Flood-fill algorithms used for passive acoustic detection and tracking

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***Abstract* – Flood-fill algorithms are used in the "bucket" tool of paint programs to fill connected parts of a bitmap with color. They establish the area connected to a given node in a multi-dimensional array. This paper outlines the implementation a recursive flood-fill algorithm. Two elements are defined as connected if a path exists between them along which the value of all elements exceeds some threshold for a given node and threshold. The flood-fill is performed recursively on all elements connected to the node of interest. Two applications for passive acoustic monitoring are explored: (1) Signal detection via two-dimensional (frequency and time) flood-fill applied to spectrograms; (2) Source tracking via four-dimensional (x, y, z, and time) flood-fill applied to source position likelihood volumes (obtained using a localization algorithm that gives the likelihood of a source occupying a point in time and space).**

I. INTRODUCTION

A basic algorithm in computer graphics [1], flood-fill (also known as a seed-fill) is used to connect neighboring and related elements of an array. The flood-fill algorithm is commonly used in paint programs such as Adobe Photoshop and Corel Paintshop, in computer puzzle games, in solving mazes and so on. Fig. 1 shows the results of a flood-fill algorithm applied to a photograph. A group of pixels is connected by a path along which the intensity of blue is below a fixed threshold. For the resulting image, each group (a fish in this example) is assigned a different color. The flood-fill algorithm can be extended to a higher dimensional space: consider filling a 3D fish (giving 3 dimensions) or consider tracking the 3D fish as it moves through time (giving 4 dimensions).

IMPLEMENTATION

Flood-fills can be implemented in various ways, some more or less complex, effective, and/or efficient than other. Here we use a very simple recursive implementation, and acknowledge that the implementation can be much improved. Along with the surface being explored, two parameters are input into the flood-fill algorithm: a threshold and a start node (whose value exceeds the threshold). The algorithm finds all points that are connected to the start node by a path along which all values exceed the threshold. This group of connected points is referred to as a "stack".

MATLAB code the recursive flood-fill used to create Fig. 1 is given in Appendix A. The start node "seeds" the stack (it is the first point added to the stack). All points neighboring the start node are then checked. The neighborhood includes 8 points: those above, below, to the left and right of the node and the 4 corner points (this is referred to as an 8 point flood-fill in graphics; a 4 point flood-fill omits the corners). Each neighbor whose value exceeds the threshold is added to the stack and a flood-fill is applied with it as the start node. The procedure continues until all connected points have been added to the stack. The procedure is illustrated in Fig.2. This implementation is for two dimensional surfaces such as images or spectrograms (discussed below). Implementation in higher dimensions is analogous.

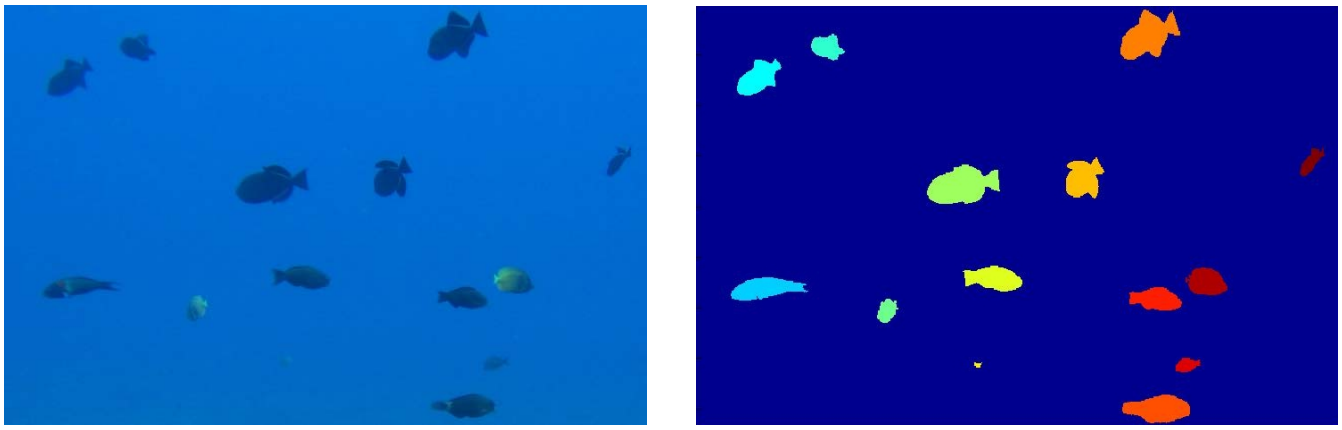


Fig. 1. The image on the right shows the result of applying the flood fill algorithm to a photograph (left) and coloring each stack of pixels differently.

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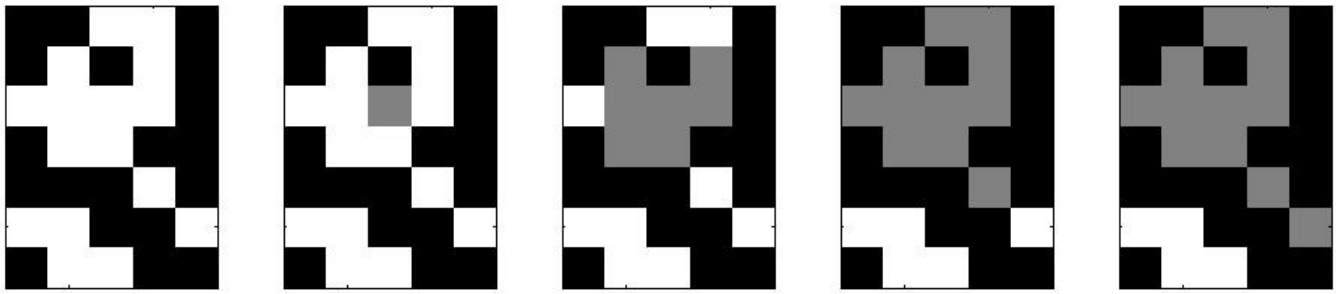


Fig. 2. Illustrating the flood-fill procedure. The original surface is shown in the left panel. Moving right: the seed is chosen; the neighbors to the seed are filled; then the neighbors to the neighbors are filled; so on until all connected points have been added to the stack.

In the applications discussed below, the flood-fill algorithm is applied to all possible start nodes to create a collection of stacks for a given surface. Only stacks that are "sufficiently long" (e.g. 20 points) are retained, which helps to ensure that the results represent actual stacks and not noise. The definition of "sufficiently long" changes with the application.

APPLICATIONS

The first application is signal detection via 2D flood-fill (time and frequency) applied to spectrograms. We found spectrogram flood-fill detection to be useful for processing large volumes of data in which potentially unexpected and unknown transients are to be detected. It will be most useful when combined with other detection schemes (such as matched filtering, click detectors, and tonal detectors) that are more suitable for detecting specific known sounds.

Data collected by a HARP [2] at about 400m depth on the summit of Cross Seamount (approximately 290 km south of the Hawaiian island of Oahu) were used to test this application. The HARP sampled with a duty cycle of 5 min on, 20 min off at 200 kHz. Further details of the data can be found in Ref [3]. Data were processed by creating spectrograms (using 1024 point Hanning windows overlapped at 50%) for 3 s subsamples. Spectrograms were de-noised and normalized by removing the mean of each frequency channel after applying a tonal detector (since boat, ship, and other tonals of interest are removed in this process). Examples of resulting spectrograms are shown in Figs 3 and 4. The flood-fill detector was applied to the resulting spectrograms, and all stacks of length 20 or more were considered a detection and stored. Detections were post-processed by grouping via an automated procedure according to frequency characteristics, duration, and contours. Detections within each group were visually inspected for consistency. Each group was classified, resulting in the following detection groups: system noise, echosounder, ship tonal, low frequency click (sperm whales), high frequency click (dolphins, pilot whales…), whistles, and frequency modulated clicks (beaked whales). Examples of whistle and beaked whale detections are of shown in Figs 3 and 4. One month of data (May 2005) took 2 weeks to process and resulted in over 100 thousand detections (almost 10 thousand of which were FM clicks). Setting a high threshold gave very few false alarms but also missed numerous detections. Future work will involve performance evaluation, including ROC curves.

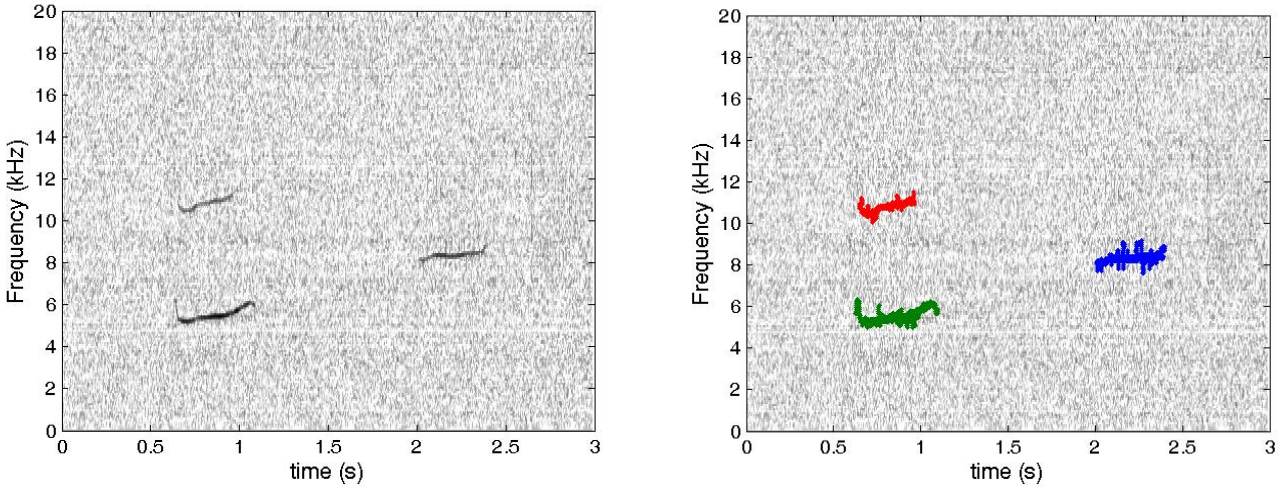


Fig. 3. Signal detection via the flood-fill algorithm applied to spectrograms: whistles. Left: De-noised spectrogram before flood-fill. Right: Three stacks, each colored differently, resulting from applying the flood-fill algorithm to the spectrogram.

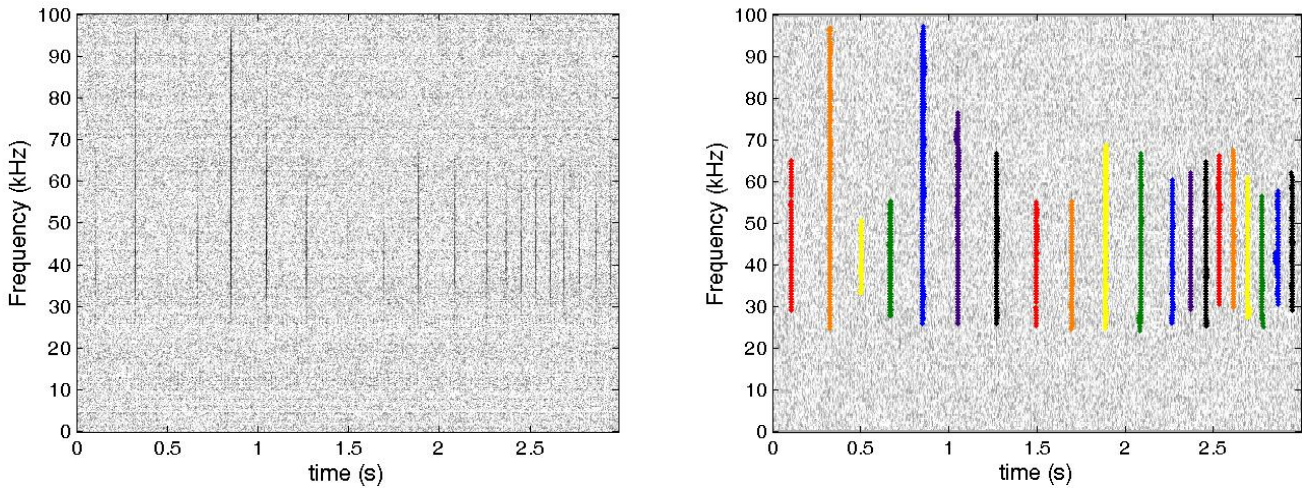


Fig. 4. Signal detection via the flood-fill algorithm applied to spectrograms: beaked whale clicks. Left: De-noised spectrogram before flood-fill. Right: Twenty stacks, each colored differently, resulting from applying the flood-fill algorithm to the spectrogram.

In a second application, the track of a sound source is estimated using a four dimensional flood fill (x, y, z, and time) applied to source position likelihood volumes. A likelihood volume is obtained using a localization algorithm and gives the likelihood of a source occupying a point in time and space. Taken in isolation, maxima in the likelihood volume do not signify the presence of a true source; they may be spurious sources due noise or to ripple effects in localization algorithms. However, since we expect a sound source to move relatively slowly in space and time, a connected path of maxima (established via the flood-fill algorithm) gives confidence in position estimates and provides and estimated of source track.

A 20 minute dataset containing clicks from multiple sperm whales recorded at the Atlantic Undersea Test and Evaluation Center was used to test this application. 6 hydrophones were bottom-mounted at depths of about 2 km and spaced several km apart (see hydrophone positions in Fig 5) and sampled at 48 kHz. Details of the dataset can be found in Refs. [4] and [5]. Pair-wise spectrogram processing [6,7] was used to create likelihood volumes at 3 s time steps over a 3D grid with 50 m spacing. A sample of a slice through a likelihood volume at a single depth is shown in Fig.5. Even at this single depth, multiple peaks in the likelihood volume are evident. While some peaks represent actual sources, many are spurious sources. The 4D flood fill algorithm was applied to the collection of likelihood volumes over all times. Stacks spanning 2 or more minutes were considered possible true source tracks, thereby eliminating spurious peaks that do not persist through time. The most prominent track obtained thus is shown in Fig.5.

CONCLUDING REMARKS

A complete performance assessment, including comparison with other detection and tracking methods, is beyond the scope of this paper and there is much room to improve the efficiency of the implementation outlined here. Nevertheless, this preliminary implementation demonstrates the potential usefulness of flood-fill algorithms in passive acoustic detection and tracking.

One limitation of the method is that overlapping tracks are connected. For example, in the detection application discussed here, the calls of multiple animals vocalizing simultaneously are not separated. Separation of overlapping stacks is a challenging problem that will require post-processing the stacks using another method (such as a particle filter). Another problem with the flood-fill method is associated with allowable stack space. That is, for very long stacks, the number of required recursions can surpass allowable recursion limits (the MATLAB default is 500). In some cases this can be avoided by raising the threshold or increasing the allowed recursion limit (done in MATLAB by: set(0,'RecursionLimit',N)). However, increasing the recursion limits can cause system crashes. Fortunately this was not a problem in the applications discussed here.

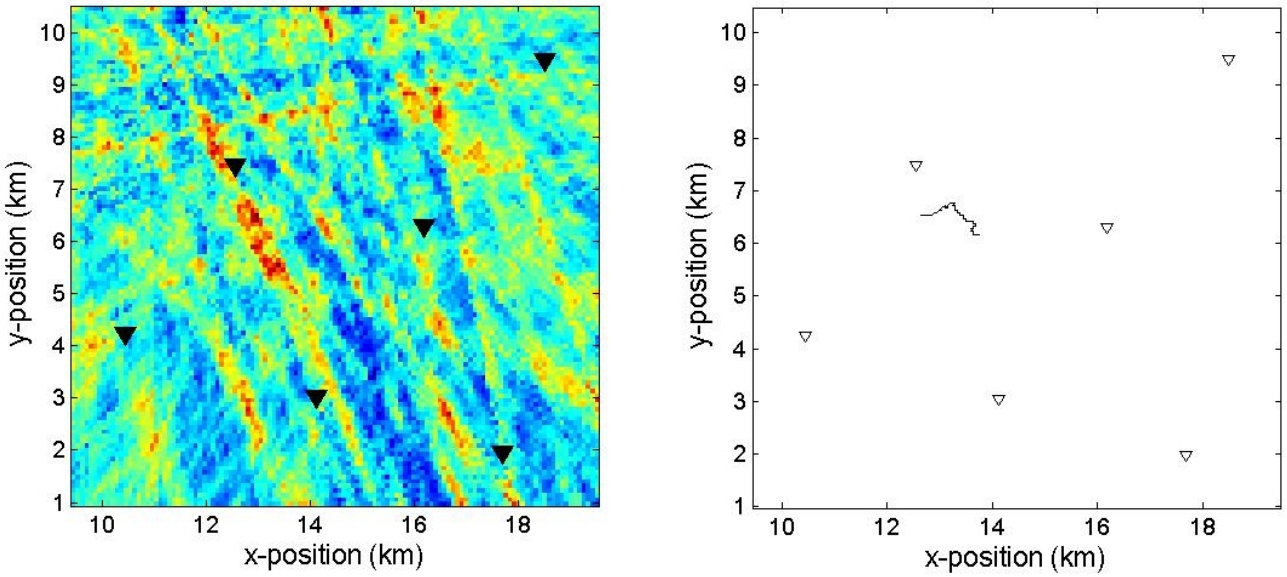


Fig. 5. Hydrophone positions indicated with triangles. Left: Slice through a likelihood volume at a single time and depth. Red (blue) indicate high (low) probability of a source at that location. Right: Most prominent sperm whale track obtained by applying a 4D (x, y, z, time) flood-fill to likelihood volumes for a collection of 3 s time steps spanning 20 minutes.

APPENDIX A

MATLAB code used for the two dimensional flood-fill.

```
function pixels = FloodFill2D(S, ix, iy, thresh, pixels)

% Recursive 2D flood-fill algorithm
%
% Inputs:
%         S = S(ix,iy) = 2D surface
%         (ix,iy) =  node indices
%         pixels  = list of pixels in the current stack (initially set as pixels = [])
%         thresh  = threshold for detection
% Outputs:
%         pixels = list of pixels on the same stack
%
% E-M Nosal 08/05/08, Honolulu

[nx,ny] = size(S);
if AS(ix,iy) >= thresh
   pixels = [ pixels; [ix iy] ] ;
   % if the neighbor point isn't in pixels, and it isn't an edge-point, do flood-fill on it
   for ix2 = max(1,ix-1):min(nx,ix+1)
      for iy2 = max(1,iy-1):min(ny,iy+1)
         if sum([ix iy] == [ix2 iy2]) < 2 & isempty(intersect(find(pixels(:,1)==ix2),find(pixels(:,2)==iy2)))
            pixels = FloodFill2D(S, ix2, iy2, thresh, pixels);
         end
      end
   end
end
```

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