunc(offset / nx), offset % nx
          a1, b1 = trunc(a0 / ny), a0 % ny
          a2, b2 = trunc(a1 / nz), a1 % nz
          return b0, b1, b2
```

```
    end
    return invertIndex0
end


function getBases(nx, ny, nz)
  """
  Compute all LAR relations
  """

  function the3Dcell(coords)
    x,y,z = coords
    return [ind(x,y,z,nx,ny),ind(x+1,y,z,nx,ny),ind(x,y+1,z,nx,ny),ind(x,y,z+1,nx,ny),ind(x+1,
           ind(x+1,y,z+1,nx,ny),ind(x,y+1,z+1,nx,ny),ind(x+1,y+1,z+1,nx,ny)]
  end

  # Calculating vertex coordinates (nx * ny * nz)
  V = Array{Int64}[]
  for z in 0:nz
    for y in 0:ny
      for x in 0:nx
        push!(V,[x,y,z])
      end
    end
  end

  # Building CV relationship
  CV = Array{Int64}[]
  for z in 0:nz-1
    for y in 0:ny-1
      for x in 0:nx-1
        push!(CV,the3Dcell([x,y,z]))
      end
    end
  end

  # Building FV relationship
  FV = Array{Int64}[]
  v2coords = invertIndex(nx,ny,nz)

  for h in 0:(length(V)-1)
    x,y,z = v2coords(h)

    if (x < nx) && (y < ny)
      push!(FV, [h,ind(x+1,y,z,nx,ny),ind(x,y+1,z,nx,ny),ind(x+1,y+1,z,nx,ny)])
    end
```

```
    if (x < nx) && (z < nz)
      push!(FV, [h,ind(x+1,y,z,nx,ny),ind(x,y,z+1,nx,ny),ind(x+1,y,z+1,nx,ny)])
    end

    if (y < ny) && (z < nz)
      push!(FV,[h,ind(x,y+1,z,nx,ny),ind(x,y,z+1,nx,ny),ind(x,y+1,z+1,nx,ny)])
    end

  end

  # Building VV relationship
  VV = map((x)->[x], 0:length(V)-1)

  # Building EV relationship
  EV = Array{Int64}[]
  for h in 0:length(V)-1
    x,y,z = v2coords(h)
    if (x < nx)
      push!(EV, [h,ind(x+1,y,z,nx,ny)])
    end
    if (y < ny)
      push!(EV, [h,ind(x,y+1,z,nx,ny)])
    end
    if (z < nz)
      push!(EV, [h,ind(x,y,z+1,nx,ny)])
    end
  end

  # return all basis
  return V, (VV, EV, FV, CV)
end

function lessThanVertices(v1, v2)
  """
  Utility function for comparing vertices coordinates
  """

  if v1[1] == v2[1]
    if v1[2] == v2[2]
      return v1[3] < v2[3]
    end
    return v1[2] < v2[2]
  end
  return v1[1] < v2[1]
end
```

```
function removeDoubleVerticesAndFaces(V, FV, facesOffset)
  """
  Removes double vertices and faces from a LAR model

  V: Array containing all vertices
  FV: Array containing all faces
  facesOffset: offset for faces indices
  """

  newV, indices = removeDoubleVertices(V)
  reindexedFaces = reindexVerticesInFaces(FV, indices, facesOffset)
  newFV = unique(FV)

  return newV, newFV

end

function removeDoubleVertices(V)
  """
  Remove double vertices from a LAR model

  V: Array containing all vertices of the model
  """

  # Sort the vertices list and returns the ordered indices
  orderedIndices = sortperm(V, lt = lessThanVertices, alg=MergeSort)

  orderedVerticesAndIndices = collect(zip(sort(V, lt = lessThanVertices),
                                          orderedIndices))
  newVertices = Array(Array{Int}, 0)
  indices = zeros(Int, length(V))
  prevv = Nothing
  i = 1
  for (v, ind) in orderedVerticesAndIndices
    if v == prevv
      indices[ind] = i - 1
    else
      push!(newVertices, v)
      indices[ind] = i
      i += 1
      prevv = v
    end
  end
  return newVertices, indices
end
```

```
function reindexVerticesInFaces(FV, indices, offset)
  """
  Reindex vertices indices in faces array

  FV: Faces array of the LAR model
  indices: new Indices for faces
  offset: offset for faces indices
  """

  for f in FV
    for i in 1: length(f)
      f[i] = indices[f[i] - offset] + offset
    end
  end
  return FV
end

function removeVerticesAndFacesFromBoundaries(V, FV)
  """
  Remove vertices and faces duplicates on
  boundaries models

  V,FV: lar model of two merged boundaries
  """

  newV, indices = removeDoubleVertices(V)
  uniqueIndices = unique(indices)

  # Removing double faces on both boundaries
  FV_reindexed = reindexVerticesInFaces(FV, indices, 0)
  FV_unique = unique(FV_reindexed)

  FV_cleaned = Array(Array{Int}, 0)
  for f in FV_unique
    if(count((x) -> x == f, FV_reindexed) == 1)
      push!(FV_cleaned, f)
    end
  end

  # Creating an array of faces with explicit vertices
  FV_vertices = Array(Array{Array{Int}}, 0)

  for i in 1 : length(FV_cleaned)
    push!(FV_vertices, Array(Array{Int}, 0))
    for vtx in FV_cleaned[i]
```

```
      push!(FV_vertices[i], newV[vtx])
    end
  end

  V_final = Array(Array{Int}, 0)
  FV_final = Array(Array{Int}, 0)

  # Saving only used vertices
  for face in FV_vertices
    for vtx in face
      push!(V_final, vtx)
    end
  end

  V_final = unique(V_final)

  # Renumbering FV
  for face in FV_vertices
    tmp = Array(Int, 0)
    for vtx in face
      ind = findfirst(V_final, vtx)
      push!(tmp, ind)
    end
    push!(FV_final, tmp)
  end

  return V_final, FV_final
end

function computeModel(imageDx, imageDy, imageDz,
                      xStart, yStart, zStart,
                      facesOffset, objectBoundaryChain)
  """
  Takes the boundary chain of a part of the entire model
  and returns a LAR model

  imageDx, imageDy, imageDz: Boundary dimensions
  xStart, yStart, zStart: Offset of this part of the model
  facesOffset: Offset for the faces
  objectBoundaryChain: Sparse csc matrix containing the cells
  """

  V, bases = getBases(imageDx, imageDy, imageDz)
  FV = bases[3]

  V_model = Array(Array{Int}, 0)
```

```julia
    FV_model = Array(Array{Int}, 0)

    vertex_count = 1

    #b2cells = Lar2Julia.cscChainToCellList(objectBoundaryChain)
    # Get all cells (independently from orientation)
    b2cells = findn(objectBoundaryChain)[1]

    debug("b2cells = ", b2cells)

    for f in b2cells
      old_vertex_count = vertex_count
      for vtx in FV[f]
        push!(V_model, [convert(Int, V[vtx + 1][1] + xStart),
                        convert(Int, V[vtx + 1][2] + yStart),
                        convert(Int, V[vtx + 1][3] + zStart)])
        vertex_count += 1
      end

      push!(FV_model, [old_vertex_count + facesOffset, old_vertex_count + 1 + facesOffset, old_ve
      push!(FV_model, [old_vertex_count + facesOffset, old_vertex_count + 3 + facesOffset, old_ve
    end

    # Removing double vertices
    return removeDoubleVerticesAndFaces(V_model, FV_model, facesOffset)

end

function isOnLeft(face, V, nx, ny, nz)
  """
  Check if face is on left boundary
  """

  for(vtx in face)
    if(V[vtx + 1][2] != 0)
      return false
    end
  end
  return true

end

function isOnRight(face, V, nx, ny, nz)
  """
  Check if face is on right boundary
  """
```

```
    for(vtx in face)
      if(V[vtx + 1][2] != ny)
        return false
      end
    end
    return true

end

function isOnTop(face, V, nx, ny, nz)
  """
  Check if face is on top boundary
  """

  for(vtx in face)
    if(V[vtx + 1][3] != nz)
      return false
    end
  end
  return true
end

function isOnBottom(face, V, nx, ny, nz)
  """
  Check if face is on bottom boundary
  """

  for(vtx in face)
    if(V[vtx + 1][3] != 0)
      return false
    end
  end
  return true
end

function isOnFront(face, V, nx, ny, nz)
  """
  Check if face is on front boundary
  """

  for(vtx in face)
    if(V[vtx + 1][1] != nx)
      return false
    end
  end
```

```
    return true
end

function isOnBack(face, V, nx, ny, nz)
  """
  Check if face is on back boundary
  """

  for(vtx in face)
    if(V[vtx + 1][1] != 0)
      return false
    end
  end
  return true
end

function computeModelAndBoundaries(imageDx, imageDy, imageDz,
                    xStart, yStart, zStart,
                    objectBoundaryChain)
  """
  Takes the boundary chain of a part of the entire model
  and returns a LAR model splitting the boundaries

  imageDx, imageDy, imageDz: Boundary dimensions
  xStart, yStart, zStart: Offset of this part of the model
  objectBoundaryChain: Sparse csc matrix containing the cells
  """

  function addFaceToModel(V_base, FV_base, V, FV, face, vertex_count)
    """
    Insert a face into a LAR model

    V_base, FV_base: LAR model of the base
    V, FV: LAR model
    face: Face that will be added to the model
    vertex_count: Indices for faces vertices
    """
    new_vertex_count = vertex_count
    for vtx in FV_base[face]
      push!(V, [convert(Int, V_base[vtx + 1][1] + xStart),
                      convert(Int, V_base[vtx + 1][2] + yStart),
                      convert(Int, V_base[vtx + 1][3] + zStart)])
      new_vertex_count += 1
    end
    push!(FV, [vertex_count, vertex_count + 1, vertex_count + 3])
    push!(FV, [vertex_count, vertex_count + 3, vertex_count + 2])
```

```
    return new_vertex_count
end

V, bases = getBases(imageDx, imageDy, imageDz)
FV = bases[3]

V_model = Array(Array{Int}, 0)
FV_model = Array(Array{Int}, 0)

V_left = Array(Array{Int},0)
FV_left = Array(Array{Int},0)

V_right = Array(Array{Int},0)
FV_right = Array(Array{Int},0)

V_top = Array(Array{Int},0)
FV_top = Array(Array{Int},0)

V_bottom = Array(Array{Int},0)
FV_bottom = Array(Array{Int},0)

V_front = Array(Array{Int},0)
FV_front = Array(Array{Int},0)

V_back = Array(Array{Int},0)
FV_back = Array(Array{Int},0)

vertex_count_model = 1
vertex_count_left = 1
vertex_count_right = 1
vertex_count_top = 1
vertex_count_bottom = 1
vertex_count_front = 1
vertex_count_back = 1

#b2cells = Lar2Julia.cscChainToCellList(objectBoundaryChain)
# Get all cells (independently from orientation)
b2cells = findn(objectBoundaryChain)[1]

debug("b2cells = ", b2cells)

for f in b2cells
  old_vertex_count_model = vertex_count_model
  old_vertex_count_left = vertex_count_left
  old_vertex_count_right = vertex_count_right
```

```
      old_vertex_count_top = vertex_count_top
      old_vertex_count_bottom = vertex_count_bottom
      old_vertex_count_front = vertex_count_front
      old_vertex_count_back = vertex_count_back

      # Choosing the right model for vertex
      if(isOnLeft(FV[f], V, imageDx, imageDy, imageDz))
        vertex_count_left = addFaceToModel(V, FV, V_left, FV_left, f, old_vertex_count_left)
      elseif(isOnRight(FV[f], V, imageDx, imageDy, imageDz))
        vertex_count_right = addFaceToModel(V, FV, V_right, FV_right, f, old_vertex_count_right)
      elseif(isOnTop(FV[f], V, imageDx, imageDy, imageDz))
        vertex_count_top = addFaceToModel(V, FV, V_top, FV_top, f, old_vertex_count_top)
      elseif(isOnBottom(FV[f], V, imageDx, imageDy, imageDz))
        vertex_count_bottom = addFaceToModel(V, FV, V_bottom, FV_bottom, f, old_vertex_count_bott
      elseif(isOnFront(FV[f], V, imageDx, imageDy, imageDz))
        vertex_count_front = addFaceToModel(V, FV, V_front, FV_front, f, old_vertex_count_front)
      elseif(isOnBack(FV[f], V, imageDx, imageDy, imageDz))
        vertex_count_back = addFaceToModel(V, FV, V_back, FV_back, f, old_vertex_count_back)
      else
        vertex_count_model = addFaceToModel(V, FV, V_model, FV_model, f, old_vertex_count_model)
      end

    end

    # Removing double vertices
    return [removeDoubleVerticesAndFaces(V_model, FV_model, 0)],
    [removeDoubleVerticesAndFaces(V_left, FV_left, 0)],
    [removeDoubleVerticesAndFaces(V_right, FV_right, 0)],
    [removeDoubleVerticesAndFaces(V_top, FV_top, 0)],
    [removeDoubleVerticesAndFaces(V_bottom, FV_bottom, 0)],
    [removeDoubleVerticesAndFaces(V_front, FV_front, 0)],
    [removeDoubleVerticesAndFaces(V_back, FV_back, 0)]
  end
  end
  ◇
```

Model2Obj

"src/Model2Obj.jl" 43≡

```
    module Model2Obj

    import LARUtils
```

```julia
using Logging

export writeToObj, mergeObj, mergeObjParallel

function writeToObj(V, FV, outputFilename)
  """
  Take a LAR model and write it on obj file

  V: array containing vertices coordinates
  FV: array containing faces
  outputFilename: prefix for the output files
  """

  if (length(V) != 0)
    outputVtx = string(outputFilename, "_vtx.stl")
    outputFaces = string(outputFilename, "_faces.stl")

    fileVertex = open(outputVtx, "w")
    fileFaces = open(outputFaces, "w")

    for v in V
      write(fileVertex, "v ")
      write(fileVertex, string(v[1], " "))
      write(fileVertex, string(v[2], " "))
      write(fileVertex, string(v[3], "\n"))
    end

    for f in FV

      write(fileFaces, "f ")
      write(fileFaces, string(f[1], " "))
      write(fileFaces, string(f[2], " "))
      write(fileFaces, string(f[3], "\n"))
    end

    close(fileVertex)
    close(fileFaces)

  end

end

function mergeObj(modelDirectory)
  """
  Merge stl files in a single obj file
```

```
modelDirectory: directory containing models
"""

files = readdir(modelDirectory)
vertices_files = files[find(s -> contains(s,string("_vtx.stl")), files)]
faces_files = files[find(s -> contains(s,string("_faces.stl")), files)]
obj_file = open(string(modelDirectory,"/","model.obj"),"w") # Output file

vertices_counts = Array(Int64, length(vertices_files))
number_of_vertices = 0
for i in 1:length(vertices_files)
  vtx_file = vertices_files[i]
  f = open(string(modelDirectory, "/", vtx_file))

  # Writing vertices on the obj file
  for ln in eachline(f)
    write(obj_file, ln)
    number_of_vertices += 1
  end
  # Saving number of vertices
  vertices_counts[i] = number_of_vertices
  close(f)
end

for i in 1 : length(faces_files)
  faces_file = faces_files[i]
  f = open(string(modelDirectory, "/", faces_file))
  for ln in eachline(f)
    splitted = split(ln)
    write(obj_file, "f ")
    if i > 1
      write(obj_file, string(parse(splitted[2]) + vertices_counts[i - 1], " "))
      write(obj_file, string(parse(splitted[3]) + vertices_counts[i - 1], " "))
      write(obj_file, string(parse(splitted[4]) + vertices_counts[i - 1]))
    else
      write(obj_file, string(splitted[2], " "))
      write(obj_file, string(splitted[3], " "))
      write(obj_file, splitted[4])
    end
    write(obj_file, "\n")
  end
  close(f)
end
close(obj_file)

# Removing all tmp files
```

```
  for vtx_file in vertices_files
    rm(string(modelDirectory, "/", vtx_file))
  end

  for fcs_file in faces_files
    rm(string(modelDirectory, "/", fcs_file))
  end

end

function assignTasks(startInd, endInd, taskArray)
  """
  This function choose the first files to merge
  creating a tree where number of processes is maximized

  startInd: starting index for array subdivision
  endInd: end index for array subdivision
  taskArray: array containing indices of files to merge for first
  """
  if (endInd - startInd == 2)
    push!(taskArray, startInd)
  elseif (endInd - startInd < 2)
    if (endInd % 4 != 0 && startInd != endInd)
      # Stop recursion on this branch
      push!(taskArray, startInd)
    end
    # Stop recursion doing nothing
  else
    assignTasks(startInd, startInd + trunc((endInd - startInd) / 2), taskArray)
    assignTasks(startInd + trunc((endInd - startInd) / 2) + 1, endInd, taskArray)
  end
end

function mergeVerticesFiles(file1, file2, startOffset)
  """
  Support function for merging two vertices files.
  Returns the number of vertices of the merged file

  file1: path of the first file
  file2: path of the second file
  startOffset: starting face offset for second file
  """

  f1 = open(file1, "a")

  f2 = open(file2)
```

```
  debug("Merging ", file2)
  number_of_vertices = startOffset
  for ln in eachline(f2)
    write(f1, ln)
    number_of_vertices += 1
  end
  close(f2)

  close(f1)

  return number_of_vertices
end


function mergeFacesFiles(file1, file2, facesOffset)
  """
  Support function for merging two faces files

  file1: path of the first file
  file2: path of the second file
  facesOffset: offset for faces
  """

  f1 = open(file1, "a")

  f2 = open(file2)
  for ln in eachline(f2)
    splitted = split(ln)
    write(f1, "f ")
    write(f1, string(parse(splitted[2]) + facesOffset, " "))
    write(f1, string(parse(splitted[3]) + facesOffset, " "))
    write(f1, string(parse(splitted[4]) + facesOffset, "\n"))
  end
  close(f2)

  close(f1)
end

function mergeObjProcesses(fileArray, facesOffset = Nothing)
  """
  Merge files on a single process

  fileArray: Array containing files that will be merged
  facesOffset (optional): if merging faces files, this array contains
    offsets for every file
  """
```

```julia
    if(contains(fileArray[1], string("_vtx.stl")))
      # Merging vertices files
      offsets = Array(Int, 0)
      push!(offsets, countlines(fileArray[1]))
      vertices_count = mergeVerticesFiles(fileArray[1], fileArray[2], countlines(fileArray[1]))
      rm(fileArray[2]) # Removing merged file
      push!(offsets, vertices_count)
      for i in 3: length(fileArray)
        vertices_count = mergeVerticesFiles(fileArray[1], fileArray[i], vertices_count)
        rm(fileArray[i]) # Removing merged file
        push!(offsets, vertices_count)
      end
      return offsets
    else
      # Merging faces files
      mergeFacesFiles(fileArray[1], fileArray[2], facesOffset[1])
      rm(fileArray[2]) # Removing merged file
      for i in 3 : length(fileArray)
        mergeFacesFiles(fileArray[1], fileArray[i], facesOffset[i - 1])
        rm(fileArray[i]) # Removing merged file
      end
    end
end

function mergeObjHelper(vertices_files, faces_files)
  """
  Support function for mergeObj. It takes vertices and faces files
  and execute a single merging step

  vertices_files: Array containing vertices files
  faces_files: Array containing faces files
  """
  numberOfImages = length(vertices_files)
  taskArray = Array(Int, 0)
  assignTasks(1, numberOfImages, taskArray)

  # Now taskArray contains first files to merge
  numberOfVertices = Array(Int, 0)
  tasks = Array(RemoteRef, 0)
  for i in 1 : length(taskArray) - 1
    task = @spawn mergeObjProcesses(vertices_files[taskArray[i] : (taskArray[i + 1] - 1)])
    push!(tasks, task)
    #append!(numberOfVertices, mergeObjProcesses(vertices_files[taskArray[i] : (taskArray[i +
  end
```

```julia
  # Merging last vertices files
  task = @spawn mergeObjProcesses(vertices_files[taskArray[length(taskArray)] : end])
  push!(tasks, task)
  #append!(numberOfVertices, mergeObjProcesses(vertices_files[taskArray[length(taskArray)] : en


  for task in tasks
    append!(numberOfVertices, fetch(task))
  end

  debug("NumberOfVertices = ", numberOfVertices)

  # Merging faces files
  tasks = Array(RemoteRef, 0)
  for i in 1 : length(taskArray) - 1

    task = @spawn mergeObjProcesses(faces_files[taskArray[i] : (taskArray[i + 1] - 1)],
                                    numberOfVertices[taskArray[i] : (taskArray[i + 1] - 1)])
    push!(tasks, task)

    #mergeObjProcesses(faces_files[taskArray[i] : (taskArray[i + 1] - 1)],
    #                  numberOfVertices[taskArray[i] : (taskArray[i + 1] - 1)])
  end

  #Merging last faces files
  task = @spawn mergeObjProcesses(faces_files[taskArray[length(taskArray)] : end],
                                  numberOfVertices[taskArray[length(taskArray)] : end])

  push!(tasks, task)
  #mergeObjProcesses(faces_files[taskArray[length(taskArray)] : end],
  #                  numberOfVertices[taskArray[length(taskArray)] : end])

  for task in tasks
    wait(task)
  end

end

function mergeObjParallel(modelDirectory)
  """
  Merge stl files in a single obj file using a parallel
  approach. Files will be recursively merged two by two
  generating a tree where number of processes for every
  step is maximized
  Actually use of this function is discouraged. In fact
  speedup is influenced by disk speed. It could work on
```

```
    particular systems with parallel accesses on disks

    modelDirectory: directory containing models
    """

    files = readdir(modelDirectory)

    # Appending directory path to every file
    files = map((s) -> string(modelDirectory, "/", s), files)

    # While we have more than one vtx file and one faces file
    while(length(files) != 2)
      vertices_files = files[find(s -> contains(s,string("_vtx.stl")), files)]
      faces_files = files[find(s -> contains(s,string("_faces.stl")), files)]

      # Merging files
      mergeObjHelper(vertices_files, faces_files)

      files = readdir(modelDirectory)
      files = map((s) -> string(modelDirectory, "/", s), files)
    end

    mergeVerticesFiles(files[2], files[1], 0)
    mv(files[2], string(modelDirectory, "/model.obj"))
    rm(files[1])

end

function mergeAndRemoveDuplicates(firstPath, secondPath)
    """
    Merge two boundary files removing common faces between
    them

    firstPath, secondPath: Prefix of paths to merge
    """

    firstPathV = string(firstPath, "_vtx.stl")
    firstPathFV = string(firstPath, "_faces.stl")

    secondPathV = string(secondPath, "_vtx.stl")
    secondPathFV = string(secondPath, "_faces.stl")

    if(isfile(firstPathV) && isfile(secondPathV))

      V = Array(Array{Int}, 0)
      FV = Array(Array{Int}, 0)
```

```
offset = 0

# First of all open files and retrieve LAR models

f1_V = open(firstPathV)
f1_FV = open(firstPathFV)

for ln in eachline(f1_V)
  splitted = split(ln)
  push!(V, [parse(splitted[2]), parse(splitted[3]), parse(splitted[4])])
  offset += 1
end

for ln in eachline(f1_FV)
  splitted = split(ln)
  push!(FV, [parse(splitted[2]), parse(splitted[3]), parse(splitted[4])])
end

close(f1_V)
close(f1_FV)

f2_V = open(secondPathV)
f2_FV = open(secondPathFV)

for ln in eachline(f2_V)
  splitted = split(ln)
  push!(V, [parse(splitted[2]), parse(splitted[3]), parse(splitted[4])])
end

for ln in eachline(f2_FV)
  splitted = split(ln)
  push!(FV, [parse(splitted[2]) + offset, parse(splitted[3]) + offset, parse(splitted[4]) +
end

close(f2_V)
close(f2_FV)

V_final, FV_final = LARUtils.removeVerticesAndFacesFromBoundaries(V, FV)

# Writing model to file
rm(firstPathV)
rm(firstPathFV)
rm(secondPathV)
rm(secondPathFV)
writeToObj(V_final, FV_final, firstPath)
```

```
    end
end

function mergeBoundariesProcess(modelDirectory, startImage, endImage,
                                imageDx, imageDy,
                                imageWidth, imageHeight)
  """
  Helper function for mergeBoundaries.
  It is executed on different processes

  modelDirectory: Directory containing model files
  startImage: Block start image
  endImage: Block end image
  imageDx, imageDy: x and y sizes of the grid
  imageWidth, imageHeight: Width and Height of the image
  """
  for xBlock in 0:(imageHeight / imageDx - 1)
    for yBlock in 0:(imageWidth / imageDy - 1)

      # Merging right Boundary
      firstPath = string(modelDirectory, "/right_output_", xBlock, "-", yBlock, "_", startImage
      secondPath = string(modelDirectory, "/left_output_", xBlock, "-", yBlock + 1, "_", startI
      mergeAndRemoveDuplicates(firstPath, secondPath)

      # Merging top boundary
      firstPath = string(modelDirectory, "/top_output_", xBlock, "-", yBlock, "_", startImage,
      secondPath = string(modelDirectory, "/bottom_output_", xBlock, "-", yBlock, "_", endImage
      mergeAndRemoveDuplicates(firstPath, secondPath)

      # Merging front boundary
      firstPath = string(modelDirectory, "/front_output_", xBlock, "-", yBlock, "_", startImage
      secondPath = string(modelDirectory, "/back_output_", xBlock + 1, "-", yBlock, "_", startI
      mergeAndRemoveDuplicates(firstPath, secondPath)
    end
  end
end

function mergeBoundaries(modelDirectory,
                         imageHeight, imageWidth, imageDepth,
                         imageDx, imageDy, imageDz)
  """
  Merge boundaries files. For every cell of size
  (imageDx, imageDy, imageDz) in the model grid,
  it merges right faces with next left faces, top faces
  with the next cell bottom faces, and front faces
  with the next cell back faces
```

```
    modelDirectory: directory containing models
    imageHeight, imageWidth, imageDepth: images sizes
    imageDx, imageDy, imageDz: sizes of cells grid
    """

    beginImageStack = 0
    endImage = beginImageStack

    tasks = Array(RemoteRef, 0)
    for zBlock in 0:(imageDepth / imageDz - 1)
      startImage = endImage
      endImage = startImage + imageDz
      task = @spawn mergeBoundariesProcess(modelDirectory, startImage, endImage,
                           imageDx, imageDy,
                           imageWidth, imageHeight)
      push!(tasks, task)
    end

    # Waiting for tasks
    for task in tasks
      wait(task)
    end
  end
  end
  ◇
```

PngStack2Array3dJulia

"src/PngStack2Array3dJulia.jl" 53≡

```
    module PngStack2Array3dJulia
```

⟨ *modules import PngStack2Array3dJulia* 11a ⟩
⟨ *Convert to png* 14 ⟩
⟨ *Get image data* 15 ⟩
⟨ *Centroid computation* 16 ⟩
⟨ *Pixel transformation* 20 ⟩

```
    end
    ◇
```

10.1 Installing the library

11 Conclusions

11.1 Results

11.2 Further improvements

References

[CL13]   CVD-Lab, *Linear Algebraic Representation*, Tech. Report 13-00, Roma Tre University, October 2013.

[PDFJ15] Alberto Paoluzzi, Antonio DiCarlo, Francesco Furiani, and Miroslav Jirik, *CAD models from medical images using LAR*, Computer-Aided Design and Applications **13** (2015), To appear.

[W3C]   W3C, *Portable Network Graphics (PNG) Specification (Second Edition)*, Tech. report.

A Utility functions

B Tests

Generation of the border matrix

```
"test/generateBorderMatrix.jl" 54≡
    push!(LOAD_PATH, "../../")
    import GenerateBorderMatrix
    import JSON
    using Base.Test

    function testComputeOriented3Border()
      """
      Test function for computeOriented3Border
      """
      boundaryMatrix = GenerateBorderMatrix.computeOriented3Border(2,2,2)

      rowcount = boundaryMatrix[:shape][1]
      @test rowcount == 36
      colcount = boundaryMatrix[:shape][2]
      @test colcount == 8
      row = boundaryMatrix[:indptr]
      @test row == [0,1,2,3,4,5,7,8,9,11,12,13,15,17,18,19,20,22,23,24,26,27,29,30,32,34,35,37,39,4
      col = boundaryMatrix[:indices]
```

```julia
    @test col == [0,0,0,1,1,0,1,1,2,0,2,2,3,1,3,2,3,3,2,3,0,4,4,4,1,5,5,4,5,5,2,6,4,6,6,3,7,5,7,
    data = boundaryMatrix[:data]
    @test data == [-1,1,-1,-1,1,1,-1,1,-1,-1,1,-1,-1,-1,1,1,-1,1,-1,-1,1,-1,1,-1,1,-1,1,1,-1,1,1

end

function testWriteBorder()
    """
    Test for writeBorder
    """
    boundaryMatrix = GenerateBorderMatrix.computeOriented3Border(2,2,2)
    filename = "borderFile"

    GenerateBorderMatrix.writeBorder(boundaryMatrix, filename)
    @test isfile(filename)

    # Loading borderMatrix from json file
    borderData = JSON.parsefile(filename)
    row = Array(Int64, length(borderData["ROW"]))
    col = Array(Int64, length(borderData["COL"]))
    data = Array(Int64, length(borderData["DATA"]))

    @test borderData["ROW"] == [0,1,2,3,4,5,7,8,9,11,12,13,15,17,18,19,20,22,23,24,26,27,29,30,3
    @test borderData["COL"] == [0,0,0,1,1,0,1,1,2,0,2,2,3,1,3,2,3,3,2,3,0,4,4,4,1,5,5,4,5,5,2,6,4
    @test borderData["DATA"] == [-1,1,-1,-1,1,1,-1,1,-1,-1,1,-1,-1,-1,1,1,-1,1,-1,-1,1,-1,1,-1,1

    rm(filename)

end

function executeAllTests()
    @time testComputeOriented3Border()
    @time testWriteBorder()
    println("Tests completed.")
end

executeAllTests()

◇
```

Conversion of a png stack to a 3D array

"test/pngStack2Array3dJulia.jl" 55≡

```julia
push!(LOAD_PATH, "../../")
import PngStack2Array3dJulia
using Base.Test

function testGetImageData()
  """
  Test function for getImageData
  """

  width, height = PngStack2Array3dJulia.getImageData("images/0.png")

  @test width == 50
  @test height == 50

end

function testCalculateClusterCentroids()
  """
  Test function for calculateClusterCentroids
  """
  path = "images/"
  image = 0
  centroids = PngStack2Array3dJulia.calculateClusterCentroids(path, image, 2)

  expected = [0, 253]
  centroids = vec(reshape(centroids, 1, 2))

  @test sort(centroids) == expected
end

function testPngstack2array3d()
  """
  Test function for pngstack2array3d
  """
  path = "images/"
  minSlice = 0
  maxSlice = 4
  centroids = PngStack2Array3dJulia.calculateClusterCentroids(path, 0, 2)
  image3d = PngStack2Array3dJulia.pngstack2array3d(path, minSlice, maxSlice, centroids)

  @test size(image3d)[1] == 5
  @test size(image3d[1])[1] == 50
  @test size(image3d[1])[2] == 200

end
```

```
function executeAllTests()
  @time testCalculateClusterCentroids()
  @time testPngstack2array3d()
  @time testGetImageData()
  println("Tests completed.")
end

executeAllTests()
```

◇

Test for LAR utilities

"test/LARUtils.jl" 57≡
```
push!(LOAD_PATH, "../../")
import LARUtils
using Base.Test

function testInd()
  """
  Test function for ind
  """

  nx = 2
  ny = 2

  @test LARUtils.ind(0, 0, 0, nx, ny) == 0
  @test LARUtils.ind(1, 1, 1, nx, ny) == 13
  @test LARUtils.ind(2, 5, 4, nx, ny) == 53
  @test LARUtils.ind(1, 1, 1, nx, ny) == 13
  @test LARUtils.ind(2, 7, 1, nx, ny) == 32
  @test LARUtils.ind(1, 0, 3, nx, ny) == 28
end

function executeAllTests()
  @time testInd()
  println("Tests completed.")
end

executeAllTests()
```

◇