2-Dimensional Shape Categorization Using Polar Coordinate Representations

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Submitted for the completion of MC397 (Honors Thesis)

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Introduction

In my experience with computer vision, the one thing that struck me most of all was the seemingly exclusive use of rectangular (x, y) coordinates for shape representations in template matching. It occurred to me that replacing such traditional representations with polar coordinates – a system I had seen used all-too-little since it was introduced to me in high school – would offer a number of advantages, especially when shapes need to be rotated to be properly compared. For my thesis, I decided to implement this idea, first in a one-on-one comparison situation, then for grouping like shapes within a scene. In doing so, I was able to come up with some surprisingly efficient algorithms, yielding promising results.

Polar Coordinates

The use of polar coordinates in this project was inspired by the fact that rectangular coordinates are not very convenient for comparisons involving rotation. When rectangular coordinates x and y are transformed through angle $\phi$ about the origin, the new coordinates $x'$ and $y'$ are determined by the following equations:

\[
x' = x \cos \phi - y \sin \phi
\]
\[
y' = x \sin \phi + y \cos \phi
\]

For each increment of the rotation, the new coordinates need to be calculated. This process can be simplified somewhat by saving values of the sine and cosine functions to a table, though doing so limits the possible angle increments to those listed in the table.
Changing over to a polar coordinate system, x and y are replaced with radius r and angle \( \theta \), which are calculated as follows:

\[
r = \sqrt{x^2 + y^2}
\]

\[
\theta = \tan^{-1}(y/x) \text{ if } x \neq 0, \pi/2 \text{ if } x = 0 \text{ and } y > 0, -\pi/2 \text{ if } x = 0 \text{ and } y > 0, 0 \text{ if } x = y = 0^*
\]

These values only need to be calculated once, when the shape is first read from the file. After that, the rotational transformations used in comparisons only involve adding the transformation angle, \( \phi \), to the value of \( \theta \), producing a new value \( \theta' \) by the following equation:

\[
\theta' = \theta + \phi
\]

As the number of comparisons increases, the running time of the polar coordinate method becomes increasingly attractive. Polar coordinates can also be simplified in a way that rectangular coordinates cannot, as I will later demonstrate.

**Stage 1: Comparing Two Single-Shape BMP Files**

The first program I wrote for this project was the simplest possible incarnation of the idea. Two separate BMP files, each containing a single shape, are compared to each other, producing a floating-point result between 0 and 1, with 1 representing a perfect match and 0 representing a perfect mismatch. Whether this comparison is done with or without accounting for rotation is left for the user to decide.

The program starts by identifying the shapes in each image via a recursive fill algorithm. This algorithm creates a list of points, and the center of these points is
calculated by averaging their x and y values. The points are then translated so that the
center becomes the origin. Finally, the points are converted into their polar equivalents
using the equations described in the previous section. Shapes are stored as a doubly-
linked list of polar coordinates, sorted by their θ values, which range from -π to π. This
list, along with important attributes such as the shape’s color and the average value of r
for the points within the shape, is stored in a class known as Shape2D.

The points in the two shapes are compared based on certain specified error values
of r and θ. The error in r specifies the maximum number of pixel widths that two points
can be separated by in their radius value while still being recorded as matching each
other. The theta error, on the other hand, does not represent the maximum allowable
difference in θ on its own, but is instead a multiplier whose value is divided by $2\pi r^*$ to
obtain the allowable interval. Both error values were set to 1.0 throughout most of the
testing at this stage, as this was found to be the value that produced the most accurate
results. Also, in the case of shapes of unequal size, the r values of the smaller shape were
multiplied by the ratio of the larger shape’s average r value to its own average r value,
and the errors were used with these new r values in mind. (The r error, for example, was
multiplied by the same ratio)

When shapes A and B are compared based on their orientations, the matching
function first tries to find a match for the first point in A by searching through the list of
points in B until it either finds a match (a point where r and θ are both within the
allowable margin of error), or it leaves the allowable θ interval. This process is repeated

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* Actually, in this last case the value of θ is undeterminable. Setting it equal to 0 was just a matter of
  personal preference.

* This value of r is actually an average of the r values from the two shapes being compared.
until all of the points in A have been checked. A result is produced by dividing the number of points in A that were successfully matched by the total number of points in A. The process is then repeated on shape B, producing a second result. The two results are then multiplied together to produce the sameness value that is returned by the program. The reason why the process is repeated is to prevent cases where one shape is small subset of another shape from being recorded as a perfect match, as well as to distinguish between a small shape within a large shape and two large shapes with a small overlap. For both stages of this project, I used 0.9 as my sameness threshold, with all shapes above the threshold being considered a match and all those below being considered a mismatch.

When comparing two shapes regardless of their orientation, the same basic process is applied, but is repeated with an increasing offset being added to the value of $\theta$ for shape A. This value is corrected for higher values of the offset so that the $\theta$ value always stays within the interval (-$\pi$, $\pi$). Once the best match from these trials is found, its $\theta$ offset is used to make the comparison to points in B. This entire process has a running time of $O(n^3)$. 
Standardizing Shapes

In order to facilitate the shape comparison process, I decided to institute a process I call “standardizing”, which involves simplifying the shape representations in several ways.

One of these simplifications consisted of normalizing the radius values of all the points in each shape, so that they all fell between 0 (the center of the object) and 1 (the farthest point from the center). Previously, I had been using a multiplier based on the average value of $r$ in both shapes to compare objects with different sizes.

A second improvement involved discarding the existing point list in favor of one in which the points are stored at regular intervals of $r$ and $\theta$. In a standardized shape (represented by the structure StdShape2D in the program), points are stored in evenly-spaced “rings”, each of which has a set radius. Each of the points along a ring can occur at any one of $(\text{int})2\pi r$ evenly-spaced positions. Once the number of rings, $x$, has been determined, the program decides whether to put a point at each position of the standardized shape by checking whether there is a point in the original Shape2D representation that falls within the error ranges for $r$ and $\theta$, which are determined by the function as follows:

\[
\begin{align*}
    r \text{ error} &= 1/x \\
    \theta \text{ error} &= 2\pi/(\text{int})2\pi r
\end{align*}
\]

Note that the $\theta$ error cannot be simplified because its denominator must be simplified to an integer before the division can take place.
For example, the possible positions for points in the first three rings are shown in the following diagram:

In the next diagram, the dots highlighted in red are those that might be chosen by the program to represent a square:

Finally, the third revision I implemented here allows the user to specify the maximum number of points that can be used to represent an object. If a Shape2D instance has fewer than the maximum number of points, the standardized shape is simply calculated by using the maximum value of \( r \) in the original representation as the value of \( x \) (after converting it to an integer, of course). If a shape exceeds the maximum number
of points, the value of x is determined by finding the largest value of x that would have a
total number of possible point positions that is less than or equal to the specified
maximum number of points. This step prevents reduces delays caused by comparing
shapes with high point totals, since point totals directly determine the running time of the
algorithm.

Stage 2: Grouping Shapes from a Scene in a BMP File

During the second stage of the project, which I will be referring to in the
examples that follow, the focus was shifted from comparing just two individual shapes to
comparing many shapes in a single image, in an effort to group together shapes that bear
a strong resemblance to each other in both shape and color. These groupings, called
“concepts”, are stored in order of decreasing popularity, so that the program can
recognize common objects faster than rare ones.

The use of standardized shapes makes the comparisons for this process
significantly faster than they were in the first stage. When comparing two shapes at a
given orientation, the program now only needs to visit each point on each shape once,
following the points around each of the rings in order. The number of different rotational
orientations that need to be tested is (int)2πx - the maximum number of points on the
outer ring of a shape, taken from whichever of the two shapes has the greater number of
rings. The error values for r and θ are the same as those used in creating standardized
shapes, taken from the shape with fewer points, since the error there is greater. The
running time for this algorithm is O((n1+n2)*sqrt(n2)), where n1 is the number of points
in the smaller shape and \( n_2 \) is the number of points in the larger one. The points in \( n_1 \) and \( n_2 \) are each checked once in the two inner loops, and the number of rotational positions checked by the outer loop is on the order of \( \sqrt{n_2} \), since it is based on the number of the points in the outermost ring, and both the number of rings and the number of points in each ring are based on \( x \), making \( n_2 \) the sum of the points in all the rings, of the order \( x^2 \).

**Experiments**

In order to test the versatility of the algorithm, I created a series of images designed to illustrate a variety of sorting abilities.

The first of these images contains a general assortment of objects, some of which are rounded “L” shapes, and the rest of which are squared-off “L” shapes, occurring in two distinctly different colors:
When given the image, the algorithm produced the following output, displaying the centers of shapes in each concept as rectangular coordinates, with (0, 0) representing the upper left corner of the bitmap and (255, 255) representing the lower right corner:

Concepts found:
Color: Red=255, Green=0, Blue=0
Center at (25.5385,34.1923)
Center at (54.2903,216.065)
Center at (170.808,145.538)
Center at (208.73,40.5421)
Instances: 4
Color: Red=255, Green=0, Blue=0
Center at (82.2759,141.342)
Center at (159.845, 208.786)
Center at (229.99,112.24)
Instances: 3
Color: Red=255, Green=255, Blue=0
Center at (29.0645,142.71)
Center at (145.555,86.8355)
Center at (218.132,213.132)
Instances: 3

The first concept shown here contains the red squared-off “L” shapes, the second represents the rounded “L” shapes, and the third represents the yellow squared-off “L” shapes.

The second image was used to test the algorithm’s ability to detect arbitrary rotations of the same shape, in this case a square:
The program produced the following output:

Concepts found:
Color: Red=0, Green=128, Blue=255
Center at (67.2016,188.903)
Center at (60.5173,74)
Center at (189,188.988)
Center at (191.798,69.9029)
Instances: 4

In the third image, holes in the shapes are introduced, demonstrating why it was important for the algorithm to use all the points in the shape for its comparisons, instead of just those on the outer edge:

The algorithm grouped the shapes as follows:
The first concept here contains the square with one hole, the second contains the squares with two holes, and the third contains the square with three holes.

A fourth image shows how the program’s ability to deal with holes allows it to recognize similar concentric shapes:

![Image of concentric circles](image)

The algorithm recognized both shapes as representing a single concept, though the centers of the two shapes are difficult to distinguish from each other:
The fifth and final image tests one of the algorithm’s limitations as it depicts shapes with increasing numbers of sides:

![Shapes with increasing numbers of sides](image)

The following output was produced:

Concepts found:
Color: Red=255, Green=255, Blue=0
Center at (35.9425,44.4441)
Instances: 1
Color: Red=255, Green=255, Blue=0
Center at (118.986,36.5139)
Instances: 1
Color: Red=255, Green=255, Blue=0
Center at (118.986,36.5139)
Instances: 1
Color: Red=255, Green=255, Blue=0
Center at (63981,118.76)
Instances: 1
Color: Red=255, Green=255, Blue=0
Center at (190.577,114.799)
Center at (65.3313,209.754)
Center at (187.02,204.288)
Instances: 3
The first four concepts represent shapes with increasing numbers of sides, from the triangle to the hexagon. The fifth concept contains the heptagon, octagon, and nonagon, which the algorithm could not distinguish from each other. In a way, this is similar to the human eye, which often cannot distinguish between shapes with more than six sides without counting the sides. (Recognition of the octagon, such as in a stop sign, is a special case, since such recognition is based partially on the shape’s orientation)

**Future Work**

As I continue to develop this algorithm, I hope to increase its versatility in a number of ways.

The first of these would be to give it the ability to process multiple files while keeping track of the concepts it recognized from previous files. A master list of concepts could then be stored, allowing the algorithm to learn in a more permanent manner.

I would also like to add to the program a smoothing algorithm, so that I can use actual photographs instead of having to manufacture my own images. This would go a long way towards moving this project from the realm of the theoretical to that of the practical.

On a less cosmetic level, I would most like to expand on the method by which concepts are stored. If the program were given a series of images that represent the same scene moving over a period of time, it should be able to recognize objects as they move through three dimensions, possibly being distorted or partially obscured. This could be done by creating multiple instances by which a concept could be identified, since a shape
will not change much between two consecutive frames of motion, but it can change considerably over long periods of time. Keeping the most recent objects used in a convenient location would also be useful for this task.

I hope to make these and many other additions to the program over time. I see in it a potential that could eventually lead to a wide variety of applications for computer vision and human-computer interaction. However, there is still much work left to be done before specific applications can be considered.

The following pages contain the final version of the source code used in the program.
/* Bitmap.h

Contains definition of Bitmap class, used for storing BMP file information.
*/

#ifndef _BITMAPH_
define _BITMAPH_

class Bitmap {
  protected:
    int x, y;   // width and height of bitmap, respectively
    char *header;  // header information from BMP file
    unsigned char ***color;  // color values of all coordinates

  public:
    Bitmap(const char *filename);
    Bitmap(int new_x, int new_y, unsigned char ***new_color);
    long getX(void) { return x; }
    long getY(void) { return y; }
    unsigned char *** getColor(void) { return color; }
    void saveToFile(char *filename);  // not yet created

};

define _BITMAPH_
#endif
/** Bitmap.cpp

    Function definitions for Bitmap class.
*/

#include <stdio.h>
#include <iostream.h>
#include "bitmap.h"
#include "misc.h"

/** Bitmap::Bitmap(const char *filename)

    Constructor for Bitmap class; reads file specified by user.

    Parameters:

    filename - name of file to be read
*/

Bitmap::Bitmap(const char *filename)
{
    FILE *bmpfile = fopen(filename,"r");
    int i, j;

    header = new char[54];

    for (i=0;i<54;i++)
        fscanf(bmpfile,"%c",header+i);

    x = BMP_WIDTH;
    y = BMP_HEIGHT;

    color = new unsigned char **[x];

    for (i=0;i<x;i++) {
        color[i] = new unsigned char *[y];
        for (j=0;j<y;j++) {
            color[i][j] = new unsigned char[3];
        }
    }

    for (j=y-1;j>=0;j--) {
        for (i=0;i<=x-1;i++) {
            fscanf(bmpfile,"%c",&color[i][j][B]);
            fscanf(bmpfile,"%c",&color[i][j][G]);
            fscanf(bmpfile,"%c",&color[i][j][R]);
        }
    }

    fclose(bmpfile);
}
/* Scene2D.h

Contains definition of Scene 2D class, a data representation
of the scene being analyzed by the program.
*/

#ifndef _SCENE2DH_
define _SCENE2DH_

#include "Bitmap.h"
#include "View2D.h"

class Scene2D {
protected:
    int max_x, max_y; //width and height of image, respectively
    Bitmap *source;  //Bitmap object used to create Scene2D
                   //instance
    unsigned char ***color; //Color values of all coordinates
                            //in scene

public:
    Scene2D(char *bitmap);
    View2D * makeView2DPtr(int x1, int y1, int x, int y, int res);
    View2D * makeView2DPtr(int res) { return
      makeView2DPtr(0,0,max_x,max_y,res); }
    //view encompasses whole scene by default
    View2D * makeView2DPtr(void) { return
      makeView2DPtr(0,0,max_x,max_y,1); }
    //blur is set to 1 by default
};
#include <stdio.h>
#include <iostream.h>
#include "Scene2D.h"
#include "Bitmap.h"
#include "misc.h"

Scene2D::Scene2D(char *bitmap)
{
    source = new Bitmap(bitmap);
    max_x = source->getX();
    max_y = source->getY();
    color = source->getColor();
}

View2D * Scene2D::makeView2DPtr(int x1, int y1, int x, int y, int res)
{ unsigned char ***new_color;
    int i, j, k, l;
    int color_sum[3];
}
if (x1<0) {
    x -= (int)((0 - x1)/res);
    x1 = 0;
}
if (y1<0) {
    y -= (int)((0 - y1)/res);
    y1 = 0;
}
if (x1+x*res>max_x) {
    x = (int)(max_x/res);
}
if (y1+y*res>max_y) {
    y = (int)(max_y/res);
}

new_color = new unsigned char **[x];

for (i=0;i<x;i++) {
    new_color[i] = new unsigned char *[y];
    for (j=0;j<y;j++) {
        new_color[i][j] = new unsigned char[3];
    }
}

for (i=x1;i<x*res;i+=res) {
    for (j=y1;j<y*res;j+=res) {
        color_sum[R] = 0;
        color_sum[G] = 0;
        color_sum[B] = 0;
        for (k=i;k<i+res;k++) {
            for (l=j;l<j+res;l++) {
                color_sum[R] += color[k][l][R];
                color_sum[G] += color[k][l][G];
                color_sum[B] += color[k][l][B];
            }
        }
        new_color[i][j][R] = color_sum[R]/(res*res);
        new_color[i][j][G] = color_sum[G]/(res*res);
        new_color[i][j][B] = color_sum[B]/(res*res);
    }
}

return new View2D(new_color,x1,y1,x,y,res);
/* View2D.h

Definition of the View2D class, representing a "view", which is a (possibly zoomed-in) portion of a Scene2D object. This class can also create a list of shapes contained within the boundaries of the view.
*/

#ifndef _VIEW2DH_
define _VIEW2DH_

#include "Shape2D.h"
#include "misc.h"

class View2D
{
    protected:
        int x1, y1; //top left corner of the view
        int x, y; //width and height of the view, respectively
        int res; //zoom level of the view
        unsigned char ***color; //colors of coordinates within the view
        bool **mark; //coordinates of the view that have been checked for shapes

    void makePoint2DList(int curr_x,int curr_y,Point2DList *pl_address);

    public:
        View2D(unsigned char ***new_color,int new_x1,int new_y1,int new_x,int new_y,int new_res);
        Shape2DList makeShape2DList(void);
};

#endif
Function definitions for the View2D class.

\/include <iostream.h>
\/include "Scene2D.h"
\/include "misc.h"

View2D::View2D(unsigned char ***new_color,int new_x1,int
new_y1,int new_x,int new_y,int new_res)

  Constructor for View2D; sets member variables and initializes
  mark list.

  Parameters:

      new_color - the color information for the view
      new_x1,new_y1 - the top-left corner of the view
      new_x,new_y - the width and height of the view, respectively
      new_res - the zoom level of the view

\/View2D::View2D(unsigned char ***new_color,int new_x1,int new_y1,int
new_x,int new_y,int new_res)
{
  int i, j;

  color = new_color;
  xl = new_x1;
  yl = new_y1;
  x = new_x;
  y = new_y;
  res = new_res;

  mark = new bool *[x];

  for (i=0;i<x;i++) {
    mark[i] = new bool[y];
    for (j=0;j<y;j++)
      mark[i][j] = false;
  }
}

Shape2DList View2D::makeShape2DList(void)

  Create a Shape2DList object by identifying and listing shapes
  in the view.

  Return Value:

      The newly-created shape list

*/
Shape2DList View2D::makeShape2DList(void)
{
  int i, j;
Shape2DList sl = NULL, new_sl, sl_counter;
Point2DList pl = NULL, pl_killer;

for (i=0;i<x;i++) {  //shape-finding loop
    for (j=0;j<y;j++) {
        if (!mark[i][j] && !isBlack(color[i][j])) {  //Black pixels are assumed to be background
            makePoint2DList(i,j,&pl);
            new_sl = new Shape2DListData;
            new_sl->s = new Shape2D(pl);
            if (sl==NULL) {
                sl = new_sl;
                sl->next = NULL;
            } else if (new_sl->s->getColorValue() > sl->s->getColorValue()) {
                new_sl->next = sl;
                sl = new_sl;
            } else if (sl->next==NULL) {
                sl->next = new_sl;
                new_sl->next = NULL;
            } else {
                sl_counter = sl;
                while (sl_counter->next!=NULL) {
                    if (new_sl->s->getColorValue() > sl_counter->next->s->getColorValue()) {
                        break;
                    }
                    sl_counter = sl_counter->next;
                }
                new_sl->next = sl_counter->next;
                sl_counter->next = new_sl;
            }
        }
    }
}

while (pl!=NULL) {
    pl_killer = pl;
    pl = pl->next;
    delete pl_killer;
}

return sl;

/* void View2D::makePoint2DList(int curr_x,int curr_y,Point2DList *pl_address)  
   Creates a Point2DList of rectangular points in a shape, using a recursive fill algorithm. 
   Parameters: 
       curr_x,curr_y - x and y view coordinates of the current point */
void View2D::makePoint2DList(int curr_x, int curr_y, Point2DList *pl_address)
{
    Point2DList new_pl;
    mark[curr_x][curr_y] = true;

    new_pl = new Point2DListData;
    new_pl->color = new unsigned char[3];
    new_pl->color[R] = color[curr_x][curr_y][R];
    new_pl->color[G] = color[curr_x][curr_y][G];
    new_pl->color[B] = color[curr_x][curr_y][B];
    new_pl->x = curr_x;
    new_pl->y = curr_y;
    new_pl->next = *pl_address;
    *pl_address = new_pl;

    if (curr_x>0) {
        if(isSameColor(color[curr_x][curr_y],color[curr_x-1][curr_y]) && !mark[curr_x-1][curr_y])
            makePoint2DList(curr_x-1,curr_y,pl_address);
    }
    if (curr_x<x) {
        if(isSameColor(color[curr_x][curr_y],color[curr_x+1][curr_y]) && !mark[curr_x+1][curr_y])
            makePoint2DList(curr_x+1,curr_y,pl_address);
    }
    if (curr_y>0) {
        if(isSameColor(color[curr_x][curr_y],color[curr_x][curr_y-1]) && !mark[curr_x][curr_y-1])
            makePoint2DList(curr_x,curr_y-1,pl_address);
    }
    if (curr_y<y) {
        if(isSameColor(color[curr_x][curr_y],color[curr_x][curr_y+1]) && !mark[curr_x][curr_y+1])
            makePoint2DList(curr_x,curr_y+1,pl_address);
    }
}
Shape2D.h

Definition of Shape2D class, used for storing polar equivalents of points forming shapes in the original image. Also contains definitions of Ring, RingList, CenterList, StdShape2D, Polar2DList, and Shape2DList structures explained below.

#ifndef _SHAPE2DH_
define _SHAPE2DH_

#include <iostream.h>
#include <math.h>
#include "misc.h"

//Standardized Shape structures

/* Ring
A list of polar points with equal radius values */

struct RingData {
  float theta; //theta value of a point in the ring
  RingData *next; // the next counterclockwise point in the ring
};
typedef RingData *Ring;

/* RingList
A list of Rings with different radii */

struct RingListData {
  Ring ring; //radius of current ring
  float r;  //maximum number of points in current ring
  int ring_size; //the next smaller ring in the list
};
typedef RingListData *RingList;

/* CenterList
A list of coordinates for centers of shapes, based on their scene coordinates. The centers of shapes are calculated by averaging the x and y coordinates of points within a shape. */

struct CenterListData {
  float x;
  float y;
  CenterListData *next;
};
typedef CenterListData *CenterList;
/ * StdShape2D

A standardized shape, consisting of a RingList containing coordinate information, the color of the shape, a list of the centers of known instances of the shape, and other statistical information about the shape.
*/

struct StdShape2DData {
    RingList rl; //the shape's points
    int point_total, ring_total; //total number of points and rings in the shape
    unsigned char *color; //the color of the shape (3-character array)
    float avg_r, stddev_r; //mean and standard deviation of points in shape
    float r_error, theta_error; //r and theta errors of shape
    CenterList cl; //List of centers of known similar shapes
};
typedef StdShape2DData *StdShape2D;

//Unstandardized Shape structures

/*
Polar2DList
A doubly-linked list of 2-dimensional polar coordinates, sorted by theta.
*/

struct Polar2DListData {
    float r;
    float theta;
    Polar2DListData *next_cw, *next_ccw; //next clockwise and counterclockwise points in list, respectively
};
typedef Polar2DListData *Polar2DList;

/*
Shape2D
An unstandardized shape, containing points sorted by their theta values.
*/

class Shape2D {
    protected:
        Polar2DList pol; //the shape's points
        int point_total; //the total number of points in the shape
        unsigned char *color; //the color of the shape (3-character array)
        float avg_r, stddev_r, max_r; //mean, standard deviation, and maximum value of r
        int min_x, max_x, min_y, max_y; //minimum and maximum values //of the shape's original x and y coordinates, based on //their absolute positions in the BMP file
        float center_x, center_y; //the coordinates of the shape's
private:
    Shape2D(Point2DList pl);
    int getColorValue(void)
    {  
        return color[R] + color[G] + color[B];
    }
    int GetMinX(void)
    {  
        return min_x;
    }
    int GetMaxX(void)
    {  
        return max_x;
    }
    int GetMinY(void)
    {  
        return min_y;
    }
    int GetMaxY(void)
    {  
        return max_y;
    }
    static float sameColor(Shape2D *s1,Shape2D *s2)
    {  
        return ((float)(abs(s1->color[R]-s2->color[R]) +  
                        abs(s1->color[G]-s2->color[G]) + abs(s1->color[B]-s2->color[B])))/765;
    }
    static float sameSize(Shape2D *s1,Shape2D *s2)
    {  
        if (s1->avg_r<s2->avg_r)  
            return s1->avg_r/s2->avg_r;
        else
            return s2->avg_r/s1->avg_r;
    }
    static float sameStdDev(Shape2D *s1,Shape2D *s2)
    {  
        if (s1->stddev_r<s2->stddev_r)  
            return s1->stddev_r/s2->stddev_r;
        else
            return s2->stddev_r/s1->stddev_r;
    }
    float sameOrientation(Shape2D *s1,Shape2D *s2,float r_error,float theta_error);
    float sameShape(Shape2D *s1,Shape2D *s2,float r_error,float theta_error);
    StdShape2D standardize(int point_limit);
    void printInfo(void)
    {  
        cout << "Average r: " << avg_r << "\n";
        cout << "Std. dev. of r: " << stddev_r << "\n";
    }
/* Shape2DList */

A linked list of Shape2D objects

struct Shape2DListData { 
    Shape2D *s;
    Shape2DListData *next;
};

typedef Shape2DListData *Shape2DList;

#error
/* Shape2D.cpp

Function definitions for the Shape2D class
*/

#include <iostream.h>
#include <math.h>
#include "Shape2D.h"
#include "misc.h"

/* Shape2D::Shape2D(Point2DList pl)

Constructor for Shape2D class; converts a list of rectangular
coordinates to polar coordinates, then calculates the shape's
other attributes.

Parameters:

   pl - a list of rectangular coordinates
*/

Shape2D::Shape2D(Point2DList pl) {
    Point2DList pl_counter;
    Polar2DList new_pol, pol_counter;
    double r_total = 0;
    double stddev_r_total = 0;
    int x_total = 0, y_total = 0;

    color = new unsigned char[3];
    color[R] = pl->color[R];
    color[G] = pl->color[G];
    color[B] = pl->color[B];

    point_total = 0;
    pl_counter = pl;

    while (pl_counter!=NULL) {
        point_total++;
        x_total += pl_counter->x;
        y_total += pl_counter->y;
        pl_counter = pl_counter->next;
    }

    center_x = (float)x_total/(float)point_total;
    center_y = (float)y_total/(float)point_total;

    pol = NULL;
    pl_counter = pl;

    double r;
    while (pl_counter!=NULL) {
        //coordinate transformation loop
        new_pol = new Polar2DListData;
        new_pol->r = (float)sqrt(((float)pl_counter->x-center_x)*((float)pl_counter->x-center_x) + ((float)pl_counter->y-center_y)*((float)pl_counter->y-center_y));
        r_total += new_pol->r;
    }
}

/* Shape2D::Shape2D(Point2DList pl)*/
if (new_pol->r > max_r) {
    max_r = new_pol->r;
}
if (pl_counter->x != center_x) {
    if ((float)pl_counter->x-center_x>0.0f) {
        new_pol->theta = (float)atan(((float)pl_counter->y-center_y)/((float)pl_counter->x-center_x));
    } else if ((float)pl_counter->y-center_y>0.0f) {
        new_pol->theta = (float)atan(((float)pl_counter->y-center_y)/((float)pl_counter->x-center_x)) + PI;
    } else {
        new_pol->theta = (float)atan(((float)pl_counter->y-center_y)/((float)pl_counter->x-center_x)) - PI;
    }
} else if (((float)pl_counter->y-center_y)>0)
    new_pol->theta = PI_OVER_2;
else
    new_pol->theta = -PI_OVER_2;
if (pol==NULL) {
    new_pol->next_ccw = new_pol;
    new_pol->next_cw = new_pol;
    pol = new_pol;
} else if (new_pol->theta<pol->theta) {
    new_pol->next_ccw = pol;
    new_pol->next_cw = pol->next_cw;
    pol->next_cw->next_ccw = new_pol;
    pol->next_cw = new_pol;
} else {
    pol_counter = pol->next_ccw;
    while ((pol_counter!=pol) && (pol_counter->theta < new_pol->theta)) {
        pol_counter = pol_counter->next_ccw;
    }
    new_pol->next_ccw = pol_counter;
    new_pol->next_cw = pol_counter->next_cw;
    pol_counter->next_cw->next_ccw = new_pol;
    pol_counter->next_cw = new_pol;
}
pl_counter = pl_counter->next;

avg_r = (float)(r_total/(double)point_total);
pol_counter = pol;
if (avg_r==0.0f) {
    stddev_r = 0.0f;
}
else {
    //standard deviation calculation loop
    stddev_r_total += fabs(pol_counter->r - avg_r);
    pol_counter = pol_counter->next_ccw;
} while (pol_counter!=pol);
stddev_r = (float)(stddev_r_total / (double)point_total) / avg_r;
}
pl_counter = pl;
min_x = BMP_WIDTH;
max_x = 0;
min_y = BMP_WIDTH;
max_y = 0;
while (pl_counter!=NULL) {
    //min/max x/y finder loop
    if (pl_counter->x<min_x)
        min_x = pl_counter->x;
    if (pl_counter->x>max_x)
        max_x = pl_counter->x;
    if (pl_counter->y<min_y)
        min_y = pl_counter->y;
    if (pl_counter->y>max_y)
        max_y = pl_counter->y;
    pl_counter = pl_counter->next;
}

/*
 * Shape2D::sameOrientation(Shape2D *s1,Shape2D *s2,float r_error,float theta_error)
 */
float Shape2D::sameOrientation(Shape2D *s1,Shape2D *s2,float r_error,float theta_error)
{
    Polar2DList pol_counter_1, pol_counter_2;
    float size_ratio;
    float result_1, result_2;
    float match_total;
    bool match_found;
    int i, j;
if (s2->avg_r==0.0f)
  return 1.0f;

size_ratio = s1->avg_r/s2->avg_r;
match_total = 0;
pol_counter_1 = s1->pol;

for (i=0;i<s1->point_total;i++) {
  pol_counter_2 = s2->pol;
  match_found = false;
  for (j=0;(j<s2->point_total) && (pol_counter_2->theta -
  pol_counter_1->theta <= theta_error*PI_OVER_2/pol_counter_1->r) &&
  !match_found;j++) {
    if ((pol_counter_1->r==0.0f) && (fabs(pol_counter_2-
    r*size_ratio - pol_counter_1->r) <= r_error*size_ratio)) {
      match_total++;
      match_found = true;
    }
    else if ((fabs(pol_counter_2->r*size_ratio -
    pol_counter_1->r) <= r_error*size_ratio) && (fabs(pol_counter_2->theta -
    pol_counter_1->theta) <= theta_error*PI_OVER_2/pol_counter_1->r)) {
      match_total++;
      match_found = true;
    }
    pol_counter_2 = pol_counter_2->next_ccw;
  }
  pol_counter_1 = pol_counter_1->next_ccw;
}

result_1 = match_total/((float)s1->point_total);

match_total = 0;
pol_counter_1 = s2->pol;

for (i=0;i<s2->point_total;i++) {
  pol_counter_2 = s1->pol;
  match_found = false;
  for (j=0;(j<s1->point_total) && (pol_counter_2->theta -
  pol_counter_1->theta <= theta_error*PI_OVER_2/pol_counter_1->r) &&
  !match_found;j++) {
    if ((pol_counter_1->r==0.0f) && (fabs(pol_counter_2-
    r*size_ratio - pol_counter_1->r) <= r_error*size_ratio)) {
      match_total++;
      match_found = true;
    }
    else if ((fabs(pol_counter_2->r - pol_counter_1->r *
    size_ratio) <= r_error/size_ratio) && (fabs(pol_counter_2->theta -
    pol_counter_1->theta) <= theta_error*PI OVER_2/pol_counter_1->r)) {
      match_total++;
      match_found = true;
    }
    pol_counter_2 = pol_counter_2->next_ccw;
  }
  pol_counter_1 = pol_counter_1->next_ccw;
}
result_2 = match_total/((float)s2->point_total);
 return result_1*result_2;
}

/* Shape2D::sameShape(Shape2D *s1,Shape2D *s2,float r_error,float theta_error)

Compares two Shape2D objects to see if they have the same shape, regardless of orientation. Not used in final code.

Parameters:

s1, s2 - the two shapes being compared
r_error - the maximum allowable error for the r value of a point
theta_error - multiplier used in calculating maximum allowable error for the theta value of a point

Return Value:

A decimal value between 0 and 1, where 1 indicates a perfect match and 0 indicates a complete mismatch.
*/

float Shape2D::sameShape(Shape2D *s1,Shape2D *s2,float r_error,float theta_error)
{
    Polar2DList pol_counter_1, pol_counter_2, pol_counter_2_start, best_pol_counter_2_start, pol_counter_2_mark;
    Shape2D *small_s, *large_s;
    float size_ratio;
    float result_1, result_2;
    float match_total, best_match_total;
    float theta_diff, theta_diff_2;
    bool match_found;
    int i, j, k;
    long order;
    float best_theta_diff;

    if (s1->avg_r<s2->avg_r) {
        small_s = s1;
        large_s = s2;
    } else {
        small_s = s2;
        large_s = s1;
    }

    if (large_s->avg_r==0.0f)
        return 1.0f;

    size_ratio = small_s->avg_r/large_s->avg_r;
    pol_counter_2_start = large_s->pol;
    best_match_total = 0;
    best_theta_diff = 0;
    best_pol_counter_2_start = pol_counter_2_start;
order = 0;

for (k=0;k<large_s->point_total;k++) {
    pol_counter_1 = small_s->pol;
    while ((fabs(pol_counter_2_start->r*size_ratio -
            pol_counter_1->r) > r_error*size_ratio) && (k<large_s->point_total)) {
        pol_counter_2_start = pol_counter_2_start->next_ccw;
        k++;
    }
    pol_counter_2 = pol_counter_2_start;
    theta_diff = pol_counter_2->theta - pol_counter_1->theta;
    match_total = 0;
    for (i=0;i<small_s->point_total;i++) {
        match_found = false;
        pol_counter_2_mark = pol_counter_2;
        theta_diff_2 = pol_counter_2->theta - pol_counter_1->theta - theta_diff;
        if (theta_diff_2 < -PI)
            theta_diff_2 += PI_TIMES_2;
        if (theta_diff_2 <= theta_error * PI_OVER_2 / pol_counter_1->r) {
            j = 0;
            while (!match_found && (j<large_s->point_total) && (theta_diff_2 <= theta_error*PI_OVER_2/pol_counter_1->r)) {
                order++;
                if ((pol_counter_1->r==0.0f) &&
                    (fabs(pol_counter_2->r*size_ratio - pol_counter_1->r) <=
                    r_error*size_ratio)) {
                    match_total++;
                    match_found = true;
                } else if ((fabs(pol_counter_2->r*
                    size_ratio - pol_counter_1->r) <= r_error*size_ratio) && (theta_diff_2 >= -theta_error*PI_OVER_2/pol_counter_1->r)) {
                    match_total++;
                    match_found = true;
                }
                pol_counter_2 = pol_counter_2->next_ccw;
                theta_diff_2 = pol_counter_2->theta -
                pol_counter_1->theta - theta_diff;
                if (theta_diff_2 < -PI)
                    theta_diff_2 += PI_TIMES_2;
                j++;
            }
        }
        pol_counter_2 = pol_counter_2_mark;
        theta_diff_2 = pol_counter_2->theta - pol_counter_1->theta - theta_diff;
        if (theta_diff_2 < -PI)
            theta_diff_2 += PI_TIMES_2;
        if (theta_diff_2 >= -theta_error*PI_OVER_2/pol_counter_1->r) {
            j = 0;
            while (!match_found && (j<large_s->point_total) &&
                    (theta_diff_2 >= -theta_error*PI_OVER_2/pol_counter_1->r)) {
                order++;
            }
if ((pol_counter_1->r == 0.0f) &&
     (fabs(pol_counter_2->r * size_ratio - pol_counter_1->r) <= r_error * size_ratio)) {
    match_total++;
    match_found = true;
}
else if ((fabs(pol_counter_2->r * size_ratio - pol_counter_1->r) <= r_error * size_ratio) &&
     (theta_diff_2 <= theta_error * PI_OVER_2 / pol_counter_1->r)) {
    match_total++;
    match_found = true;
}
pol_counter_2 = pol_counter_2->next_cw;
theta_diff_2 = pol_counter_2->theta -
    pol_counter_1->theta - theta_diff;
    if (theta_diff_2 < -PI)
        theta_diff_2 += PI_TIMES_2;
j++;
}
pol_counter_1 = pol_counter_1->next_ccw;

if (match_total > best_match_total) {
    best_match_total = match_total;
    best_theta_diff = theta_diff;
    best_pol_counter_2_start = pol_counter_2_start;
}
pol_counter_2_start = pol_counter_2_start->next_ccw;

result_1 = best_match_total / ((float)small_s->point_total);

pol_counter_1 = best_pol_counter_2_start;
pol_counter_2 = small_s->pol;
theta_diff = -best_theta_diff;
match_total = 0;

for (i=0; i<large_s->point_total; i++) {
    match_found = false;
pol_counter_2_mark = pol_counter_2;
theta_diff_2 = pol_counter_2->theta -
    pol_counter_1->theta - theta_diff;
    if (theta_diff_2 < -PI)
        theta_diff_2 += PI_TIMES_2;
    else if (theta_diff_2 > PI)
        theta_diff_2 -= PI_TIMES_2;
    if (theta_diff_2 <= theta_error * PI_OVER_2 / pol_counter_2->r) {
        j = 0;
        while (!match_found && (j < small_s->point_total) &&
            (theta_diff_2 <= theta_error * PI_OVER_2 / pol_counter_2->r)) {
            order++;
            if ((pol_counter_1->r == 0.0f) &&
                (fabs(pol_counter_2->r * size_ratio - pol_counter_1->r) <=
                r_error * size_ratio)) {
                match_total++;
match_found = true;
}
else if ((fabs(pol_counter_2->r/size_ratio - pol_counter_1->r) <= r_error/size_ratio) && (theta_diff_2 >= -theta_error*PI_OVER_2/pol_counter_2->r)) {
    match_total++;
    match_found = true;
}
pol_counter_2 = pol_counter_2->next_ccw;
theta_diff_2 = pol_counter_2->theta - pol_counter_1->theta - theta_diff;
if (theta_diff_2 < -PI)
    theta_diff_2 += PI_TIMES_2;
else if (theta_diff_2 > PI)
    theta_diff_2 -= PI_TIMES_2;
j++;
}
}
pol_counter_2 = pol_counter_2_mark;
theta_diff_2 = pol_counter_2->theta - pol_counter_1->theta - theta_diff;
if (theta_diff_2 < -PI)
    theta_diff_2 += PI_TIMES_2;
else if (theta_diff_2 > PI)
    theta_diff_2 -= PI_TIMES_2;
if (theta_diff_2 >= -theta_error*PI_OVER_2/pol_counter_2->r) {
    j = 0;
    while (!match_found && (j<large_s->point_total) && (theta_diff_2 >= -theta_error*PI_OVER_2/pol_counter_2->r)) {
        order++;
        if ((pol_counter_1->r==0.0f) && (fabs(pol_counter_2->r/size_ratio - pol_counter_1->r) <= r_error / size_ratio)) {
            match_total++;
            match_found = true;
        }
    }
}
else if ((fabs(pol_counter_2->r/size_ratio - pol_counter_1->r) <= r_error/size_ratio) && (theta_diff_2 <= theta_error*PI_OVER_2/pol_counter_2->r)) {
    match_total++;
    match_found = true;
}
pol_counter_2 = pol_counter_2->next_cw;
theta_diff_2 = pol_counter_2->theta - pol_counter_1->theta - theta_diff;
if (theta_diff_2 < -PI)
    theta_diff_2 += PI_TIMES_2;
else if (theta_diff_2 > PI)
    theta_diff_2 -= PI_TIMES_2;
j++;
}
}
pol_counter_1 = pol_counter_1->next_ccw;

result_2 = match_total/((float)large_s->point_total);
return result_1*result_2;
}

/* StdShape2D Shape2D::standardize(int point_limit)

Converts the current Shape2D object into a StdShape2D structure.

Parameters:

point_limit - maximum number of points allowed in StdShape2D representation being created

Return Value:

The StdShape2D structure created from the current Shape2D object
*/

StdShape2D Shape2D::standardize(int point_limit)
{
    StdShape2D new_ss = new StdShape2DData;
    Ring r_counter;
    RingList rl_counter;
    Polar2DList pol_counter;
    float curr_theta, theta_inc;
    float r_total = 0.0f, stddev_total = 0.0f;
    bool match_found;
    int i, j;

    new_ss->cl = new CenterListData;
    new_ss->cl->x = center_x;
    new_ss->cl->y = center_y;
    new_ss->cl->next = NULL;

    new_ss->color = new unsigned char[3];
    new_ss->color[R] = color[R];
    new_ss->color[G] = color[G];
    new_ss->color[B] = color[B];

    if (point_total<=point_limit) {
        new_ss->ring_total = (int)max_r;
    }
    else {
        new_ss->ring_total = (int)((sqrt(4*point_limit/PI+1)-1)/2);
    }

    new_ss->r_error = 1.0f/(float)new_ss->ring_total;
    new_ss->theta_error = PI_TIMES_2/(float)((int)(PI_TIMES_2 *
new_ss->ring_total));
    new_ss->point_total = 0;
    new_ss->rl = new RingListData;
    rl_counter = new_ss->rl;

    for (i=new_ss->ring_total;i>0;i--) {
        //StdShape2D creation
        rl_counter->ring_size = (int)(i*PI_TIMES_2);
rl_counter->ring = new RingData;
rl_counter->r = (float)i/(float)new_ss->ring_total;
r_counter = rl_counter->ring;
r_counter->theta = -PI_TIMES_2;
pol_counter = pol;
curr_theta = -PI;
theta_inc = PI_TIMES_2/(float)((int)(i*PI_TIMES_2));
for (j=0;j<(int)(i*PI_TIMES_2);j++) {//Ring creation loop
  match_found = false;
  while ((fabs(pol_counter->theta-curr_theta) <= theta_inc) && !match_found) {
    if (fabs(pol_counter->r-rl_counter->r * max_r) <= 1.0f) {
      if (r_counter->theta>-PI_TIMES_2) {
        r_counter->next = new RingData;
        r_counter = r_counter->next;
      }
      r_total += rl_counter->r;
      new_ss->point_total++;
      r_counter->theta = curr_theta;
      match_found = true;
    }
    pol_counter = pol_counter->next_ccw;
  }
  while (fabs(pol_counter->theta-curr_theta) <= theta_inc) {
    pol_counter = pol_counter->next_ccw;
  }
  curr_theta += theta_inc;
}
if (r_counter->theta==-PI_TIMES_2) {
  delete r_counter;
  rl_counter->ring = NULL;
} else {
  r_counter->next = rl_counter->ring;
}
if (i>1) {
  rl_counter->next = new RingListData;
  rl_counter = rl_counter->next;
}
}
if (new_ss->point_total==0) {
  return NULL;
}
rl_counter->next = NULL;
new_ss->avg_r = r_total/(float)new_ss->point_total;
rl_counter = new_ss->rl;
do { //standard deviation calculation loop
  if (rl_counter->ring!=NULL) {
    r_counter = rl_counter->ring;
    do {
      stddev_total += (float)fabs(r_counter->r-
      new_ss->avg_r);
    }
    while (r_counter->next != rl_counter->ring);
  }
  rl_counter->next = NULL;
}
r_counter = r_counter->next;
} while (r_counter!=rl_counter->ring);

rl_counter = rl_counter->next;
} while (rl_counter!=NULL);

new_ss->stddev_r = stddev_total/new_ss->point_total;

return new_ss;
}
/* Concept.h

Contains information for Concept class, used for storing previously identified shapes. Also contains ConceptList structure, which is used to form a linked list of concepts.
*/

#ifndef _CONCEPTH_
#define _CONCEPTH_

#include "Shape2D.h"
#include "misc.h"

class Concept {
  protected:
    StdShape2D s;  //Representative shape instance for concept
    int instances; //Number of found instances of the concept
  public:
    Concept(StdShape2D new_s) {
      s = new_s;
      instances = 1;
    }
    float sameShape(StdShape2D s1, StdShape2D s2);
    float sameColor(StdShape2D s1, StdShape2D s2) {
      return ((float)(765 - (abs(s1->color[R]-s2->color[R])
        + abs(s1->color[G]-s2->color[G]) + abs(s1->color[B]-s2->color[B])))) / 765;
    }
    bool isInstance(StdShape2D nominee);
    StdShape2D getS(void) {
      return s;
    }
    int getInstances(void) {
      return instances;
    }
    void printStdShape(void);
  };

struct ConceptListData {
  Concept *c;
  ConceptListData *next;
};
typedef ConceptListData *ConceptList;
#endif
Function definitions for Concept class.

#include <iostream.h>
#include "Concept.h"
#include "Shape2D.h"

/*
float Concept::sameShape(StdShape2D s1, StdShape2D s2)
Compares two StdShape2D structures (see Shape2D.h).
Parameters:
s1, s2 - The two shapes being compared.
Return Value:
A decimal value between 0 and 1, where 1 indicates
a perfect match and 0 indicates a complete mismatch.
*/

float Concept::sameShape(StdShape2D s1, StdShape2D s2) {
    StdShape2D s_temp;
    RingList rl_counter_1, rl_counter_2;
    Ring r_counter_1, r_counter_2, r_counter_1_start;
    int match_total_1, match_total_2, best_match_total_1,
    best_match_total_2;
    float result, best_result = 0.0f;
    float theta_diff = 0.0f, theta_inc, theta_1_adjusted,
    last_theta_1_adjusted;
    bool match_found, ring_1_start, ring_2_start, new_ring_1;
    if (s1->rl->ring_size > s2->rl->ring_size) {
        s_temp = s1;
        s1 = s2;
        s2 = s_temp;
    }
    theta_inc = PI_TIMES_2/(float)s2->rl->ring_size;
    do { /* Main comparison loop */
        rl_counter_1 = s1->rl;
        rl_counter_2 = s2->rl;
        match_total_1 = 0;
        match_total_2 = 0;
        new_ring_1 = true;
        do { /* Orientation comparison loop */
            r_counter_1 = rl_counter_1->ring;
            r_counter_2 = rl_counter_2->ring;
            match_found = false;
            theta_1_adjusted = -PI_OVER_2;
            do { /* last_theta_1_adjusted = theta_1_adjusted; */
                last_theta_1_adjusted = theta_1_adjusted;
            } while (theta_1_adjusted < PI && match_found == false);
            theta_1_adjusted = last_theta_1_adjusted;
            match_found = true;
            theta_1_adjusted = -PI_OVER_2;
            do { /* last_theta_1_adjusted = theta_1_adjusted; */
                last_theta_1_adjusted = theta_1_adjusted;
            } while (theta_1_adjusted > -PI && match_found == false);
            theta_1_adjusted = last_theta_1_adjusted;
            theta_diff = theta_1_adjusted - theta_1_adjusted - theta_diff;
            theta_1_adjusted = -PI_OVER_2;
            do { /* last_theta_1_adjusted = theta_1_adjusted; */
                last_theta_1_adjusted = theta_1_adjusted;
            } while (theta_1_adjusted < PI && match_found == false);
            theta_1_adjusted = last_theta_1_adjusted;
            match_found = true;
            theta_1_adjusted = PI_OVER_2;
            do { /* last_theta_1_adjusted = theta_1_adjusted; */
                last_theta_1_adjusted = theta_1_adjusted;
            } while (theta_1_adjusted > PI && match_found == false);
            theta_1_adjusted = last_theta_1_adjusted;
            theta_diff = theta_1_adjusted - theta_1_adjusted - theta_diff;
            theta_1_adjusted = PI_OVER_2;
            do { /* last_theta_1_adjusted = theta_1_adjusted; */
                last_theta_1_adjusted = theta_1_adjusted;
            } while (theta_1_adjusted < -PI && match_found == false);
            theta_1_adjusted = last_theta_1_adjusted;
            match_found = true;
            theta_1_adjusted = -PI_OVER_2;
            do { /* last_theta_1_adjusted = theta_1_adjusted; */
                last_theta_1_adjusted = theta_1_adjusted;
            } while (theta_1_adjusted > -PI && match_found == false);
            theta_1_adjusted = last_theta_1_adjusted;
            theta_diff = theta_1_adjusted - theta_1_adjusted - theta_diff;
        } while (theta_diff > 0.0f && match_total_1 < 1.0f);
        if (theta_diff <= 0.0f)
            match_1 = true;
        else
            match_1 = false;
        match_total_1 = match_1 ? 1.0f : 0.0f;
    } while (new_ring_1 == true);
    return match_total_1;
theta_1_adjusted = r_counter_1->theta + theta_diff;

if (theta_1_adjusted>PI) {
    theta_1_adjusted -= PI_TIMES_2;
}
if (theta_1_adjusted>last_theta_1_adjusted) {
    r_counter_1 = r_counter_1->next;
} while (theta_1_adjusted>last_theta_1_adjusted);

r_counter_1_start = r_counter_1;
ring_1_start = true;
ring_2_start = true;
do {  // Ring comparison loop
    theta_1_adjusted = r_counter_1->theta + theta_diff;
    if (theta_1_adjusted>PI) {
        theta_1_adjusted -= PI_TIMES_2;
    }
    if (fabs(theta_1_adjusted-r_counter_2->theta) < sl->theta_error/r1_counter_1->r-0.0001f) {
        if (ring_2_start) {
            match_total_2++;
            match_found = true;
            r_counter_2 = r_counter_2->next;
            ring_2_start = false;
        } else if (r_counter_2!=r1_counter_2->ring) {
            match_total_2++;
            match_found = true;
            r_counter_2 = r_counter_2->next;
        } else {
            r_counter_1 = r_counter_1_start;
        }
    } else if (theta_1_adjusted>r_counter_2->theta) {
        if (ring_2_start) {
            r_counter_2 = r_counter_2->next;
            ring_2_start = false;
        } else if (r_counter_2!=r1_counter_2->ring) {
            r_counter_2 = r_counter_2->next;
        } else {
            r_counter_1 = r_counter_1_start;
        }
    } else {
        if (match_found && new_ring_1) {
            match_total_1++;
        }
    }
    match_found = false;
    if (ring_1_start) {
        r_counter_1 = r_counter_1->next;
        ring_1_start = false;
    }
}
} else if (r_counter_1!=r_counter_1_start)
{
    r_counter_1 = r_counter_1->next;
}
else {
    r_counter_2 = r_counter_2->ring;
}
}
}
while ((r_counter_1!=r_counter_1_start) || (r_counter_2!=rl_counter_2->ring));
rl_counter_2 = rl_counter_2->next;
while (rl_counter_2!=NULL) {
    if (rl_counter_2->ring!=NULL)
        break;
    else
        rl_counter_2 = rl_counter_2->next;
}
new_ring_1 = false;
while ((rl_counter_1!=NULL) && (rl_counter_2!=NULL)) {
    if ((fabs(rl_counter_1->r-rl_counter_2->r) < s1->r_error-0.0001) && (rl_counter_1->ring!=NULL) && (rl_counter_2->ring!=NULL))
        break;
    if (rl_counter_1->r>rl_counter_2->r) {
        while (rl_counter_1!=NULL) {
            if (((rl_counter_1->r < rl_counter_2->r) || (fabs(rl_counter_1->r-rl_counter_2->r)<s1->r_error-0.0001)) && (rl_counter_1->ring!=NULL))
                break;
            rl_counter_1 = rl_counter_1->next;
        }
    }
    else {
        while (rl_counter_2!=NULL) {
            if (((rl_counter_2->r<rl_counter_1->r) || (fabs(rl_counter_1->r-rl_counter_2->r)<s1->r_error-0.0001)) && (rl_counter_1->ring!=NULL))
                break;
            rl_counter_2 = rl_counter_2->next;
        }
    }
}
}
result = ((float)match_total_1/(float)s1->point_total) *
((float)match_total_2/(float)s2->point_total);
if (result>best_result) {
    best_match_total_1 = match_total_1;
    best_match_total_2 = match_total_2;
    best_result = result;
}
theta_diff += theta_inc;
}
while (theta_diff<PI_TIMES_2);
return best_result;
bool Concept::isInstance(StdShape2D nominee)
{
    CenterList cl_counter;
    if ((sameShape(nominee,s)>=MIN_SAMENESS) &&
        (sameColor(nominee,s)>=MIN_SAMENESS)) {
        instances++;
        cl_counter = s->cl;
        while (cl_counter->next!=NULL) {
            cl_counter = cl_counter->next;
        }
        cl_counter->next = nominee->cl;
        if (nominee->point_total>s->point_total) {
            nominee->cl = s->cl;
            s = nominee;
        }
        return true;
    } else {
        return false;
    }
}

void Concept::printStdShape(void)
{
    CenterList cl_counter;
    cout << "Color: Red=" << (int)s->color[R] << ", Green=" <<
           (int)s->color[G] << ", Blue=" << (int)s->color[B] << "\n";
    cl_counter = s->cl;
    while (cl_counter!=NULL) {
        cout << "Center at (" << cl_counter->x << ", " <<
                   cl_counter->y << ")\n";
        cl_counter = cl_counter->next;
    }
}
The Tommy class, responsible for using the other classes to extract shapes from image files and for categorizing the shapes into concepts.

```c
#ifndef _TOMMYH_
#define _TOMMYH_

#include "Concept.h"
#include "misc.h"

class Tommy {
    protected:
        ConceptList cl, last; // the list of known concepts, and
                           // the last concept in that list
    public:
        Tommy(int a);
        void processFile(char *bitmap);
        void addConcept(Concept *new_c);
        void printConceptList(void);
    };
#endif
```
/* Tommy.cpp

Function definitions for the Tommy class.
*/

#include <stdio.h>
#include <iostream.h>
#include "Tommy.h"
#include "Scene2D.h"
#include "View2D.h"
#include "Shape2D.h"
#include "Concept.h"

/* Tommy::Tommy(int a)

The constructor for the Tommy class; creates an empty concept list.

Parameters:

  a - a dummy variable created to fix a glitch in the compiler that caused the default constructor to be called instead of this one
*/

Tommy::Tommy(int a)
{
  cl = NULL;
  last = NULL;
}

/* void Tommy::processFile(char *bitmap)

Reads in a BMP file and adds its shapes to the current concept list.

Parameters:

  bitmap - the file name of the BMP file
*/

void Tommy::processFile(char *bitmap)
{
  Scene2D *sc;
  View2D *v;
  Shape2DList sl, sl_counter;
  ConceptList cl_counter;
  StdShape2D std;

  sc = new Scene2D(bitmap);
  v = sc->makeView2DPtr();
  sl = v->makeShape2DList();
  sl_counter = sl;

  while (sl_counter!=NULL) {
    //loop comparing shapes to known concepts
    std = sl_counter->s->standardize(POINT_LIMIT);
if (std!=NULL) {
    cl_counter = cl;
    while (cl_counter!=NULL) {
        if (cl_counter->c->isInstance(std))
            break;
        cl_counter = cl_counter->next;
    }
    if (cl_counter==NULL) {
        addConcept(new Concept(std));
    }
    sl_counter = sl_counter->next;
}
}

*/
void Tommy::addConcept(Concept *new_c)
{
    ConceptList cl_counter, new_cl;

    new_cl = new ConceptListData;
    new_cl->c = new_c;
    new_cl->next = NULL;

    if (cl==NULL) {
        cl = new_cl;
    } else {
        cl_counter = cl;
        while (cl_counter->next!=NULL) {
            if (new_c->getInstances()>=cl_counter->c->getInstances()) {
                new_cl->next = cl_counter->next;
                cl_counter->next = new_cl;
                break;
            }
            cl_counter = cl_counter->next;
        }
        if (cl_counter->next==NULL) {
            cl_counter->next = new_cl;
        }
    }
}

/*/
void Tommy::printConceptList(void)
{
    ConceptList cl_counter = cl;
    while (cl_counter!=NULL) {
        cl_counter->c->printStdShape();
        cout << "Instances: " << cl_counter->c->getInstances() << \
             "\n";
        cout << "\n";
        cl_counter = cl_counter->next;
    }
}
/ * misc.h

   Miscellaneous constants, structures and
   function headers that didn't fit under any
   one class.
*/

#ifndef _MISCH_
#define _MISCH_

#define PI 3.14159265f //Value of PI
#define PI_OVER_2 1.57079633f //Value of PI/2
#define PI_TIMES_2 6.28318531f //Value of PI*2

#define BMP_WIDTH 256 //width, in pixels, of BMP file
#define BMP_HEIGHT 256 //height, in pixels, of BMP file

#define MAX_DIST 1000000.0f
#define R 0      //red value in a color array
#define G 1      //green value in a color array
#define B 2      //blue value in a color array
#define MIN_SAMENESS 0.9f //threshold for determining whether two
                      //colors or shapes are the same

//"type" values for Tommy constructor; not used in current program
#define LOAD_TOMMY 0;
#define NEW_TOMMY 1;

#define POINT_LIMIT 5000  //maximum number of points in allowed in
                        //a standardized shape

/* Point2DList

   A linked list of rectangular integer coordinates
*/

struct Point2DListData
{
    int x, y;
    unsigned char *color;  //color at coordinate (x,y)
    Point2DListData *next;
};
typedef Point2DListData *Point2DList;

bool isBlack (unsigned char *c);
bool isSameColor(unsigned char *c1,unsigned char *c2);

#endif
#include "misc.h"

/*
 * isBlack(unsigned char *c)
 * Determines whether a given color value is black
 * Parameters:
 * c - A color value, stored as a 3-character array
 * Return Value:
 * "Is the specified color black?"
 */

bool isBlack(unsigned char *c)
{
    return (c[R]==0) && (c[G]==0) && (c[B]==0);
}

/*
 * isSameColor(unsigned char *c1,unsigned char *c2)
 * Determines whether two color values are exactly the same
 * Parameters:
 * c1, c2 - the two colors being compared.
 * Return Value:
 * Are the two specified colors exactly the same?
 */

bool isSameColor(unsigned char *c1,unsigned char *c2)
{
    return (c1[R]==c2[R]) && (c1[G]==c2[G]) && (c1[B]==c2[B]);
}
/*     testmain.cpp

Location of the main function, which uses an instance of the
Tommy class to convert a BMP file into a list of Concept objects.
*/

#include <stdio.h>
#include <stdlib.h>
#include <iostream.h>
#include "Bitmap.h"
#include "Scene2D.h"
#include "View2D.h"
#include "Shape2D.h"
#include "Concept.h"
#include "Tommy.h"
#include "misc.h"

void main(void)
{
    char bmp[40];
    Tommy *t;
    char end;
    int x = (int)22.9;

    cout << "Enter name of the image to examine: ";
    cin >> bmp;
    t = new Tommy(0);
    t->processFile(bmp);
    cout << "The image contained the following distinct concepts:
";
    t->printConceptList();
    cin >> end;
}