

CS301 Project 1

Image Warping and Mosaic

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February 10, 2012

1 Project Goals

In this project, a MATLAB program was designed to stitch two images together to create a larger mosaic. The program first showed the user a source image, allowing him to click four image features that laid on a planar surface in the image. After pressing “enter”, the user was shown the destination image and chose the same four feature points. After pressing “enter” a second time, the program calculated a homography matrix that mapped points from the source image into the destination image. The program then used a warping technique to transform the source image so that it had the four selected points from both images would be in the same plane. The images were then “stitched” together using an image stitching algorithm, and the result was shown to the user.

The aim of this project was to gain a better understanding of homography matrices, image warping, and MATLAB programming by implementing image warping and stitching algorithms in MATLAB. This project also allowed developers to compare the different algorithms that were used to compute homography matrices, warp images, and stitch images together.

2 Homographies

The purpose of a homography in this context is to map points from one projected plane in an image to points in a projected plane from a different image. This is particularly useful when stitching images together. Images that are taken at different perspectives can be transformed using a homography so that they all lie in the same plane. The images can then be placed next to one another or overlapped to create a single image with a broader view.

In this project, homography matrices were calculated using two methods: the pseudo-inverse method and the single value decomposition method.

The Pseudo-Inverse Method Using the pseudo-inverse method, we first assume that h_{33} of the homography matrix will be 1.

$$\begin{bmatrix} x' \\ y' \\ 1 \end{bmatrix} \sim \begin{bmatrix} h_{11} & h_{12} & h_{13} \\ h_{21} & h_{22} & h_{23} \\ h_{31} & h_{32} & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix}$$



Figure 1: Image Warping

We can then perform matrix multiplication to develop a system of linear equations relating x' and y' to x , y , and the elements of the homography matrix. These equations can be rearranged so that unknown variables are the elements of the homography matrix.

$$\begin{bmatrix} x_1 & y_1 & 1 & 0 & 0 & 0 & -x_1x'_1 & -y_1x'_1 \\ 0 & 0 & 0 & x_1 & y_1 & 1 & -x_1y'_1 & -y_1y'_1 \\ x_2 & y_2 & 2 & 0 & 0 & 0 & -x_2x'_2 & -y_2x'_2 \\ 0 & 0 & 0 & x_2 & y_2 & 2 & -x_2y'_2 & -y_2y'_2 \\ x_3 & y_3 & 3 & 0 & 0 & 0 & -x_3x'_3 & -y_3x'_3 \\ 0 & 0 & 0 & x_3 & y_3 & 3 & -x_3y'_3 & -y_3y'_3 \\ x_4 & y_4 & 4 & 0 & 0 & 0 & -x_4x'_4 & -y_4x'_4 \\ 0 & 0 & 0 & x_4 & y_4 & 4 & -x_4y'_4 & -y_4y'_4 \end{bmatrix} \begin{bmatrix} h_{11} \\ h_{12} \\ h_{13} \\ h_{21} \\ h_{22} \\ h_{23} \\ h_{31} \\ h_{32} \end{bmatrix} = \begin{bmatrix} x'_1 \\ y'_1 \\ x'_2 \\ y'_2 \\ x'_3 \\ y'_3 \\ x'_4 \\ y'_4 \end{bmatrix}$$

Or more compactly...

$$\mathbf{A}\mathbf{h} = \mathbf{b}$$

By creating a new matrix for these equations, we can solve for the homography matrix a couple of ways. We can either compute a pseudo-inverse by doing $\mathbf{h} = (\mathbf{A}^T \mathbf{A})^{-1}(\mathbf{A}^T \mathbf{b})$ or we can use $\mathbf{h} = \mathbf{A} \backslash \mathbf{b}$ in MATLAB.

We chose to use $\mathbf{h} = \mathbf{A} \backslash \mathbf{b}$ to compute the homography with our pseudo inverse method. This operator was obviously faster than $\mathbf{h} = (\mathbf{A}^T \mathbf{A})^{-1}(\mathbf{A}^T \mathbf{b})$, taking 0.000149 seconds instead of 0.062804 seconds according to *tic* and *toc*. Because the longer operation also used matrix inverse, MATLAB warned that the result may be inaccurate. However, any errors that may have been present were not visible in the image to the naked eye.

The Single Value Decomposition Method Instead of constraining h_{33} to 1, the SVD method constrains the norm of \mathbf{h} , $\|\mathbf{h}\|$ to 1. This allows the value of h_{33} to be 0, which is obviously not possible with the pseudo-inverse method. To compute a homography matrix using SVD, we must create a set of linear equations, much like we did for pseudo-inverse, with the elements of the homography matrix as unknowns. This time, however, we arrange the equations slightly differently.

$$\begin{bmatrix} x_1 & y_1 & 1 & 0 & 0 & 0 & -x_1x'_1 & -y_1x'_1 - x'_1 \\ 0 & 0 & 0 & x_1 & y_1 & 1 & -x_1y'_1 & -y_1y'_1 - y'_1 \\ x_2 & y_2 & 2 & 0 & 0 & 0 & -x_2x'_2 & -y_2x'_2 - x'_2 \\ 0 & 0 & 0 & x_2 & y_2 & 2 & -x_2y'_2 & -y_2y'_2 - y'_2 \\ x_3 & y_3 & 3 & 0 & 0 & 0 & -x_3x'_3 & -y_3x'_3 - x'_3 \\ 0 & 0 & 0 & x_3 & y_3 & 3 & -x_3y'_3 & -y_3y'_3 - y'_3 \\ x_4 & y_4 & 4 & 0 & 0 & 0 & -x_4x'_4 & -y_4x'_4 - x'_4 \\ 0 & 0 & 0 & x_4 & y_4 & 4 & -x_4y'_4 & -y_4y'_4 - y'_4 \end{bmatrix} \begin{bmatrix} h_{11} \\ h_{12} \\ h_{13} \\ h_{21} \\ h_{22} \\ h_{23} \\ h_{31} \\ h_{32} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

Or, again, more compactly...

$$\mathbf{A}\mathbf{h} = \mathbf{0}$$

To solve this matrix equation, we cannot perform a matrix inverse as we did before because $\mathbf{A}\mathbf{0}$ will always be $\mathbf{0}$. Instead, can either perform computations involving eigenvalues, or we use MATLAB's SVD function. For simplicity and speed, we chose to use the SVD function. This function returns several items, but our item of interest was the last column of \mathbf{V}^T , which corresponded to the values in our homography matrix.

Neither method was particularly more difficult to implement than the other, especially considering the convenience functions offered by MATLAB. The homography matrix generated by each method was the same, but off by a scalar multiple.

Below is a snippet of a MATLAB session that shows the similarities between the homography generated by the pseudo-inverse method and the SVD method. The "h1" variable holds the pseudo-inverse homography, its $h_{33} = 1$, and the "h2" variable holds the SVD homography. By scaling h2 by its h_{33} value, we can see that the matrices are the same (as they should be).

h1 =

```
1.1804    -0.0167   -196.4375
0.0636     1.1141   -20.5098
0.0003     0.0000     1.0000
```

h2 =

```

0.0060    -0.0001    -0.9945
0.0003     0.0056    -0.1038
0.0000     0.0000     0.0051

>> h2 * 1/h2(3,3)
ans =

1.1804    -0.0167   -196.4375
0.0636     1.1141   -20.5098
0.0003     0.0000     1.0000

```

3 Warping

After computing the homography matrix, one must apply the homography to each pixel in an image to warp it to a new projected plane. This can be accomplished several different ways. For this project, three different methods were used: forward warping, backward warping, and `interp2`.

Forward Warping To forward warp, we first create an solid black, empty image which will hold the result of the warp. We then use nested for loops to iterate through each pixel in the source image, applying the homography matrix to each one. The result gives us the coordinates for each pixel in the resulting image. We can then copy the color value for each pixel to the appropriate locations in the resulting image.

The disadvantage to this is that the method maps every pixel in the source to a location in the result, but not every result is covered by a source pixel. Each spot in the result that was not covered by a pixel in the source is left black. This leaves us with a grid of black lines on the resulting warped image (see Figure 2). These lines can be corrected by processing the image after warping it.

Backward Warping To backward warp, we first create an solid black, empty image which will hold the result of the warp. We then use nested for loops to iterate through each pixel in the *empty* image, and instead, apply \mathbf{h}^{-1} to each pixel, to determine which pixel in the source should map to that location. If the calculated location is outside of the bounds of the source image, we ignore it. If the location is within the image, it is unlikely that we will land directly on a pixel. Instead, we will likely land at a location that is between pixels.

To determine the color value for a pixel in the warped image, we have several options. The easiest option is to round the x and y coordinates of the result, and use that color value found at that pixel. This is called the *nearest* interpolation method (see Figure 3). The other option is to take a weighted average of the pixels surrounding the calculated location. This method is called the *bilinear* interpolation method (see Figure 4). By closely inspecting the two produced images, one can see that the nearest interpolation method produces a blockier image than the bilinear method. The bilinear backward warped image looks smoother.

Interp2 MATLAB provides a function named `interp2`, which can perform warping and interpolation. The results of this warp look very smooth, and appear to match the destination image the



Figure 2: Forward Warping with SVD Homography and Blended Mosaic

best. However, in our experience, it cropped the side of our image, and the mosaic looks strange (see Figure 5).

Summary Of the three interpolation options, `interp2` was obviously the fastest. It is a MATLAB function, and makes use of high performance code behind the scenes. The for-loop method used with backward and forward warping took seconds, if not minutes, to complete, while the `interp2` function took a fraction of a second. However, because `interp2` cropped part of our image, the resulting mosaic image appeared strange. The backward warping method with bilinear interpolation produced the best warped mosaic.

4 Mosaic

After warping a source image to match the same projected plane as the destination image, one must put the two images together. We used two different methods to accomplish this. The “nearest” method (Figure ??) considers the area where the two images overlap, and for each pixel, determines whether the source pixel or the destination pixel should be chosen based on whether it is closer to the source’s center of mass or the destination’s center of mass. Similarly, the “blended” method (Figure 2) considers overlapping areas, but takes a weighted average of the source and destination pixels at that spot and adds that result to the mosaic.



Figure 3: Backward Warping with Nearest Interpolation, SVD Homography, and Nearest Mosaic

5 Design Decisions

The general flow of the program can be seen in Figure 6.

User Configuration To make this program flexible for the user, several configuration options are provided at the beginning of `main.m`.

`click_new_points`

Can be **yes** or **no**. If yes, the program will prompt the user for image files to warp together, and it will ask them to manually select points in those images. If no, the program will use the default “snow” images and use preselected points. The no option is for debugging.

`homography_method`

Can be **pseudo_inverse** or **svd**. Determines which method should be used to calculate the homography matrix.

`warping_method`

Can be **forward**, **backward**, or **interp2**. This option allows the user to decide which warping method to use. The default interpolation for backward warping is “bilinear”, but it can be changed to the blocker “nearest” by uncommenting a line in `warp_backward.m`.

Image Masking The mosaic function needs a way to determine if a pixel in an input image has valid data. A first attempt used the heuristic where any black pixel was assumed to be invalid.



Figure 4: Backward Warping with Bilinear Interpolation, SVD Homography, and Nearest Mosaic

This happens to work for the input data provided, however some of the data we generated included black windows on buildings, leading to odd artifacts in the final image. Our next attempt used the concept of an image mask. An image mask is an auxiliary array of pixels, paired up with a given image. Anywhere the image data is valid, the mask contains a one. Anywhere the image data is invalid due to it actually being a black border location with no real physical meaning, the mask contains a zero. Before using image pixel data, the mosaic function consults the mask to determine the validity of that data.

6 Experimental Observations

Overall, things turned out the way we expected. This project was fun and interesting to work on, though neither of us are huge fans of MATLAB. We decided that MATLAB is a great tool for image processing because of its vector and matrix features, allowing for complex slicing and manipulation of those data structures. These features allowed for easier and faster manipulation of images. However for future projects, we are considering using python with numpy instead. We would lose the ability to use instructor code outright, however a cursory glance at our submitted code shows that very little instructor code can be found in our final product anyway.



Figure 5: Interp2 Warping, SVD Homography, and Blended Mosaic

7 Group Contribution

Matt Matt developed the homography computation code, the warping code, and the main MATLAB script. He also contributed to the report.

Michael Michael worked on the mosaic code and contributed to the warping code. He worked on much of the report.

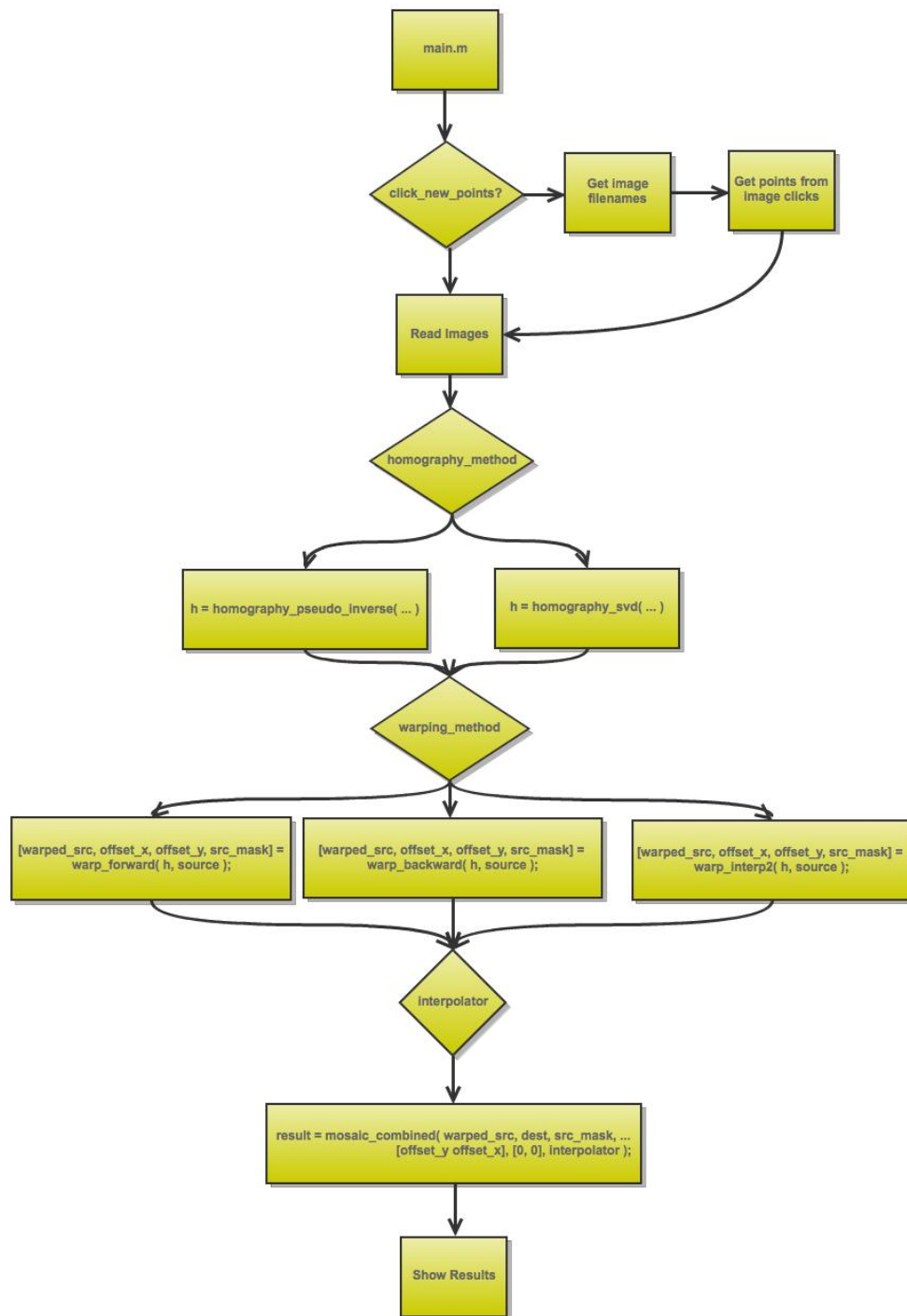


Figure 6: High Level Flow Control