A study of different unwarping methods for omnidirectional imaging

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Abstract—This paper evaluates the performance of the 3 universal un-warping methods currently applied actively around the world in transforming omnidirectional image to panoramic image, namely the pano-mapping table method, discrete geometry method (DGT) and the log-polar mapping method. The algorithm of these methods will first be proposed, and the code will then be generated and be tested on several different omnidirectional images. The images converted will then be compared among each other and be evaluated based on their performance on the resolutions, quality, algorithm used, complexity based on Big-O computations, processing time, and finally their data compression rate available for each of the methods. The most preferable unwarping method will then be concluded, taking into considerations all these factors.

Keywords: omnidirectional image, evaluation of image quality, un-warping.

I. INTRODUCTION

With the widespread adoption of imaging system, it is desirable to maximize the coverage area with the minimum number of cameras in order to reduce the cost and the complexity in installing and calibrating cameras. However, due to cameras are usually having a very limited field of view, which leads to the increased in network cost and the needs for mutual camera calibration as well as additional maintenance effort, omnidirectional imaging system is devised to overcome this problem. Omnidirectional imaging system uses a special type of mirror to reflect light rays from 360º into a perspective camera lens and forms an omnidirectional image [1,2]. However, these images captured have different properties compared to perspective images in terms of imaging deformation. Such distortion leads to the images being difficult to be directly implemented. Thus, it is necessary to work out an efficient method to un-warp the omni-image. Un-warping, generally, is a method used in digital image processing in 'opening' up an omnidirectional image into a panoramic image, making the information on the image to be able to be directly implemented and understood. Un-warping method is actively adopted in the application of camera visual surveillance system [3,4,5] as well as thermal monitoring system [6] in omnidirectional imaging system. There are 3 unwarping method currently in practice actively around the world being studied, which are the pano-mapping table method [3], discrete geometry techniques (DGT) method [4], and log-polar mapping method [5]. This paper studies the advantages and disadvantages for each method, compared and evaluated their performance in order to select an optimum unwarping method for omnidirectional imaging. The paper is organized in the following way: Section II will be briefly comment on the different types of un-warping method currently in practice actively around the world and their corresponding algorithm. Section III presents the experimental setup which are the few conditions or parameters that is needed to be determined before processing the conversion of omnidirectional image to a panoramic image, while section IV reports some experimental resultswith comparison. Finally in section V, we draw some conclusion and envision future studies.

II. UNWARPING METHODS

Three universal un-warping methods are selected, studied, and evaluated. They are pano-mapping table method, discrete geometry techniques (DGT) method, and log-polar mapping method.

A. Pano-mapping method.

This method uses a table, which is so-called the pano-mapping table, to process the image conversion. Panomapping table will be created "once and forever", consisting of many co-ordinates corresponding to the co-ordinates taken from the omnidirectional image which will then be mapped into a new panoramic image respectively. It is practically used in omnidirectional visual tracking [7], and the unwarping process of omni-images taken by almost any kind of omni-cameras prior to requiring any knowledge about the camera parameters in advance, as proposed by Jeng, Tsai and Wu [3,8].

In pano-mapping table method, it is required to select 5 landmark points from the omnidirectional image first. These points will be taken from the same line, drawing from the center of the omni-image to the circumference of the image which in other words, called the radius of the image. 5 points in between the end of this line will be picked, and the value corresponding to their radius from the center is obtained. It is then used in order to obtain the 5 co-efficient of $a_0$ through $a_4$. 

...
in the 'radial stretching function', \( f_r(\rho) \), described by the following 4th-degree polynomial function of:

\[
r = f_r(\rho) = a_0 + a_1\rho + a_2\rho^2 + a_3\rho^3 + a_4\rho^4
\]

where \( r \) correspond to the radius, \( \rho \) is the particular radius for each of the 5 points taken, and \( a_0-a_4 \) are five co-efficient to be estimated using the values obtained from the landmark points.

Once the 5 co-efficient has been obtained, the pano-mapping table, \( T_{MN} \) can then be generated. The size of the table will first be determined manually, by setting it to a table of size \( M \times N \). Hence, in order to fill up a table with \( M \times N \) entries, the landmark point \( \rho_i \), which correspond to the radius of the omnidirectional image will be divided into \( M \) separated parts, and the angle, \( \alpha \) will be divided into \( N \) parts as follows:

\[
\rho_{ij} = i \times \text{radius} / M \quad (2)
\]

\[
\alpha = j \times 360^\circ / N \quad (3)
\]

and the calculation will be processed, by taking the first point where \( i=1 \) and \( j=1 \), which gives \( \rho_{11} = \text{radius}/M \), and \( \alpha_{11} = 360^\circ/N \). The value of \( \rho_{ij} \) will then be substituted into the 'radial stretching function' in order to obtain the particular radius at that particular landmark point. This radius obtained, will then be substituted into the equation below and to be rounded up, in order to get the corresponding co-ordinates in the omnidirectional image.

\[
v = \rho \cos \alpha \quad (4)
\]

\[
u = \rho \sin \alpha \quad (5)
\]

where \( v \) and \( u \) correspond to the x and y co-ordinates of the omnidirectional image.

This co-ordinate \((u_v)\) obtained will then be inserted into the pano-mapping table \( T_{MN} = T_{ij} \). The \( u \) and \( v \) will then be processed for \( N \) times by increasing \( j \) for \( N \) times to obtain different angle, \( \alpha \) to later determine all the co-ordinates corresponding to the value of landmark point. These co-ordinates obtained will then be inserted into the table of \( i = 1 \) with their corresponding \( j = 1 \) to \( j = N \), and the \( i \) will then be increased by 1, and the process is repeated for \( j = 1 \) to \( j = N \) to determine all co-ordinates related to \( i = 2 \). This \( i \) will be repeated for \( M \) times, and a table of \( M \times N \) entries with all the co-ordinates can be generated. The co-ordinates in each of the entries will then be taken one by one, in order to map each and every pixel in the omnidirectional image with the co-ordinate in the current entry, into a new panoramic-image. The conversion is completed upon the end of mapping of the table.

B. Discrete Geometry Techniques (DGT) method.

Discrete Geometry Techniques (DGT) method, by the name itself, means that this technique is used by applying one-by-one, the geometry of the image, discretely, in order to successfully un-warp the omnidirectional image into a panoramic image. This method is practically used in transforming the omnidirectional images into panoramic images on a cylindrical surface using PDE based resampling models [4].

In DGT method, it is required to perform the calculation of each and every pixels in the omni-image first, and then check for its corresponding radius from the center of the omnidirectional image, and later to determine whether it should be considered or not. The calculations will start from a fixed position and direction, such as from the right, going counter-clockwise for 360°. For a radius of 1, a circle of radius 1 will be visualized in the center of omnidirectional image, which in other words means that the circle will be in size of 3x3 pixels. All the pixels in this boundary of 3x3 pixels, will be considered, and their corresponding radius will be calculated. For all pixels which falls into the radius of 1, which is the radius currently in concern, these pixels will be considered in the conversion. However, due to the pixels are generally an area of data information, it is possible that the circle will lie in between the pixels:

![Fig. 1. Circle lying in between pixels](image1)

Therefore, a tolerance of \( \pm \frac{1}{2} \) radius is set to counter this problem. In other words, a circle of radius 1, will consider the pixels lying in radius of 0.5 to 1.4, and a circle of radius 2, will consider the pixels lying in radius of 1.5 to 2.4, and so on. An example is shown in Fig. 1.

As soon as a pixel in the boundary is deemed to be considered or in range of the radius, it will be mapped into a new matrix of panoramic-image. However, since the pixels mapped into the panoramic image must be in order so that the image will not be distorted, the image will be split into 4 sections of 90° each, as show in Fig. 2, where each section will perform the calculations based on the direction move of the circle.

![Fig. 2. Circle being split into 4 sections](image2)

For example, for a circle drawn, starting from right in a counter-clockwise direction, the pixels in the section at the upper right part, will be taken and calculated one by one, from the bottom part of the section, and from right to left, which will then be increased one by one, till the upper part of the section, from right to left as well. On the other hand, for the lower left part of the section, the calculation will go from the top of the section, going from left to right.

However, due to the pixels being considered for different circle of different radius will be non-uniform, as shown in Fig.
3, a re-sampling process is needed to standardize the pixels in every row of the panoramic image.

Fig. 3. Non-uniform resolution of panoramic image

Therefore, after finished mapping every pixel in the whole omni-image onto the panoramic image plane, spacing will be inserted between pixels in every row (as shown in Fig. 4) in order to standardize the resolution of the panoramic image for each row.

Fig. 4. Spacing is inserted in between pixels, denoted by black dots

This will generate a standard resolution of panoramic image. However, due to spacing are generally empty pixels with no data information, a row with very little pixels will be hardly understandable. Therefore, the pixels will be duplicated over the spacing, instead of inserting empty pixels into it, and an understandable uniform resolution panoramic image can be generated, as shown in Fig. 5.

Fig. 5. Uniform resolution panoramic image

C. Log-polar mapping method.

Log-polar mapping is a type of spatially-variant image representation whereby pixel separations increase linearly with distance. It enables the concentration of computational resource on a region of interest as well as maintaining the information from a wider view. This method is implemented by applying log-polar geometry representations. The captured omnidirectional image will first be sampled by spatially-variant grid from a Cartesian form into a log-polar form. The spatially-variant grid representing log-polar mapping will then be formed by i number of concentric circles with N number of samples and the omnidirectional image will then be unwrapped into a panoramic image in another Cartesian form.

This method is practically used in robust image registration, [5], or in robotic vision, particularly in visual attention, target tracking, egomotion estimation, and 3D perception, [9] as well as in vision-based navigation, environmental representations and imaging geometries, [10], by José Santos-Victor, and Alexandre Bernardino.

In log-polar mapping method, the center pixel for log-polar sampling is calculated by:

\[
x_c(\rho, \theta) = \rho \cos \theta + x_c
\]

\[
y_c(\rho, \theta) = \rho \sin \theta + y_c
\]

and the center pixel for log-polar mapping is calculated by:

\[
x_o(\rho, \theta) = \rho \cos \theta + x_c
\]

\[
y_o(\rho, \theta) = \rho \sin \theta + y_c
\]

where \(x_c, y_c\) is the center point of our original cartesian form co-ordinate, and \(N\) is the number of samples in each and every concentric circles taken.

Fig. 6. Process of log-polar mapping

The original \((x, y)\) in Cartesian form is sampled into log-polar co-ordinate of \((\rho, \theta)\), as shown in Fig. 6. The center point will then be calculated by using (6) and (7) to get the respective \(\rho\) and \(\theta\), which will cover a region of the original Cartesian pixels of radius:

\[ r_n = br_{n-1} \]

and

\[ b = \frac{N + \pi}{N - \pi} \]

where \(r\) is the sampling circle radius and \(b\) is the ratio between 2 apparent sampling circles. Fig. 7 shows the circular sampling structure and the unwarping process done by using the log-polar mapping method [5].

Fig. 7. Circular Sampling Structure and the un-warping process

The mean value of pixels within each and every circular sampling will then be calculated and will be assigned to the center point of the circular sampling. The process will then continue by mapping the mean value at log-polar pixel \((\rho, \theta)\) into another Cartesian form using equation (8) and (9), and the un-warping is done at the end of mapping.

III. EXPERIMENTAL SETUP

This section presents the experimental setup for each of the tested unwarping method. 10 omni-directional images had been tested to prove the functionality of the un-warping methods proposed in section II. 3 of the images are presented...
as reference. For each of the un-warped method, it is required to pre-set some parameters.

A. Pano-mapping table method.

In pano-mapping table method, it is first required to select the first 5 landmark points in order to obtain the coefficient of \( a_0 \) through \( a_4 \). The 5 landmark points are selected to be \( \rho = 5, 25, 90, 180 \), and 243, and their radius is calculated, and coincidently to be equals to \( r = 5, 25, 90, 180 \) and 243 as well. These points will then be used to calculate the coefficient of \( a_0 \) through \( a_4 \) of the radial stretching functions, where we obtain: \( a_0 = a_2 = a_3 = a_4 = 0, a_1 = 1 \). In order to generate the pano-mapping table of size \( M \times N \), the \( M \) is selected to be the largest size of the omni-image, also known as the circumference of the omni-image, and \( N = 243 \), which correspond to the radius of the image. These values are chosen so that the resolution of the converted panoramic image will be of size \( 1146 \times 243 \), which will be the same for the other 2 methods for comparison purposes so that the 3 methods are compared in the same size. These \( M \) and \( N \) values are then substituted into (2) and (3) with the respective \( i \) and \( j \) to obtain their respective \( \rho_i \) and \( \rho_j \). Equations (4) and (5) will later be used to calculate the co-ordinates corresponding to the particular \( \rho_i \) and \( \rho_j \), and then be inserted into the pano-mapping table. These co-ordinates will next be used in the mapping function, and the conversion of omnidirectional image into a panoramic image is completed at the end of mapping.

B. Discrete Geometry Techniques (DGT) method.

In transforming an omnidirectional image into a panoramic image using DGT method, it is necessary to first determine the radius of the omni-image, which will be the boundary of the circle taken to check for all the pixels in the image. The largest dimension of the panoramic image, which is the \( x \)-coordinate of the image, will also be determined by taking the circumference of the omni-image. The radius shall be equals to 243, and the \( x \)-coordinate will be 1146 in this case. This value will correspond to the \( x \) dimension of the panoramic image, which is also a reference to how many times the pixels will be duplicated in order to obtain a uniform resolution image. Fig. 9.2 shows some output of panoramic images using DGT method.
C. Log-polar mapping method.

In log-polar mapping method, it is necessary to set N equals to 473, due to the omnidirectional image taken or cropped, is of resolution 473 x 473, and the center point of the omnidirectional image is to be approximated by taking the integer round value of 473/2. Fig. 10.2 shows some panoramic images examples generated using log-polar mapping method.

![Panoramic images generated by using log-polar method.](image)

Fig. 10.2. Panoramic images generated by using log-polar method.

IV. PERFORMANCE EVALUATION

This section reports the performance evaluation for different unwarping methods. Few important factors selected for the performance evaluation of the unwarping methods. These factors include: resolution of the image generated, quality of image, algorithm used in performing the unwarping process, complexity, processing time, and data compression.

A. Resolution of the image generated.

The resolutions of each generated panoramic images using log-polar mapping method, discrete geometry techniques and pano-mapping table method is discussed in this subsection. The log-polar mapping method provides a smaller resolution of dimension equals to 1/4 fold of the omnidirectional image, whereas for the discrete geometry methods and pano-mapping table method, the resolution of the panoramic-image produced can be as large as the length of the perimeter of the omnidirectional image, with the width equals to the radius of the omnidirectional image. However, due to the images had been re-scaled for viewing purposes; the difference is not obvious in this paper.

B. Quality of image.

The pano-mapping method produces a smooth image where the distortion is almost negligible, whereas for DGT method, the image generated is pretty much distorted and rough. For log-polar mapping method, the image is smooth, though there are some distortion. Therefore, pano-mapping method produces the highest quality of image.

C. Algorithm used in performing the un-warping process.

In log-polar mapping algorithm, the omnidirectional image is considered in the form of a number of sectors in which each sector consists of a group of pixels, that will be extracted later in sector by sector to be arranged into a rectangular form of image; whereas for the DGT method, pixels by pixels is to be extracted and arranged into a rectangular form image. These pixels will then be re-produced, or duplicated, in order to standardize the number of pixels available in each row of the panoramic image. For the pano-mapping table method, an algorithm is using whereby a table will be created at initialization, to indicate the co-ordinates of the pixels to be extracted from the omnidirectional image. Once the table is created, it will then be used over and over again to map each of the pixel at that particular co-ordinate, one by one, from the omnidirectional image into a panoramic image, hence the name "once and forever".

D. Complexity.

Table below shows the Big-O complexity of log-polar mapping method, DGT method, and pano-mapping table method.

<table>
<thead>
<tr>
<th></th>
<th>DGT</th>
<th>Log-polar mapping</th>
<th>Pano-mapping table</th>
</tr>
</thead>
<tbody>
<tr>
<td>Addition</td>
<td>O(XY²)</td>
<td>O(X²Y²)</td>
<td>O(Y²)</td>
</tr>
<tr>
<td>Subtraction</td>
<td>O(Y)</td>
<td>O(X²)</td>
<td>O(Y²)</td>
</tr>
<tr>
<td>Multiplication</td>
<td>O(Y)</td>
<td>O(X²)</td>
<td>O(Y²)</td>
</tr>
<tr>
<td>Division</td>
<td>-</td>
<td>O(log(X)/log(Y))</td>
<td>-</td>
</tr>
</tbody>
</table>

where X = length of the panoramic image = perimeter of the omnidirectional image taken into considerations. and Y = height of the panoramic image = radius of the omnidirectional image taken into considerations.

E. Processing time.

The processing time for all the 3 methods to successfully convert an omnidirectional image into a panoramic image is calculated using matlab function "cputime". The codes are processed 5 times on 5 different images, and the average
processing time is computed. It is found that pano-mapping table method having the fastest computation time, which is 1.220 seconds, followed by log-polar mapping method being 2.003 seconds, and 3.426 seconds for the DGT method.

F. Data compression.

The generated panoramic image produces by log-polar mapping method has the resolution, which is 473 x 114, DGT method has a resolution of 1472 x 235, and 1146 x 243 for pano-mapping table method, in which the original omnidirectional image is of resolution 473 x 473. From the resolutions, it is clear that log-polar mapping has the highest compression, which compresses the image up to 4 folds, compared to DGT method and pano-mapping table method.

In terms of **resolution of the image generated**, although the image generated by DGT method and pano-mapping table method are larger as compared to the image generated by log-polar mapping method, these 2 methods seems to elongate the actual size of the image. In other words, this method tends to make the objects in the image extended, and 'fatter' than the original image. Due to this elongation, it will be harder to examine the picture and the objects, as the sense of the size had been eliminated. For log-polar mapping method, the extension is not much, and it is not as obvious as DGT method and pano-mapping table methods.

In terms of **quality of image**, pano-mapping table method produces the highest quality out of the 3 methods, followed by log-polar mapping method with a slightly lower in image quality but still within an acceptable range, and lastly the blurred DGT method.

In terms of **algorithm used in performing the un-warping process**, pano-mapping table method uses the simplest and easiest algorithm, followed by a simple but slightly complex algorithm which is the log-polar method, and lastly a complicated and complex algorithm from the DGT method.

In terms of **complexity**, it is found that pano-mapping table method has the least complexity, followed by DGT method, and lastly log-polar mapping method in Big-O notation.

In terms of **processing time**, on average, pano-mapping table method has the fastest processing time to transform an omnidirectional image into a panoramic image, followed by log-polar mapping method and DGT method.

In terms of **data compression**, log-polar mapping method has the best data compression rate in compare to pano-mapping table method and DGT method. This is very good in comparison to pano-mapping and DGT methods. Although the quality generated is not as good as pano-mapping method, it has a compression rate much superior than the pano-mapping and DGT methods. This can save unnecessary memory usage. Besides that, the quality is still within an acceptable range, and is still understandable. Since log-polar mapping provides a highest compression rate, it produces an image with a smallest resolution compared to the pano-mapping and DGT methods. However, this can be fixed by capturing an omni-directional image with higher resolution if a larger image is preferred. Moreover, the algorithm used for log-polar mapping methods is simple and easy to be understood. Although the BigO complexity computed for log-polar mapping has the highest complexity, the processing speed is sufficiently fast, Besides that, as a memory is very limited, it has a very high priority in a system.

Therefore, log-polar mapping methods is most preferred to be used in omnidirectional to panoramic image conversion, given that it has a good quality of image with the highest data compression rate, and a fastest processing speed out of the 3 methods. In future, we plan to implement log-polar mapping algorithm on DSP development board, making it to process omnidirectional image in a faster manner onto a smaller processing unit, to be carried by a moving robot in a mobile surveillance way. Besides that, we also plan to modify log-polar mapping method to be implemented in un-warping 3D omni-directional images. This will be addressed in future work.

**REFERENCES**


