UG3 Introduction to Vision and Robotics
Vision Assignment

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1 Introduction

Finding (known) objects of interest in an image and following those objects over a sequence of frames is called object tracking. Its applications are manifold, ranging from augmented reality to medical imaging.
Inter-frame and intra-frame variability make the task a challenging one: difficulties in tracking can arise due to abrupt object motion, changing appearance patterns of both the object and its surroundings, dropped frames, image noise, and many other factors. This makes general-purpose object tracking a tremendous challenge - and means that object tracking systems will limit themselves to function under some simplifying assumptions and for some specific, well defined task only [1].
This report presents an algoritm to track circular red, blue, and green robots under varying illumination and scene background conditions. The algorithm is described in Section 2 (a sample MATLAB implementation is provided as an appendix). Section 3 evaluates the algorithm's performance under a number of different capture conditions. The results and possible avenues for improvement are discussed in Section 4.

2 Methods

Several simplifying assumptions were made to constrain the tracking problem. It was assumed that:

1. The objects to be tracked will be puck-like ”robots”, coloured in different shades of red, blue, and green.
2. A triangle of a darker colour will sit on top of the robots, indicating their directions.
3. The camera observing the scene will be set up in an angle not less than 45% with respect to the plane it is observing.
4. The background of the scene will have a different colour than the robots.

2.1 Detection of Robots

Input

I, a three channel image of dimensions $m \times n$ in the RGB colorspace.

Output

M, a $m \times n \times 3$ binary matrix where for each pixel P_{ij} of I, it holds that:
$M(i, j, 1) = 1 \leftrightarrow P_{ij}$ belongs to the red robot,
$M(i, j, 2) = 1 \leftrightarrow P_{ij}$ belongs to the green robot,
$M(i, j, 3) = 1 \leftrightarrow P_{ij}$ belongs to the blue robot.

Algorithm

1. Apply approximate RGB-normalisation to I, giving I_n:
   - For each pixel in I_n, calculate the sum S_{rgb} of the red, green, and blue values of that pixel.
   - If $S_{rgb} \neq 0$ (the pixel is not absolute black), set each of the pixel's red, green, and blue values to that value divided by S_{rgb}.
2. Calculate μ_r, μ_g, μ_b and $\sigma_r, \sigma_g, \sigma_b$, the means and standard deviations of the values in the three channels of I_n.
3. Assign each pixel P_{ij} in I to one of the robots or to the background:
   - Normalise P's red, green, and blue values, giving P_n.
   - Calculate the probabilities p_r, p_g, p_b that P_n was generated by the gaussian distributions $\mathcal{N}_r = (\mu_r, \sigma_r), \mathcal{N}_g = (\mu_g, \sigma_g), \mathcal{N}_b = (\mu_b, \sigma_b)$.
   - Calculate P's hue value h.
   - If h is whithin a certain range defined as red and p_r is sufficiently small, set $M(i, j, 1) = 1$ (similarly for ranges defined as green/blue and p_g/p_b. If none of these conditions are met, set $M(i, j, 1) = M(i, j, 2) = M(i, j, 3) = 0$.
4. Remove noise from each channel in M:
   - Set pixels to zero if they have fewer neighbours with value one than they have adjacent pixels with value zero.
   - Set zero-valued pixels to one if they have two one-valued horizontal or vertical neighbours.
5. Remove components that are distant from the main concentration of mass in each channel in M:
   - Compute the center of mass C of the channel.
   - Compute $c_1, c_2, \ldots$, the centers of mass of each connected component in the channel.
   - Compute the mean distance δ of the c_k to C.
   - Set $M(i, j) = 0$ for all the pixels (i, j) in the components k that satisfy $c_k > \tau\delta$ for some fixed threshold τ.
6. Exploit the fact that all robots have similar sizes by setting every channel in M to all-zeros if the number of pixels set in that channel is smaller than the number of pixels set in the most populated channel by some margin.

Figure 1 shows a visualisation of the output matrix M.

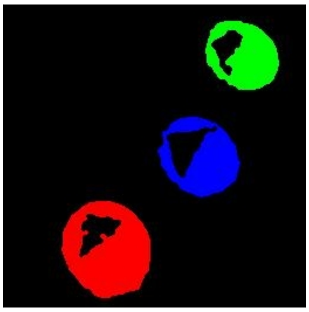


Figure 1: Result of Robot detection

2.2 Finding Robot Directions

Input

I, a three channel image of dimensions $m \times n$ in the RGB colorspace.

Output

$\Lambda = \{(c_r^m, c_r^t), (c_g^m, c_g^t), (c_b^m, c_b^t)\}$, a set where c_r^m is the center of mass of the red robot and c_r^t is the point towards which the robot is facing (similarly for the green and blue robots).

Algorithm

1. Get a matrix of robot masks M using the algorithm in Section 2.1. Let M_i be the ith channel of M i.e. the set of points $\{M(a,b,i)|1 \leq a \leq m, 1 \leq b \leq n\}$. Apply the remainder of the algorithm to each channel ξ in M.

2. Calculate the convex hull H of the points in the channel and create the set of pixels of I that are inside H: $P = \{p_{ij}|p_{ij} \in \xi \wedge M(i,j,\xi) = 1\}$

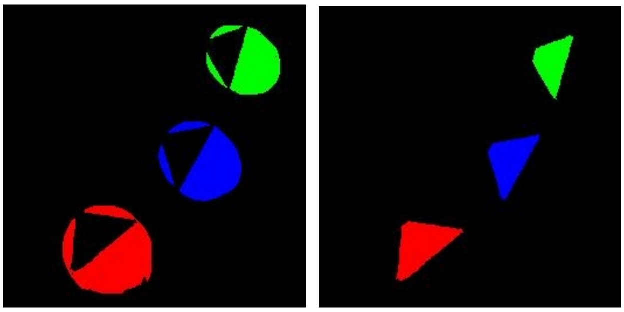
3. Calculate μ, the average rgb-value over P. Generate $\Pi = \{p|p \in P \wedge rgbvalue(p) < \mu\}$, the set of pixels in P that have a below-average rgb value.

4. The black triangles on the robots are the pixels in Π. Get rid of them by setting the relevant indices in M to zero.
   Recompute the convex hull of M.

5. Repeat the previous step and remember the pixels in Π.
   This reduces noise in M by giving a tighter estimate on the robot's pixels when the triangles were under-detected by the algorithm in Section 2.1.
   Figure 2 shows the result of this step - a notable improvement in clarity of the triangles compared to Figure 1.

6. Update Λ: c_ξ^m is the center of mass of M_ξ, c_ξ^t is the center of mass of Π.
   A line from c_ξ^m to c_ξ^t indicates the direction of the robot.

Figure 3 shows a visualisation of the output set Λ.



(a) After Removing Triangles (b) Removed Triangles

Figure 2: Triangle Detection via Local Thresholding

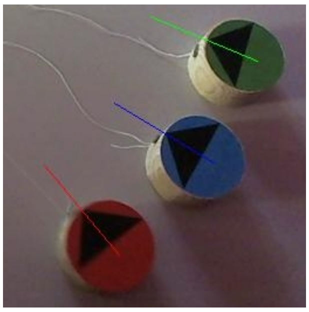


Figure 3: Detected Directions

2.3 Tracking Robots Over a Sequences of Frames

Input

$\Upsilon = \{I_1, I_2, \cdots\}$, a sequence where each of the I_i is a three channel image of dimensions $m \times n$ in the RGB colorspace.

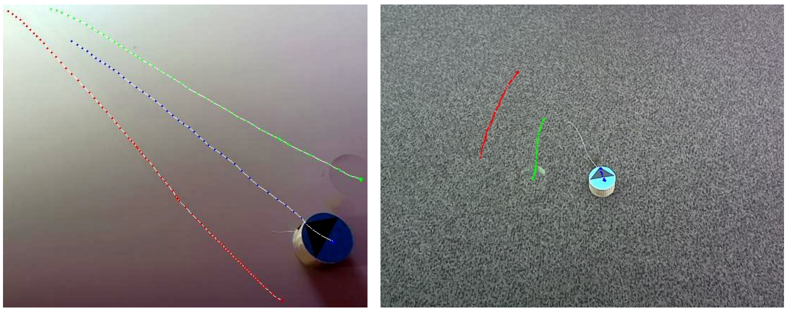
Output

Ω, a visualisation of the robot positions over Υ.

Algorithm

1. Use a median-filter to generate a background Ω from Υ.
   For each $1 \leq i \leq m, 1 \leq j \leq n$:
   - Create $\omega_{ij} = \{I_k(i, j) | I_k \in \Upsilon\}$, the set of the colors of the pixels at location (i, j) of all the images in Υ.
   - Set $\Omega(i, j) = median(\omega_{ij})$.
2. For each $I_i \in \Upsilon$:
   - Use the algorithm in Section 2.2 to get the set Λ. Let $\lambda = \{c | (c, \_) \in \Lambda\}$.
   - Overlay Ω with a line from each element in λ_{i-1} to the corresponding element in λ_i, thus linking the centroids from image I_{i-1} to the centroids in image I_i.

Figure 4 shows a visualisation of the resulting track.



(a) Dataset 1 (b) Dataset 2

Figure 4: Output of Tracing Algorithm

3 Results

This section evaluates and visualises the performance of the three algorithms presented in Sections 2.1, 2.2, and 2.3. Table 1 describes the properties of the datasets used for this evaluation.

#	Background	Robot Size	Robot Color	Illumination
1	uniform, gray	large	saturated, dark	uniform, red hue
2	noisy, gray	small	faded, blue robot is cyan	histograms are bell-shaped
3	patterned, brown	large	saturated	daylight only
4	patterned, brown	large	saturated	daylight and artificial light

Table 1: Properties of evaluation datasets

3.1 Detection of Robots

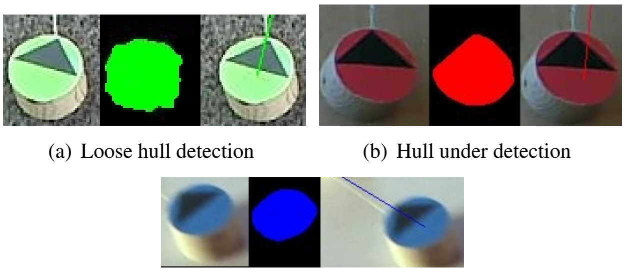
The algorithm described in Section 2.1, worked perfectly on datasets 1 and 2. Evaluation on the third dataset led to the worst performance over all datasets, with $\sim$60% of the occurences of the blue robot being undetected and $\sim$40% of the occurences of the green robot being under-detected (leading to bad direction detection). The performance on the fourth dataset was interesting: the red robot was under- detected in $\sim$45% of the cases (with the blue and green robots being found just fine) - while in the other datasets the red robot was usually detected with the highest confidence. Over all four datasets, about 10% of the robot instances were badly detected.

The fact that the color-detection algorithm works well on both datasets 1 and 2 leads to the conjecture that it is invariant under texture changes in the scene background and variations in robot-color saturation. The bad performance on dataset 3 can be explained by interference from the color of the scene background and by changes in scene illumination. The fact that the algorithm offers almost top-level performance on dataset 4 (captured on the same background as dataset 3) implies that the change in scene illumination is probably the largest influence on the algorithm's performance.

This is in keeping with the intuition that daylight has more inherent variation than artificial light, thus introducing a higher degree of variability into the characteristics of the captured images.

3.2 Detection of Directions

Performance of robot direction detection, understandably, is heavily dependent on the performance of the detection of the robots. If the robots are well isolated by Section 2.1's algorithm, robot orientations are perfectly detected.
The algorithm is invariant under loose detection - false positive cases where some addition non-robot region is misleadingly detected as a robot. This is due to the algorithm's ability to filter-out noisy detections.
In case of under-detection - false negative cases where some parts of the image representing the robot where not detected - the algorithm breaks: the predicted direction is skewed towards the opposite side of the under-detection. This is due to the algorithm not putting strict circular or elipsoidal constraints on the shape of the robots: under detection is thus able to move the center of mass of either the triangle or the robot-convex-hull. The error introduced by this is proportional to the area of the under-detected region.



(a) Loose hull detection

(b) Hull under detection

(c) Good hull detection

Figure 5: Direction detections for convex hulls of different qualities

3.3 Tracking of the robots

Section 2.3's algorithm to track robots over consecutive frames is trivial - a mere visualisation of half of the results of the robot-direction- detection algorithm presented in Section 2.2. The tracking algorithm's performance is therefore directly related to the performance of the robot-direction-detection algorithm and the same observations as in Section 3.2 apply: generally speaking, the algorithm performed well.
Figure 4 begets one additional observation related to the evaluation of the robot-tracking algorithm: both datasets considered in this report exhibit the property that one of the objects of interest does not move much for most of the frames. This entails that generating a background from data employing a simple frame-difference base approach (such as the median- filter used in Section 2.3) to perform background subtraction is bound to fail as one of the objects of interest will be considered a part of the background due to being mostly stationary. This is unfortunate since pre-processing the datasets with background subtraction would increase the accuracy of Section 2.1's algorithm by reducing noise and increasing resolution in the image.

4 Discussion

The algorithms in Sections 2.1, 2.2, and 2.3 operate under a limited number of reasonable simplifying assumptions and performed well across a range of datasets captured under very different conditions.
The robot color detection algorithm of Section 2.1 could be improved by adding more stringent conditions on the shape of the robots e.g. fitting a circle or ellipse to them rather than a convex hull. This should improve the subsequent performance of the direction-detection algorithm by reducing the amount of under-detections.
If assumptions about the size, scale, and shape of the robots can be made, Hugh transforms or other shape-based techniques could be used to detect the robots. This would be more robust than the current color/pixel based approach but not invariant under scale or differences in camera positions.
Another way to improve the detection of the robots could be augmenting the current approach with the utilisation of second order spatial image statistics to pre-process the images. This would lead to a rough estimate of the robot positions with few false negatives, thus improving the currently utilised algorithms due to a reduced search space (implying a denser signal). A reduced search space also allows for computationally expensive but high-precision techniques to be used. One example of such a technique is a local color-based search starting from a small seed of pixels that are hypothesised to be part of a robot.
Direction detection could be improved by making it less dependent on the accuracy of the robot detection. One way to achieve this would be to base the direction calculation on properties of the detected triangles (e.g. direction = tangent line to the longest side) rather than on the triangles' centers of mass. This would increase robustness to under-detections.
Cross-frame tracking could be improved by abusing spatio-temporal proximity. One way to do this would be put a cap on how far the centroid of the robot can move in a certain frame interval, thus smoothing out the odd completely wrong prediction.

References

[1] Yilmaz, A., Javed, O., and Shah, M., "Object Tracking: A Survey", ACM Comput. Surv. 38, 4, Article 13, 2006.

```
%%%%%%%% file: main.m %%%%%%%
function res = main(path, image_type, start_offset, time_step)
    if nargin < 2
        image_type = 'jpg';
    end
    if nargin < 3
        start_offset = 0;
    end
    if nargin < 4
        time_step = 0.33;
    end

    _path = mfilename('fullpath');
    [_path, _, _] = fileparts(_path);
    addpath(fullfile(_path, 'algo'));
    addpath(fullfile(_path, 'draw'));
    addpath(fullfile(_path, 'test'));

    files = dir(sprintf('%s/*.%s', path, image_type));
    filenames = {files.name};
    [~, num_files] = size(filenames);

    [m n ~] = size(imread(sprintf('%s/%s', path, filenames{1})));
    track_mask = zeros(m, n);

    rc = zeros(num_files - start_offset, 2);
    gc = zeros(num_files - start_offset, 2);
    bc = zeros(num_files - start_offset, 2);

    reds = cell(num_files - start_offset, 1);
    greens = cell(num_files - start_offset, 1);
    blues = cell(num_files - start_offset, 1);

    for i = 1 + start_offset : num_files
        image = imread(sprintf('%s/%s', path, filenames{i}));
        [directions, centroids] = analyse_image(image);

        r = uint16(centroids(1,:));
        if r(1) > 0 && r(2) > 0
            track_mask = overlay_cross(track_mask, 1, r(1), r(2));
            rc(i,:) = [r(1), r(2)];
        end

        g = uint16(centroids(2,:));
        if g(1) > 0 && g(2) > 0
            track_mask = overlay_cross(track_mask, 2, g(1), g(2));
            gc(i,:) = [g(1), g(2)];
        end

        b = uint16(centroids(3,:));
        if b(1) > 0 && b(2) > 0
```

```
            track_mask = overlay_cross(track_mask, 3, b(1), b(2));
            bc(i,:) = [b(1), b(2)];
        end

        reds{i} = image(:,:,1);
        greens{i} = image(:,:,2);
        blues{i} = image(:,:,3);
        imshow(overlay_mask(image, directions));

        pause(time_step);
    end

    rc = rc(any(rc,2),:);
    gc = gc(any(gc,2),:);
    bc = bc(any(bc,2),:);

    red_median = median(cat(3, reds{:}), 3);
    green_median = median(cat(3, greens{:}), 3);
    blue_median = median(cat(3, blues{:}), 3);

    bg = cat(3, red_median, green_median, blue_median);

    bg = overlay_polygon(bg, rc, [255, 255, 255]);
    bg = overlay_polygon(bg, gc, [255, 255, 255]);
    bg = overlay_polygon(bg, bc, [255, 255, 255]);
    bg = overlay_mask(bg, track_mask);
    imshow(bg)
end


%%%%%%% file: analyse_image.m %%%%%%%
function [pretty_mask, varargout] = analyse_image(image)
    [num_rows, num_cols, num_channels] = size(image);
    blob_mask = mask_colors(image);
    [convex_mask, ~] = mask_convex_regions(image, blob_mask);
    [convex_mask]=demask_triangles(image, convex_mask, false);
    [convex_mask, ~] = mask_convex_regions(image, convex_mask);
    [~, centroids, ~, triangle_centroids] = ...
                            demask_triangles(image, convex_mask, true);
    pretty_mask = overlay_rays(zeros(num_rows,num_cols,num_channels),...
                            centroids,triangle_centroids, 99, ...
                           'Color', [1 0 0; 0 1 0; 0 0 1]);
    varargout{1} = centroids;
    varargout{2} = triangle_centroids;
    varargout{3} = convex_mask;
end


% this function can used to find both - triangles and masks without
% triangles. To find triangles it must be run with
```

```matlab
% get_triangle_centroids=true. Also application of the function int the
% following fashion gives better results.
%    [convex_mask, ~] = mask_convex_regions(image, blob_mask);
%    [convex_mask]=demask_triangles(image, convex_mask, false);
%    [convex_mask, ~] = mask_convex_regions(image, convex_mask);
function [mask, varargout] = demask_triangles(image, mask, ...
                                           get_triangle_centroids)
    [num_rows, num_cols, num_channels] = size(image);
    centroids = zeros(num_channels, 2);
    triangle_centroids  = zeros(num_channels, 2);
    trinagle_mask = mask;
    for c = 1 : num_channels
        channel = image(:,:,c);
        channel_mask = mask(:,:,c);
        channel_trinagle_mask =  mask(:,:,c);
        if ~any(channel_mask)
            continue;
        end
        rgb_values = zeros(sum(channel_mask(:)), 1);
        idx = 1;
        for nr = 1 : num_rows
            for nc = 1 : num_cols
                if channel_mask(nr, nc) == 0
                    continue;
                end
                rgb_values(idx) = channel(nr, nc);
                idx = idx + 1;
            end
        end
        mean_rgb = mean(rgb_values(:));
        channel_mask(channel < mean_rgb) = 0;
        mask(:,:,c) = channel_mask;
        props = regionprops(channel_mask, 'Centroid');
        centroid = props.Centroid;
        centroids(c,:) = [centroid(2), centroid(1)];
        if get_triangle_centroids
            channel_trinagle_mask(channel > mean_rgb) = 0;
            channel_trinagle_mask=filter_mask(channel_trinagle_mask);
            trinagle_mask(:,:,c) = channel_trinagle_mask;
            props = regionprops(channel_trinagle_mask, 'Centroid');
            centroid = props.Centroid;
            triangle_centroids(c,:) = [centroid(2), centroid(1)];
        end
    end
    varargout{1} = centroids;
    varargout{2} = trinagle_mask;
    varargout{3} = triangle_centroids;
end
```

```
function [color_mask, varargout] = mask_convex_regions(image, mask)
  [num_rows, num_cols, num_channels] = size(image);
  color_mask = zeros(num_rows, num_cols, num_channels);
  convex_centroids = zeros(num_channels, 2);
  for c = 1 : num_channels
    channel = mask(:,:,c);
    if ~any(channel(:))
      continue;
    end
    props = regionprops(channel, ’Centroid’, ’ConvexImage’, ’BoundingBox’);
    convex_props = regionprops(props.ConvexImage, ’Centroid’);
    convex_centroid = convex_props.Centroid;
    convex_centroid = [convex_centroid(2) + props.BoundingBox(2), ...
                       convex_centroid(1) + props.BoundingBox(1)];
    convex_centroids(c,:) = convex_centroid;
    convex_image = props.ConvexImage;
    [num_rows_convex, num_cols_convex] = size(convex_image);
    for row = 1 : num_rows_convex
      for col = 1 : num_cols_convex
        if convex_image(row, col) == 1
          newrow = round(row + props.BoundingBox(2));
          newcol = round(col + props.BoundingBox(1));
          color_mask(newrow, newcol, c) = 1;
        end
      end
    end
  end
  varargout{1} = convex_centroids;
end


function image_mask = mask_colors(image)
  [num_rows, num_cols, ~] = size(image);
  num_pixels = num_rows * num_cols;
  image_mask = zeros(num_pixels, 3);
  rgb = double(reshape(image, num_pixels, 3));
  rgbN = double(reshape(normalise_rgb(image, ’approximate’), num_pixels, 3));
  rN_sdev = std(rgbN(:,1));
  gN_sdev = std(rgbN(:,2));
  bN_sdev = std(rgbN(:,3));
  rN_mean = mean(rgbN(:,1));
  gN_mean = mean(rgbN(:,2));
  bN_mean = mean(rgbN(:,3));
  hsv = reshape(rgb2hsv(image), num_pixels, 3);
  for c = 1 : num_pixels
    rN = rgbN(c,1);
    gN = rgbN(c,2);
    bN = rgbN(c,3);
    hue = hsv(c,1) * 360;
    % current pixel is red
```

```
        if    (hue >= 330 || hue <= 30) && ...
                (normal_prob(rN, rN_mean, rN_sdev) <  0.001)
                  image_mask(c,1) = 1;
        % current pixel is green
        elseif  (hue >= 80 && hue < 180) && ...
                (normal_prob(gN, gN_mean, gN_sdev) <  0.007)
                  image_mask(c,2) = 1;
        % current pixel is blue
        elseif  (hue >= 150 && hue <= 270) && ...
                (normal_prob(bN, bN_mean, bN_sdev) < 0.0000085)
                  image_mask(c,3) = 1;
        end
    end
    image_mask = reshape(image_mask, num_rows, num_cols, 3);
    image_mask = remove_noise(image_mask);
    image_mask = remove_outliers(image_mask);
    image_mask = enforce_similar_channel_areas(image_mask);
end


function x = normal_prob(val, mu, sigma)
    x = 1.0 / (sigma * sqrt(2 * pi)) * exp(-(val - mu) ^ 2 / (2 * sigma ^ 2));
end


function image = remove_noise(image)
    [~, ~, num_channels] = size(image);
    for c = 1 : num_channels
        channel = image(:,:,c);
        channel = bwmorph(channel, 'majority', Inf);
        channel = bwmorph(channel, 'bridge', Inf);
        image(:,:,c) = channel;
    end
end


% finds the connected components in each channel of |image| and removes those
% that are far away from the centroid of the pixels in that channel
% here, 'far away' means more distant than |distance_proprtion_threshold| times
% the average distance of each connected component to the channel centroid
% this removes big areas of noise such as the big green blob inside of the black
% arrow of the red robot in data/1/00000006.jpg
function image = remove_outliers(image, distance_proportion_threshold)
    if nargin < 2
        distance_proportion_threshold = 0.5;
    end
    [~, ~, num_channels] = size(image);
    for c = 1 : num_channels
        channel = image(:,:,c);
        if ~any(channel(:))
```

```
            continue;
        end
        channel_properties = regionprops(channel, 'Centroid');
        channel_centroid = channel_properties.Centroid;
        regions = bwconncomp(channel);
        regions_properties = regionprops(regions, 'Centroid', 'PixelIdxList');
        regions_centroids = {regions_properties.Centroid};
        distances = cellfun(@(x) norm(x - channel_centroid), regions_centroids);
        mean_distance = mean(distances);
        for d = 1 : length(distances)
            if distances(d) > mean_distance * distance_proportion_threshold
                idx = regions_properties(d).PixelIdxList;
                channel(idx) = 0;
            end
        end
        image(:,:,c) = channel;
    end
end


% we know that the robots are all about the same size - we can thus remove any
% channels in the mask that have a much smaller area than the other channels
% this catches some problems like the shadow of the blue robot in
% data/1/00000095.jpg being detected as a red blob
function image = enforce_similar_channel_areas(image, area_proportion_threshold)
    if nargin < 2
        area_proportion_threshold = 0.5;
    end
    [~, ~, num_channels] = size(image);
    areas = zeros(num_channels, 1);
    for c = 1 : num_channels
        channel = image(:,:,c);
        if ~any(channel(:))
            continue;
        end
        region_props = regionprops(channel, 'Area');
        areas(c) = region_props.Area;
    end
    max_area = max(areas(areas > 0));
    for c = 1 : num_channels
        area = areas(c);
        if area == 0
            continue;
        end
        if  (area < max_area * area_proportion_threshold) || ...
            (area > max_area / area_proportion_threshold)
                image(:,:,c) = image(:,:,c) * 0;
        end
    end
end
```

```
% this filters out all conneceted regions but the biggest one
function mask = filter_mask(mask)
  [x, y, num_channels] = size(mask);
  for c = 1 : num_channels
    channel = zeros(x, y);
    channel = reshape(channel, x * y, 1);
    blob_info = bwconncomp(mask(:,:,c));
    blob_list = blob_info.PixelIdxList;
    [nrows, ncols] = cellfun(@size, blob_list);
    largest_blob_pixels = blob_list{find(nrows == max(nrows))};
    for i = 1 : max(nrows)
      channel(largest_blob_pixels(i)) = 1;
    end
    channel = reshape(channel, x, y);
    mask(:,:,c) = channel;
  end
end

% normalises the values of the red, green, and blue channels of |image| in order
% to eliminate illumination differences in the image
% formula used: {r, g, b} = {r, g, b} / sqrt(r^2 + g^2 + b^2)
% if 'approximate' is passed as an additional parameter, instead use
% {r, g, b} = {r, g, b} / (r + g + b)
% this is approximately two times faster than the exact normalisation
function normalised_image = normalise_rgb(image, varargin)
  approximate = ~isempty(find(strcmpi(varargin, 'approximate')));
  red = double(image(:,:,1));
  green = double(image(:,:,2));
  blue = double(image(:,:,3));
  if approximate
    euclid_rgb = red(:,:) + green(:,:) + blue(:,:);
  else
    euclid_rgb = sqrt(red(:,:).^2 + green(:,:).^2 + blue(:,:).^2);
  end
  red_norm = round(red(:,:) ./ euclid_rgb .* 255);
  green_norm = round(green(:,:) ./ euclid_rgb .* 255);
  blue_norm = round(blue(:,:) ./ euclid_rgb .* 255);
  % some pixels are absolute black (r = g = b = 0) which causes division by
  % zero errors during normalisation and NaN values in the normalised channels
  % need to filter these values out
  red_norm(isnan(red_norm)) = 0;
  green_norm(isnan(green_norm)) = 0;
  blue_norm(isnan(blue_norm)) = 0;
  red_norm = uint8(red_norm);
  green_norm = uint8(green_norm);
  blue_norm = uint8(blue_norm);
  normalised_image = cat(3, red_norm, green_norm, blue_norm);
```

```
end
%%%%%%%% end of file: analyse_image.m %%%%%%%%


%%%%%%%% file: median_filter.m %%%%%%%%
% generates a background image from a set of sample images
% subtracting the background from the sample images eases object detection
% does not work on these datasets because the blue/cyan robot does not move
% for most of the images i.e. will be considered part of the background
function background = median_filter(path, image_type, start_offset, step)
    if nargin < 2
        image_type = 'jpg';
    end
    if nargin < 3
        start_offset = 0;
    end

    dim = 2;

    files = dir(sprintf('%s/*.%s', path, image_type));
    filenames = {files.name};
    [~, num_files] = size(filenames);

    reds = cell(num_files - start_offset, 1);
    greens = cell(num_files - start_offset, 1);
    blues = cell(num_files - start_offset, 1);
    for c = 1 + start_offset :step: num_files
        image = imread(sprintf('%s/%s', path, filenames{c}));
        reds{c} = image(:,:,1);
        greens{c} = image(:,:,2);
        blues{c} = image(:,:,3);
    end
    red_median = median(cat(dim + 1, reds{:}), dim + 1);
    green_median = median(cat(dim + 1, greens{:}), dim + 1);
    blue_median = median(cat(dim + 1, blues{:}), dim + 1);

    background = cat(dim + 1, red_median, green_median, blue_median);
end
%%%%%%%% end of file: median_filter.m %%%%%%%%


%%%%%%%% file: normalise_rgb.m %%%%%%%%
% normalises the values of the red, green, and blue channels of |image| in order
% to eliminate illumination differences in the image
% formula used: {r, g, b} = {r, g, b} / sqrt(r^2 + g^2 + b^2)
% if 'approximate' is passed as an additional parameter, instead use
% {r, g, b} = {r, g, b} / (r + g + b)
% this is approximately two times faster than the exact normalisation
function normalised_image = normalise_rgb(image, varargin)
    approximate = ~isempty(find(strcmpi(varargin, 'approximate')));
```

```

    red = double(image(:,:,1));
    green = double(image(:,:,2));
    blue = double(image(:,:,3));

    if approximate
        euclid_rgb = red(:,:) + green(:,:) + blue(:,:);
    else
        euclid_rgb = sqrt(red(:,:).^2 + green(:,:).^2 + blue(:,:).^2);
    end
    red_norm = round(red(:,:) ./ euclid_rgb .* 255);
    green_norm = round(green(:,:) ./ euclid_rgb .* 255);
    blue_norm = round(blue(:,:) ./ euclid_rgb .* 255);

    % some pixels are absolute black (r = g = b = 0) which causes division by
    % zero errors during normalisation and NaN values in the normalised channels
    % need to filter these values out
    red_norm(isnan(red_norm)) = 0;
    green_norm(isnan(green_norm)) = 0;
    blue_norm(isnan(blue_norm)) = 0;

    red_norm = uint8(red_norm);
    green_norm = uint8(green_norm);
    blue_norm = uint8(blue_norm);
    normalised_image = cat(3, red_norm, green_norm, blue_norm);
end
%%%%%%% end of file: normalise_rgb.m %%%%%%%


%%%%%%% file: overlay_circles.m %%%%%%%
% draws the circles defined by the centres in |centers| and radiuses in |radii|
% onto |image| and returns the modified image
% [0, 0] is the top left corner of the image
% if |radii| is a number, draw all circles with that radius
function image = overlay_circles(image, centers, radii, varargin)
    % parse options
    argc = size(varargin, 2);
    c = 1;
    while c <= argc
        arg = varargin{c};
        if strcmpi(arg, 'Color')
            if c + 1 > argc
                error('Color option should be followed by an integer tripplet');
            end
            colors = varargin{c + 1};
            c = c + 1;
        end
    end
    % option defaults
    if ~exist('colors', 'var')
```

```
        colors = [255 255 255];
    end

    num_circles = size(centers, 1);
    if size(radii, 1) == 1
        radii = repmat(radii, num_circles, 1);
    end
    if size(colors, 1) == 1
        colors = repmat(colors, num_circles, 1);
    end

    centers = round(centers);
    radii = round(radii);

    [~, ~, num_channels] = size(image);
    for c = 1 : num_channels
        channel = image(:,:,c);
        channel = overlay_circles_channel(channel, centers, radii, colors(:,c));
        image(:,:,c) = channel;
    end
end


function channel = overlay_circles_channel(channel, centers, radii, colors)
    [xmax, ymax] = size(channel);
    num_circles = size(centers, 1);
    for c = 1 : num_circles
        Xc = centers(c,1);
        Yc = centers(c,2);
        radius = radii(c);

        for theta = 0 : 0.1 : 359
            x = round(Xc + radius * cos(theta));
            y = round(Yc + radius * sin(theta));
            if x <= xmax && x > 0 && y <= ymax && y > 0
                channel(x, y) = colors(c,:);
            end
        end
    end
end
%%%%%%%% end of file: overlay_circles.m %%%%%%%%


%%%%%%%% file: overlay_cross.m %%%%%%%%
% returns image with a cross centered on pixel (|x|, |y|) drawn in |channel|
% [0, 0] is the top left corner of the image
function image = overlay_cross(image, channel, x, y)
    [h w ~] = size(image);

    if channel == 1
```

```
        other1 = 2;
        other2 = 3;
    end
    if channel == 2
        other1 = 1;
        other2 = 3;
    end
    if channel == 3
       other1 = 1;
       other2 = 2;
    end

    if y + 1 < h
        image(x, y + 1, channel) = 1;
        image(x, y + 1, other1) = 0;
        image(x, y + 1, other2) = 0;
    end

    if y - 1 > 0
        image(x, y - 1, channel) = 1;
        image(x, y - 1, other1) = 0;
        image(x, y - 1, other2) = 0;
    end

    if x + 1 < w
        image(x + 1, y, channel) = 1;
        image(x + 1, y, other1) = 0;
        image(x + 1, y, other2) = 0;
    end

    if x - 1 > 0
        image(x - 1, y, channel) = 1;
        image(x - 1, y, other1) = 0;
        image(x - 1, y, other2) = 0;
    end

    image(x, y, channel) = 1;
    image(x, y, other1) = 0;
    image(x, y, other2) = 0;

end

%%%%%%%% end of file: overlay_cross.m %%%%%%%%


%%%%%%%% file: overlay_mask.m %%%%%%%%
% returns the result of putting |mask| onto |image|
% for each pixel that is set in some channel of |mask|, saturates the pixel in
% the equivalent channel of |image|
function image = overlay_mask(image, mask, varargin)
```

```
% parse options
argc = size(varargin, 2);
c = 1;
while c <= argc
    arg = varargin{c};
    if strcmpi(arg, 'GrayScale')
        grayscale = 1;
    elseif strcmpi(arg, 'Saturation')
        if c + 1 > argc
            error('Saturation option should be followed by a double');
        end
        saturation = varargin{c + 1};
        c = c + 1;
    elseif strcmpi(arg, 'Lightness')
        if c + 1 > argc
            error('Lightness option should be followed by a double');
        end
        lightness = varargin{c + 1};
        c = c + 1;
    end
    c = c + 1;
end

% modify background image
if exist('grayscale', 'var')
    gray_image = rgb2gray(image);
    image = cat(3, gray_image, gray_image, gray_image);
end
if exist('saturation', 'var')
    hsv_image = rgb2hsv(image);
    hsv_image(:,:,2) = hsv_image(:,:,2) * saturation;
    image = hsv2rgb(hsv_image);
end
if exist('lightness', 'var')
    hsv_image = rgb2hsv(image);
    hsv_image(:,:,3) = hsv_image(:,:,3) * lightness;
    image = hsv2rgb(hsv_image);
end

% lay mask onto background image
num_channels = size(image, 3);
channels = 1 : num_channels;
for c = 1 : num_channels
    channel = image(:,:,c);
    mask_pixels = find(mask(:,:,c) == 1);
    channel(mask_pixels) = 255;
    image(:,:,c) = channel;
    for d = setdiff(channels, c)
        channel = image(:,:,d);
        channel(mask_pixels) = 0;
```

```
            image(:,:,d) = channel;
        end
    end
end
%%%%%%% end of file: overlay_mask.m %%%%%%%


%%%%%%% file: overlay_polygon.m %%%%%%%
% returns image with lines drawn from the nth point in |points| to the n+1th
% [0, 0] is the top left corner of the image
function image = overlay_polygon(image, points, color)
    if nargin < 3
        color = [255 255 255];
    end

    points = round(points);

    num_channels = size(image, 3);
    for c = 1 : num_channels
        channel = image(:,:,c);
        channel = overlay_polygon_channel(channel, points, color(c));
        image(:,:,c) = channel;
    end
end


% Bresenham's line algorithm (simplified version)
% http://en.wikipedia.org/wiki/Bresenham's_line_algorithm#Simplification
function channel = overlay_polygon_channel(channel, points, color)
    [xmax, ymax] = size(channel);
    for c = 1 : length(points) - 1
        start = points(c,:);
        stop = points(c + 1,:);
        x0 = start(1);
        y0 = start(2);
        x1 = stop(1);
        y1 = stop(2);

        dx = abs(x1 - x0);
        dy = abs(y1 - y0);

        if x0 < x1
            sx = 1;
        else
            sx = -1;
        end
        if y0 < y1
            sy = 1;
        else
            sy = -1;
```

```
      end

      err = dx - dy;

      while 1
         if x0 > 0 && x0 <= xmax && y0 > 0 && y0 <= ymax
            channel(x0, y0) = color;
         end
         if x0 == x1 && y0 == y1
            break;
         end
         e2 = 2 * err;
         if e2 > -dy
            err = err - dy;
            x0 = x0 + sx;
         end
         if e2 < dx
            err = err + dx;
            y0 = y0 + sy;
         end
      end
   end
end
%%%%%%%% end of file: overlay_polygon.m %%%%%%%%


%%%%%%%% file: overlay_rays.m %%%%%%%%
function image = overlay_rays(image, from, to, length, varargin)
   % parse options
   argc = size(varargin, 2);
   c = 1;
   while c <= argc
      arg = varargin{c};
      if strcmpi(arg, 'Color')
         if c + 1 > argc
            error('Color option should be followed by an integer tripplet');
         end
         colors = varargin{c + 1};
         c = c + 1;
      end
      c = c + 1;
   end
   % option defaults
   if ~exist('colors', 'var')
      colors = [255 255 255];
   end

   num_rays = size(from, 1);
   if size(colors, 1) == 1;
      colors = repmat(colors, num_rays, 1);
```

```
    end

    for c = 1 : num_rays
        if from(c,:) == to(c,:)
            continue;
        end
        x0 = from(c,1);
        y0 = from(c,2);
        x1 = to(c,1);
        y1 = to(c,2);
        dx = x0 - x1;
        dy = y0 - y1;
        lambda = min(sqrt(length ^ 2 / (dx ^ 2 + dy ^ 2)), ...
                    -sqrt(length ^ 2 / (dx ^ 2 + dy ^ 2)));

        x = x0 + lambda * dx;
        y = y0 + lambda * dy;

        image = overlay_polygon(image, [x0 y0; x y], colors(c,:));
    end
end
%%%%%%% end of file: overlay_rays.m %%%%%%%


%%%%%%% file: random_image.m %%%%%%%
% returns a random image from some directory D and print the path to that image
% the function understands the following options:
%   'Quiet'          don't print the path to the image
%   'ImageType', C      look for images of type C (default = "jpg")
% any remaining parameters are taken to be the path to D
% if D is not specified, default to a random sub-directory of "ug3_Vision/data"
function [image, varargout] = random_image(varargin)
    TL_DIR = 'ug3_Vision';
    BRANCH_DIR = 'data';
    % parse options
    argc = length(varargin);
    c = 1;
    while c <= argc
        arg = varargin{c};
        if strcmpi(arg, 'Quiet')
            quiet = 1;
        elseif strcmpi(arg, 'ImageType')
            if c + 1 > argc
                error('ImageType option should be followed by a string');
            end
            image_type = varargin{c + 1};
            c = c + 1;
        else
            path = arg;
        end
```

```
        c = c + 1;
    end
    % option defaults
    if ~exist('quiet', 'var')
        quiet = 0;
    end
    if ~exist('image_type', 'var')
        image_type = '.jpg';
    end
    if ~exist('path', 'var')
        path = random_dir(TL_DIR, BRANCH_DIR);
    end

    if ~strcmp(image_type(1), '.')
        image_type = strcat('.', image_type);
    end

    image_path = random_file(path, image_type);
    image = imread(image_path);

    if ~quiet
        idx = strfind(image_path, TL_DIR);
        if isempty(idx)
            idx = 1;
        end
        fprintf(1, 'image = %s\n', image_path(idx : end));
    end
    varargout{1} = image_path;
end


% looks for a directory |tl_dir| somewhere up from this file's location
% returns the absolute path to one of the directories in |tl_dir|/|branch_dir|
function path = random_dir(tl_dir, branch_dir)
    cur_path = mfilename('fullpath');
    tl_path = cur_path(1 : strfind(cur_path, tl_dir) + length(tl_dir));
    branch_path = strcat(tl_path, branch_dir);
    branch_path_contents = dir(branch_path);
    branch_path_dirs = {};
    for c = 1 : length(branch_path_contents)
        elem = branch_path_contents(c);
        if ~elem.isdir || strcmp(elem.name, '.') || strcmp(elem.name, '..')
            continue;
        end
        branch_path_dirs{end + 1} = fullfile(branch_path, elem.name);
    end
    path = branch_path_dirs{randi([1 length(branch_path_dirs)])};
end
```

```
% returns a random file ending with |extension| found at |path|
function path = random_file(path, extension)
    if nargin < 2
        extension = ’’;
    end

    file_type = strcat(’*’, extension);
    files = dir(fullfile(path, file_type));
    filenames = {files.name};

    path = fullfile(path, filenames{randi([1 length(filenames)])});
end
%%%%%%% end of file: random_image.m %%%%%%%


%%%%%%% file: run_on_data.m %%%%%%%
clear all;
clc;

if ~exist(’TL_DIR’, ’var’)
    TL_DIR = ’ug3_Vision’;
end
if ~exist(’IN_DIR’, ’var’)
    IN_DIR = ’data’;
end
if ~exist(’FILTER_FN’, ’var’)
    FILTER_FN = ’analyse_image’;
end
if ~exist(’OUT_DIR’, ’var’)
    OUT_DIR = fullfile(’res’, strrep(FILTER_FN, ’_’, ’-’));
end
filter_fn = str2func(FILTER_FN);
disp(sprintf(’function: %s\ninput: %s\n’, FILTER_FN, fullfile(TL_DIR, IN_DIR)));

curpath = mfilename(’fullpath’);
tlpath = curpath(1 : strfind(curpath, TL_DIR) + length(TL_DIR));
inpath = strcat(tlpath, IN_DIR);
outpath = strcat(tlpath, OUT_DIR);
inpath_contents = dir(inpath);
inpath_dirs = {};
for c = 1 : length(inpath_contents)
    elem = inpath_contents(c);
    if ~elem.isdir || strcmp(elem.name, ’.’) || strcmp(elem.name, ’..’)
        continue;
    end
    inpath_dirs{end + 1} = fullfile(inpath, elem.name);
end

num_dirs = length(inpath_dirs);
times = [];
```

```
for c = 1 : num_dirs
    in_dir = inpath_dirs{c};
    files = dir(strcat(in_dir, filesep, '*.jpg'));
    file_names = {files.name};
    out_dir = fullfile(outpath, strcat(IN_DIR, '-', num2str(c)));
    if ~exist(out_dir, 'dir')
        mkdir(out_dir);
    end
    num_files = length(file_names);
    for d = 1 : num_files
        file_name = file_names{d};
        input = fullfile(in_dir, file_name);
        disp(sprintf('[dir %d/%d] [file %d/%d]', c, num_dirs, d, num_files));
        disp(sprintf('\tinput = %s', input(strfind(input, TL_DIR) : end)));
        image = imread(input);
        timer = tic;
        mask = filter_fn(image);
        elapsed = toc(timer);
        times(end + 1) = elapsed;
        output = fullfile(out_dir, file_name);
        image = overlay_mask(image, mask, 'Saturation', 1);
        imwrite(image, output, 'jpg');
        disp(sprintf('\toutput = %s', output(strfind(input, TL_DIR) : end)));
        disp(sprintf('\tprocessing time = %fs', elapsed));
    end
end

disp(sprintf('\naverage processing time per image: %fs', mean(times)));
%%%%%%% end of file: run_on_data.m %%%%%%%
```