

University of  
St Andrews

CS4099 MAJOR SOFTWARE PROJECT

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## Graph matching with Lobsters

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APRIL 2, 2018

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# Abstract

The ability to measure lobsters is important to be able to monitor the size and health of the creatures. By being able to do this task with images and automatically with software, we can aid scientists in this field accomplish their work more quickly. There is currently an existing dataset of images where efforts have been made to determine the size and sex of the lobsters using global features such as total length.

This project aims extend that work by representing images of lobsters as graphs and use graph matching techniques to compare between them. We aim to use these techniques to discover properties of the lobster, for example its age, gender and health. The effectiveness of these techniques will be evaluated against the existing dataset to discover if graph matching is a suitable method for lobster recognition and characterisation. Extensions to this project would be to develop a new algorithm for create graphs rather than using existing ones and to try the same techniques on more complex images with lobsters in their natural environment.

# **Declaration**

I declare that the material submitted for assessment is my own work except where credit is explicitly given to others by citation or acknowledgement. This work was performed during the current academic year except where otherwise stated.

The main text of this project report is NN,NNN\* words long, including project specification and plan.

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# 1 Introduction

In this project, the application of subgraph matching and interest point detectors is explored to automatically identify different parts of a lobster such as the claw, body or tail. This was done by representing the body parts as a set of nodes connected by weighted edges to represent the distance between the parts.

TODO

## 1.1 Background

The fishing industry plays a large role in the Scottish economy. Many rules and regulations have been put into place to improve the management of inshore fisheries in Scotland for sustainable fishing. The minimum landing size is an example of a simple regulation to protect breeding stock, not allowing any catches below the minimum size to be landed. This insures a proportion of the animal population continues to grow and reproduce [9] and is used particularly for inshore shellfisheries. Lobsters are an example of a family of crustaceans affected by the application of this regulation.

Typically, the catches have to be sorted and measured manually in order to adhere to regulations on minimum landing size. Illegal and unwanted products are then discarded back to the sea. Rochet [20] notes that discarding continues to be an important problem in world fisheries as discarded products often do not survive. This defeats the purpose of the regulation to preserve breeding stock and further hurts the industry as discarded products are lost without economic gain.

There has been some research in the area of applying computer vision techniques to automatically identify and detect species of fish [16] [6] and research into automatic measurement of fish size [10] [21] which can be applied to reduce discarding. Much work is focused on fish due to the impractical nature of manual observation and measurement. Though there is little work that focuses on using such techniques for lobsters.

## 1.2 Objectives

Below the primary and secondary objectives of the project are listed.

### 1.2.1 Primary objectives

- Explore and create suitable graph representations for lobsters
- Measure similarity of lobster graphs with existing software
- Automatically detect interest points from images
- Evaluate this method of graph matching on lobsters against the existing dataset

All primary objectives were met, resulting in a complete method that could take an image of a lobster from the dataset and create a graph that detects and labels the different body parts of the lobster. The accuracy of the method is then analysed and evaluated.

### 1.2.2 Secondary objectives

- Extending existing or coming up with new algorithms for creating lobster graphs from images, knowing what we've learned so far.

- Apply this technique on more complex images with noise such as natural lobsters in their environment
- Apply this technique for video/real time instead of images to give properties and information on the lobster in real time.

# 2 Context Survey

## 2.1 Previous work

A large part of this project follows on from Abdallah's master's thesis [1]. In his work, Abdallah created a dataset consisting of images and features of lobsters. The lobsters were measured and categorised and segmentation and feature extraction techniques were applied to create a more diverse dataset with baseline results. Additionally, machine learning techniques of classification and regression were used to classify the category (juvenile or mature) and sex of the lobster and to predict the carapace length.

The methods used in Abdallah's work was simple in that to be able to segment the lobsters from the image backgrounds, a high contrasting background was required, meaning the method was prone to noise. Further, his method of feature extraction using linear regression and principle component analysis was based mostly on the shapes of the segmented images, which were negatively affected by the posture of the lobster and asymmetric lobster shapes. This project is a continuation of Abdallah's work for a more accurate evaluation by automatically detecting the individual parts of a lobster to overcome issues of noise and shape.

## 2.2 Related work

### 2.2.1 Human pose recognition

The use of graphs in human pose estimation has been studied in the past [11] [23] where labelled nodes that represent important features such as hands and head are used to build skeleton models.

Some of the methodology used in human pose estimation can be applied to our lobster matching problem. In particular, the paper on human pose estimation using a topological graph database [11] by Tanaka et al. also uses a graph matching technique with an attributed graph to match skeletons to corresponding human postures. In their paper, example skeletons with different human topologies are developed into attributed graphs with manually assigned body part labels and stored in a model graph database. Any input skeletons can then also be converted to an attributed graph and matches with the examples in the database. Because their method of subgraph matching produces multiple results, further filters were needed to reduce the remaining graphs to one correct match.

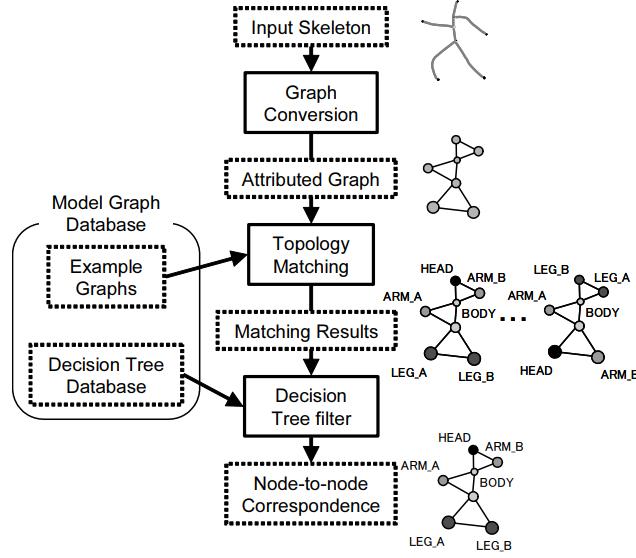


Figure 1: Body part identification algorithm using a model graph database (MGDB). Extracted from [11].

The aspect of having labelled attributed graphs of human skeletons extends well to labelled graphs of lobster. In the methodology of this project - which is explained in section 4 - some parts of Tanaka's method were followed. Most notably, the use of example lobster graphs stored in a database for input subgraphs to match to as an initial filter and the application of further techniques from the matched results to arrive at the final lobster graph were all inspired from Tanaka's paper.

### 2.2.2 Cattle identification

The concept of combining local invariant features (keypoints) and graph matching has also been studied for use in automatic cattle identification [18]. The application of feature extraction and graph matching in Monteiro's paper is different from the approach taken in this project, it showed the concept of combining feature extraction with computer vision algorithms and graph matching could be used in complement as the graph structure is able to preserve the point neighbouring structure of extracted features. This is relevant to the problem of lobster part identification as different body parts have a clear neighbouring structure with other body parts.

In the paper, the goal of graph matching was to match images of the same muzzle as a means of identification (like human fingerprints). This is similar to classic computer vision matching with k-nearest neighbours matching between keypoints to match objects in a scene. The paper shows how graph matching with attributed graphs can take advantage of the associated attributes in each node and edge to represent the relationship between two features. Aspects of this are used in the final stages of graph creation (section 4.6.2) in this project when building the full lobster graph from a pool of smaller labelled subgraphs.

## 2.3 Graph matching problem

The graph matching, or subgraph isomorphism problem is where given two undirected graphs  $G_1$  and  $G_2$ , it must be determined whether the graph  $G_1$  contains a subgraph that is isomorphic to  $G_2$  [7]. Cook showed in his paper that subgraph isomorphism was NP-complete with a reduction to the 3-SAT problem. This problem applies to the project from the use of subgraph matching to determine if a labelled subgraph is contained in a larger complete graph of a lobster.

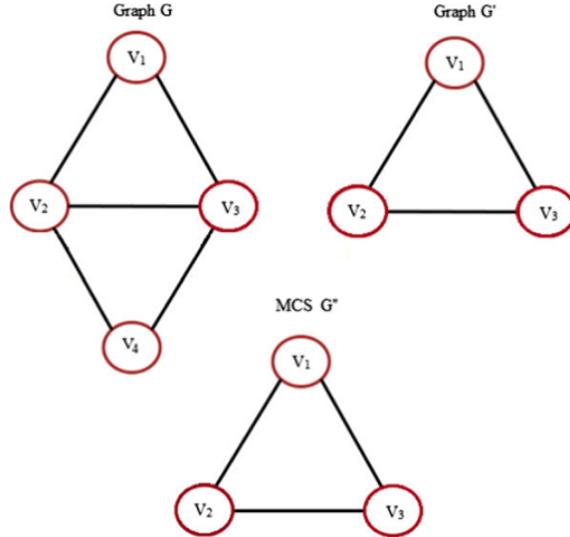


Figure 2: Example of matching two graphs  $G$  and  $G'$  and the resultant Maximum Common Subgraph ( $MCS$ ). The  $MCS$  is simply a subgraph of both  $G$  and  $G'$  which contains the maximum number of nodes of all possible subgraphs of  $G$  and  $G'$  [22].

In this project, the problem of graph matching extends beyond that of pure subgraph isomorphism, where only the number of vertices and its connections are relevant, though the normal subgraph isomorphism problem is also applied as part of the method pipeline. The extension comes from the fact that the shape of the lobster is a crucial part in determining successful matches. As was shown in section 2.2.2, the size of each node in the graph and the length (weight) of the edges are all important aspects in matching and are included during the final matching step. This leads to two different graph matching steps used in methodology of this project. First, the normal subgraph isomorphism problem is applied to get a list of matched subgraphs, then another complicated problem of rebuilding the complete graph from a list of subgraphs is applied to get to the final lobster graph.

# 3 Software Engineering Process

Many different tools and technologies were used in this project to help facilitate the research. The use of these tools and libraries allowed the project to be focused on its methodology without the need or difficulty to implement known algorithms and methods.

## 3.1 Existing software

### 3.1.1 Graph visualisation

In order to visualise what a graph representation of a lobster may look like, graph drawing software that could import and export into a graph data format was needed. Initially the popular Graphviz and its .dot graph format [25] was explored. The dot graph format had all the attributes needed such as size of nodes and weights of edges, however there was no readily available GUI tool for drawing graphs as Graphviz mostly works on rendering existing .dot files. This was not ideal as the initial stage of the project involved manual annotation of the dataset with graph drawing software, to be done before any automatic generation graph files.

The open source Gephi [2] tool was the next piece of software explored and it was exactly what was needed in terms of a graph drawing tool. It allowed a simple graph to be drawn with nodes and edges labelled, so this could be done on top of a lobster image from the dataset. Further, the software was able to import and export from and into various different file formats such as .graphml, .gml, .gdf and .d1. Unfortunately it did not handle the .dot file format, so a choice had to be made between choosing the drawing tool or more powerful file format.

---

Listing 1: Header formats for .gdf files showing the kind of node and edge data it could keep.

---

```
1 nodedef> name VARCHAR,label VARCHAR,width DOUBLE,height DOUBLE,x DOUBLE,y DOUBLE,color  
      VARCHAR  
2  
3 edgedef> node1,node2,weight DOUBLE,directed BOOLEAN,color VARCHAR
```

---

From exploring the various file formats that Gephi could use, it was discovered that the .gdf format contained enough information for our purposes. Specifically it contained a label, width, height, x and y coordinates for nodes and weights for edges. As such the Gephi tool was used over the Graphviz library and graph format due to its ease of use for drawing and file formats that contained enough information for its intended purpose.

### 3.1.2 Graph matching

Different graph matching and graph querying software was explored to deal with subgraph matching without the need for our own implementation. What was needed was a tool that could find if a labelled subgraph was part of a larger graph in a database of pre-defined lobster graphs. The tool also had to be fast and able to query a large number ( $> 100,000$ ) of subgraphs with sufficient speed. Two tools, GraphGrep [8] and APPAGATO [3] were looked at for this purpose.

Both tools were similar, using the same input/output formats for graphs and matches. They allowed input graphs nodes to be labelled with names, which was convenient for labelling the different parts of a lobster. The advantage APPAGATO offered over GraphGrep was its parallel GPU implementation for large speed up. During the initial prototyping stage, both tools were tested for their speed and suitability to the problem. Example graphs and queries were created and ran with large numbers of queries to test the speed and scalability of the tools. There was little difference in speed between the two tools for the scale of subgraphs needed in this project as both performed very reasonably for up to 500,000 subgraphs. The one issue found with APPAGATO

was that it did not support matching multiple target and query graphs easily as its file format only support one graph per file. GraphGrep on the other hand allowed multiple graphs to be defined in a single file for both its database and queries. For this reason, GraphGrep was used in the subgraph matching stage of the project.

## 3.2 Technologies used

### 3.2.1 OpenCV

OpenCV (Open Source Computer Vision Library) [4] is an open source library which contains a vast number of functions and interfaces for computer vision algorithms. The library was used heavily to prevent the need for implementing classical computer vision algorithms such as SIFT [15] and to make use of its image processing functions such as drawing detected keypoints and calculating colour histograms. This allowed much of the project to focus on the application of these algorithms and the combination of these computer vision techniques with probabilistic graph matching models, rather than need to produce new or classic keypoint detection algorithms. Further, the use of OpenCV exposed many practical underlying concepts and approaches in computer vision which were explored and used.

As OpenCV supports C++, Python, Java and MATLAB, the choice of language used was between these languages.

### 3.2.2 Python

Python was chosen as the primary language used for development. It is popular in the scientific community thanks to its extensive library support and ease of writing. Since performance was not a major issue, using Python would make it easier and faster to test and prototype different methods without the need for heavy error checking and debugging. Using Python also gives access to powerful libraries such as NumPy and SciPy, providing useful functionality such as probability distributions and matrix manipulation out of the box. Additionally, before the use of OpenCV in the project, the prototyping for probabilistic models, subgraph creation and subgraph matching was already written in Python, making it natural to extend from the prototype after the introduction of OpenCV functions.

Although Python is a dynamically typed language, newer versions (Python 3.5 and above) have added support for type hints and static type checking with `mypy` [14]. As the implementation of the project grew, the addition of type hints was added to keep the code organised and readable. This was especially helpful to express the types of data contained in lists and tuples.

# 4 Methodology

## 4.1 Overview

Figure 3 shows the key steps of the overall method used to go from an image of a lobster to a labelled graph of the lobster. In the initial stages, keypoints are extracted and filtered from the image through the use of various OpenCV algorithms and techniques such as SIFT for keypoint detection and colour histograms for keypoint filtering. The remaining set of keypoints are then labelled using Bayes' theorem and all permutations of possible subgraphs are created. Next, the subgraphs are matched using GraphGrep [8] and finally all matches combined using probability models to get the final lobster graph.

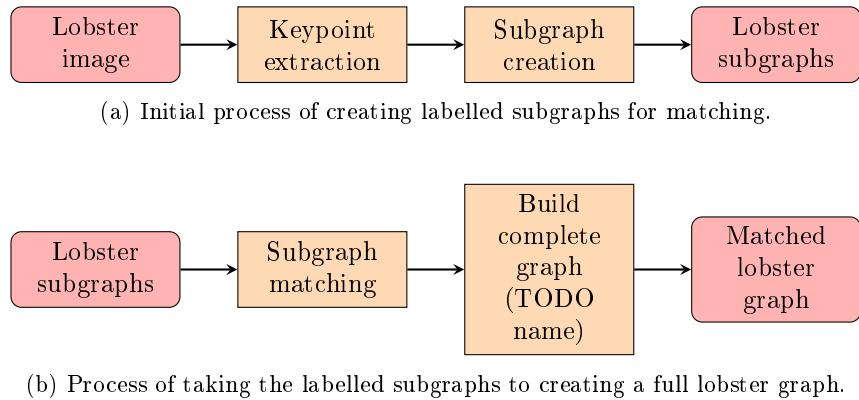


Figure 3: Flow chart of the whole matching process from getting keypoints to creation of the lobster graphs.

A subset of the dataset was taken to create a database of manually annotated attributed lobster graphs. This dataset is important for many aspects of the overall method as it is the set of complete graphs for subgraph matching. Further, the attributes such as node labels, node sizes and edge weights contribute as a basis for the probability models used in both subgraph creation and rebuilding a complete lobster graph.

## 4.2 Keypoint detection

First, to identify important parts from our lobster images, keypoints or areas of interest must be identified. OpenCV provides a host of different algorithms for feature detection such as Harris and Shi-Tomasi corner detectors and SIFT, SURF, ORB keypoint detectors [24]. All these algorithms were tried and tested on a small subset of the dataset to see if any would provide both useful and consistent features that can be used.



(a) Harris corner detection



(b) Shi-Tomasi corner detection



(c) SIFT keypoint detection

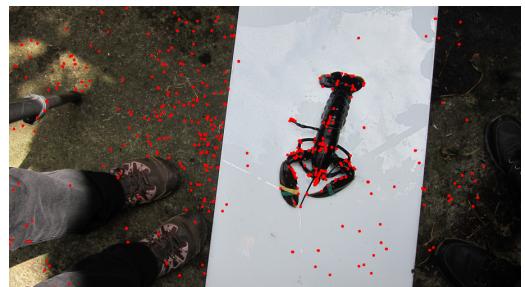


(d) SURF keypoint detection

Figure 4: Comparison of different feature detection algorithms. The images have been scaled down after applying the detection to more clearly show the keypoints. Further comparison of the different detection algorithms on more images can be found in appendix A



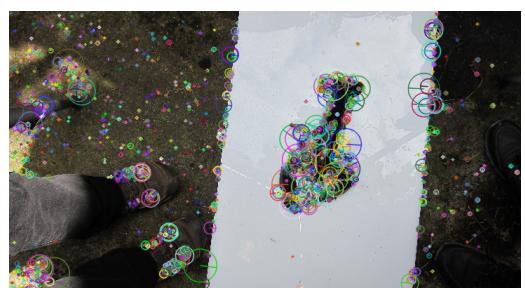
(a) Harris corner detection



(b) Shi-Tomasi corner detection



(c) SIFT keypoint detection



(d) SURF keypoint detection

Figure 5: Comparison of different feature detection algorithms on an image with more noise.

From visually seeing the effects of each algorithm, it can be seen that the corner detectors do not work very well for our purpose. The shape of the lobster is not fully detected reliably. For images with a noisier background, much of the background such as slabs with sharp contrasting corners are also detected, as shown in figure 5. Furthermore, although corner detectors have applications in image matching [5], our goal from feature detection is to be able to extract graph like objects or features to apply graph matching on and so corner detection is unsuitable as we are not looking to match the different images to each other directly.

The keypoint detectors are able to provide better results for our objective, as we can see keypoints of important body parts being identified, such as the body, tail and claws. These keypoints are further able to be consistently identified from multiple images, showing that use of these algorithms are promising for automatically detecting the various parts of the lobster for construction of a graph. There is still a lot of noise in the detected keypoints, but we shall see later in section 4.4 that different methods can be applied to filter out unwanted keypoints. It is also non-trivial to create a graph from an outline of corners to represent the shape of a lobster, whereas the keypoints naturally translate well as nodes of a graph, with edges connecting them to form the shape and pose of a lobster. Because of these reasons, the keypoint detection algorithms in SIFT, SURF and ORB were further investigated while the corner detectors were discarded.

TODO fig of keypoint detector algorithm comparison

Figure 6: Comparison of different keypoint detection algorithms on multiple lobster images. See comparison of more images in appendix A

Between the different keypoint detection algorithms, SIFT was chosen as it gave the most consistent results and the kind of useful keypoints that are needed.

### 4.3 Annotation of dataset

The dataset provided by [1] was tagged with information on each image such as the lobster's sex, length of the carapace and width of the tail. To be able to apply the probability models to the dataset and match to complete lobster graphs, the dataset had to be further annotated as attributed graphs. This was initially done and prototyped using Gephi to explore different graph configurations, but only with dummy values for the edge weights and size of the nodes. Later, with the introduction of applying OpenCV keypoint detection algorithms, the annotations were amended with the detected keypoints to include the real node sizes and edge lengths.

TODO Gephi prototype lobster graph

Figure 7: Examples of different configurations of lobster graphs that were explored on the same lobster image.

In the initial lobster graph prototyping done with Gephi, different configurations were explored to see how more or less information from the lobster graphs could influence the matching process. At this stage, the use of OpenCV keypoint detectors were not yet used, as the goal was to prototype the graphs and probability models for matching.

After the use of computer vision algorithms was explored, the annotated step was revisited to update the graphs to correspond to keypoints that could be detected in the images. This improved the annotated dataset by adding more data such as size of nodes and lengths of edges which would be used. This annotation took a few steps to complete:

1. Run SIFT to detect all keypoints on the image, then output all the keypoints as nodes in .gdf format.
2. By looking at the corresponding images, manually annotate the edge connections between relevant keypoints and remove all other keypoints.
3. Translate the annotated graphs in .gdf format to .gfu format for graph matching tools to use. The .gdf graph formats are still kept as they are used for the probabilistic models.



Figure 8: Example of annotated lobster image with nodes and edges of the graph perfectly labelled.

Because the process of manual annotation could have human errors, the final completed annotations are drawn as nodes and edges on top of the raw image again to visually check for mistakes made during the annotation of edges and removal of other keypoints.

#### 4.4 Keypoint filtering

From just running a SIFT detector on the lobster images, it can be seen that there are a lot of small keypoints that are unimportant for our purposes. There are also many keypoints around the lobster that we would like to filter out, as we want all our keypoints to be on the lobster. Initially, the classic vision approach for feature matching using the keypoint descriptors [15] was tried, but the results obtained were surprisingly poor. Because of this, a more novel approach was taken for filtering. The small keypoints are filtered out by specifying an octave where all keypoints coming from that octave or above are kept. Finally, remaining keypoints that are not on the lobster are filtered with a colour histogram method where the colour histograms of the keypoints are compared and any below a certain difference threshold are filtered away.

#### 4.4.1 SIFT descriptors

In computer vision, keypoint descriptors obtained from detectors like SIFT and SURF are often used for feature matching [13]. Lowe's paper [15] on the SIFT detector states that keypoints descriptors are highly distinctive, allowing a single feature to be correctly matching with good probability in a large database of features. This is exactly what we want, as we wish to extract the different features of a lobster (tail, claws, head). The only difference is we do not have a dataset of the lobsters, but not of dataset of individual lobster parts.

Because we do not have a dataset for individual parts, it made more sense to do the opposite of matching. Instead of using the distance between descriptors to match a detected keypoint with a known keypoint, the distance can be used as filter out keypoints that do not match closely to known ones. This distance can then be used as a threshold to filter more or less keypoints away.

As a test, the descriptor for the important body keypoint was taken from one image and calculated. The descriptor was then matched to the closest other keypoints on another image to see if the body could be identified again.

TODO keypoint descriptor matching other image

Figure 9: The image on the left shows the keypoint that the descriptor was calculated from and the image on the right is the closest TODO matched keypoints to that descriptor.

Figure 9 shows that the use of keypoint descriptors as a means of matching or filtering was not very reliable. TODO. As the traditional method of descriptors proved unreliable for our means, a slightly more novel method was needed to filter out keypoints.

#### 4.4.2 Octave filtering

The method of filtering by the actual size of the keypoints was first looked at before looking at octaves. It was found to be less robust and less general than using octave levels. There are a few issues involved in using size of the keypoint for filter, namely how to choose a suitable threshold. The size threshold must be constant across all images, otherwise the method will not be able to generalise to unseen images. The size of the keypoints is directly related to the size of the original image, so any size filter threshold must be calculated based on the size of the image. This is not an issue, as a constant size threshold can be relative to the size of the image. However, with different sizes of lobsters, an aggressive threshold may remove important keypoints that we wanted to keep. Conversely a more conservative threshold would not remove enough keypoints and cause a large combinatorial explosion, a problem explained later in section 4.5.1 that we wish to avoid. This makes it difficult to set a good threshold as it would have to be arbitrarily defined and based solely on manual inspection of the images and keypoints sizes of the dataset. Furthermore, this seems to be quite a crude method with little support in existing research and doesn't take advantage of any properties in the SIFT algorithm.

Octaves in SIFT are created by continually blurring an image. The idea behind this is to emulate looking at the image from different distances to get a varied set of keypoints. This means different features may be found at different octave levels. The high resolution of the images in our dataset causes many small keypoints to be found in the first few octave levels. These keypoints show many details that are irrelevant as we are concerned with the overall pose and size of the lobster.

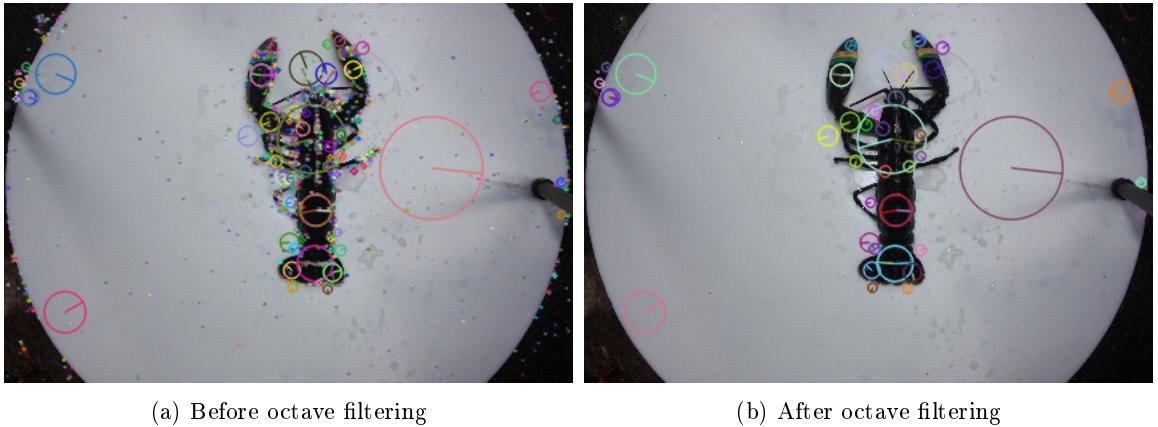


Figure 10: Before and after applying a filter on keypoints based on the octave level the keypoints were found in.

From this observation, we can apply a filter on all keypoints found below a certain octave level so that we are only left with the larger keypoints that capture the features we are looking for. A filter for all keypoints found below octave level 3 was used. This octave level threshold is highly dependent on the size and resolution of the original image. An image with lower size and resolution may need a lower threshold or none at all as the lowered resolution effectively emulates octave levels applying their blur to the original image.

#### 4.4.3 Colour histogram filtering

After applying the octave filter, there still remains some noisy keypoints that need to be removed. Most notably are the keypoints found on the white background of the images. There have been studies [19] [12] that show applying a colour filter to eliminate unwanted feature points can be quite effective, especially if the background is very different from the target of the image. Following from this, colour histograms of each keypoints were calculated and compared to a set of pre-defined histograms. The difference between the histograms was compared and only keypoints whose difference is above a certain threshold are kept.

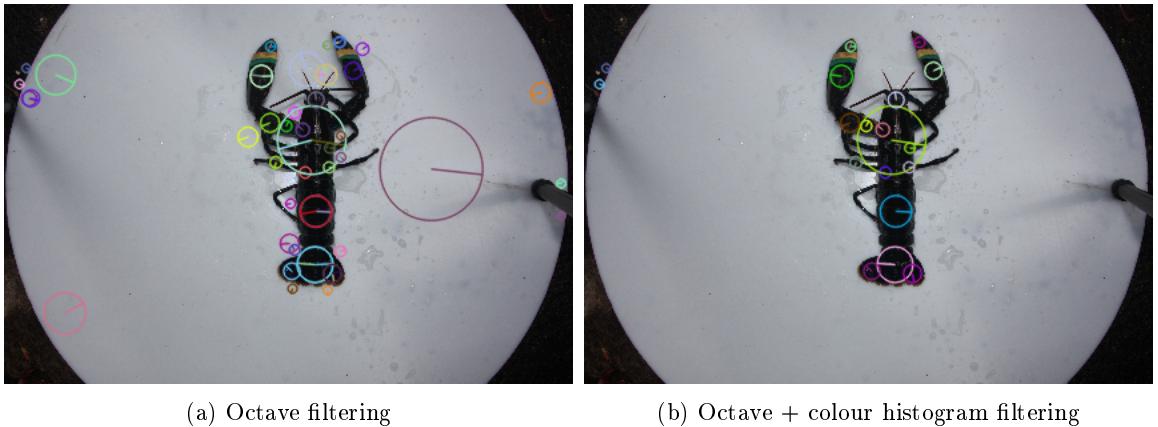


Figure 11: Difference between applying only octave filtering and applying both octave and colour histogram filtering.

The pre-defined histograms are taken from one of the lobster images from the dataset. A keypoint is taken and a mask applied to the image so only the area of the keypoint remains, then the histogram is calculated and saved as a NumPy array. The saved array can then be loaded later

and compared to any keypoint to find the difference between them. Initially only one histogram was used, which was taken from the body keypoint of one image. However, this was not very effective as often the other keypoints had a large difference which meant the threshold had to be set to very low to capture important keypoints. This is not desirable as the lowered threshold causes more noisy keypoints to also be captured. To alleviate this issue, a separate histogram was calculated and saved for each different body part. This allowed TODO.



Figure 12: Keypoints detected after filtering, showing the weakness of colour histogram filtering against noise.

A potential issue that was not fully explored is the application of this approach to noisy backgrounds. The colour histograms are effective due to the large contrast between the white background and the lobster. However, this means that keypoints detected in noisy backgrounds that have similar dark colours are not filtered out. Figure 12 shows an image with more in the background and it can be seen that multiple keypoints from the background not belonging to the lobster still are kept.

#### 4.5 Subgraph creation

With a set of keypoints extracted and filtered from the image, the next step was to label the keypoints and create permutations of subgraphs to be matched. To reduce problems with combinatorial explosions when creating subgraph permutations, the number of labels assigned to each point and the size of the subgraphs have to be kept low. The idea of starting from creating subgraphs rather than try to create the entire lobster graph is to reduce the initial complexity of the problem. With a set of matched subgraphs, the larger lobster graph can be built incrementally. This method would also be more reliable than trying the whole lobster graph initially as more subgraphs can be taken into account during the rebuilding stage. Additionally, errors would be more easily accountable as the errors would only occur per mismatched subgraph rather than the whole lobster graph being mismatched in one step.

#### 4.5.1 Node labelling

A simple probabilistic model was used to determine how to label the keypoints through the use of Bayes' Theorem.

$$P(\text{label} \mid \text{size}) = \frac{P(\text{size} \mid \text{label})P(\text{label})}{P(\text{size})} \quad (1)$$

The three probabilities  $P(\text{size}|\text{label})$ ,  $P(\text{label})$ ,  $P(\text{size})$  are defined as follows:

- $P(\text{size}|\text{label})$  - This probability was found using a normal distribution for all sizes of the particular label found in the annotated dataset.
- $P(\text{label})$  - This is defined as how often that label appears in the annotated dataset relative to the total number of all labels. For example, if there were a total of 100 labels and the *body* label appears 20 times, then  $P(\text{label} = \text{body}) = \frac{20}{100}$ .
- $P(\text{size})$  - The probability of keypoint sizes again uses a normal distribution for all keypoint sizes in the annotated dataset.

With the probability calculated for each possible labelling for every keypoint, the labels can be applied based on a threshold. This means multiple labels can be applied to the same keypoint and each separate labelling must be treated as a separate node during subgraph creation. The threshold for labelling represents the trade off between computation required and completeness. If the threshold is too high, then we may miss many potential labels. This is important because the size of the annotated dataset is quite small, so there is a high standard deviation in the distributions for label sizes. On the other hand, if the threshold is too low, then too many labels are applied, leading to a combinatorial explosion when creating the permutations of subgraphs. The result of the labelling process is a list of tuples containing a keypoint and its label. Having all the keypoints labelled, the next step is to create subgraphs where the nodes are represented by labelled keypoints and edges are defined between the nodes to create the subgraph.

#### 4.5.2 Subgraph permutations

To create labelled subgraphs from the labelled keypoints, all possible permutations are produced. The size of the subgraph to create (and therefore the size of the permutation) is an important consideration in this step. The equation for the number of permutations of size  $k$  from  $n$  labelled keypoints is as follows:

$$P(n, k) = \frac{n!}{(n - k)!} \quad (2)$$

A large  $k$  would make the matching step easier as a larger subgraph conveys more information about the node labels and connectivity, so there would be fewer but more distinct matches. However, this would lead to considerably more permutations, for example, given 20 labelled nodes, there would be 6840 possible permutations for  $k = 3$  while  $k = 4$  would give 116280 permutations. Having this combinatorial explosion is unsustainable. Though a single permutation cannot contain the same keypoint with two different labels, each permutation of a single keypoint and its multiple labels must be explored. Further these are permutations so the order matters as it directly represents the connection of the nodes to edges.

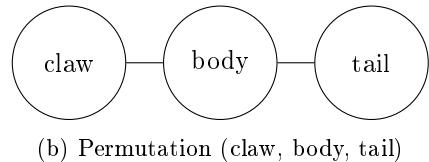
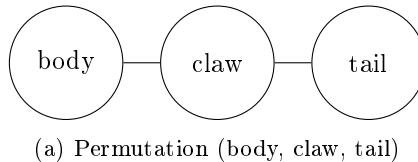


Figure 13: The order of the permutations matters as it determines the edges between the nodes.

A subgraph size of 3 was chosen in the end as it was a strong middle ground between retaining enough information for effective subgraph matching and not causing a large number of permutations to match. A size of 2 is ineffective for matching, it leads to too many successful matches because it is easy to find subgraphs of two nodes and one connecting edge as long as the labels are correct. However using 4 nodes as the subgraph led to too many permutations being produced, leading to a slow process in matching. This is why subgraphs of size 3 were chosen.

## 4.6 Graph matching

The crucial step of taking a large set of subgraphs and matching them to rebuild the complete lobster graph consists of two main steps:

1. Run GraphGrep to find all subgraphs of valid configurations against the database of complete lobster graphs.
2. Use the probability of each remaining subgraph to piece together the complete lobster graph.

### 4.6.1 Subgraph matching

All subgraph permutations created are written as a query for GraphGrep to match. The reason for this matching step is to filter out subgraph configurations that are not possible based on the annotated dataset. Any invalid configurations will not have appeared in the database of complete lobster graphs and therefore will not be matched. A single subgraph can match to multiple database graphs and can also match multiple times to a single database graph. This does not matter as extra matches are redundant information.

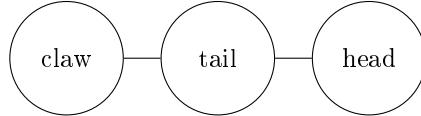


Figure 14: An example of an invalid subgraph configuration that is filtered out by subgraph matching.

Listing 2: Example of matching output from GraphGrep

---

```

1 475:1:{(0,3),(1,1),(2,2)}
2 475:2:{(0,0),(1,3),(2,4)}

```

---

The output of running GraphGrep gives a list of graph ids of the subgraphs and database graphs that were matched. Any subgraph that appears in the list is taken as a matched permutation. After, there is a further step where the lengths of the edges between each node is taken into account. This acts as a late filter step for keypoints that may not be on the lobster, not allowing graph configurations where the points are too far apart to make sense. For example if the distance between an *arm* node and *claw* node is the same as the distance between a *body* and *tail*, the *arm/claw* permutation will be discarded. This is helpful in discarding keypoints that are far away from the lobster, for example on the edges of the background. Furthermore, this filters out subgraphs where the labelling was valid, but the distances between the nodes were not, which acts as a premature step to remove mislabelled subgraphs, for example if the tail or back was labelled as a claw and connected to a correctly labelled arm.

### 4.6.2 Subgraph rebuilding

The final stage of the whole matching process is to take the pool of valid, matched and labelled subgraphs and piece together the complete lobster graph. Often there are many more subgraphs

than are needed to rebuild the graph, so the best subgraphs and configurations should be chosen. To choose whether a subgraph was better than another, a probability model was used again. The probability of each subgraph is calculated as the product of the probability of each node labelling and probability of each edge.

$$P(\text{subgraph}) = \prod_{i=0} P(\text{node}_i) \times \prod_{j=0} P(\text{edge}_j) \quad (3)$$

The probability of each node labelling is already defined as it was used to assign the labels during the creation of the subgraph. The probability of the edges is computed using Bayes' Theorem with a probability distribution for each type of edge based on the nodes it connects. To prevent floating point issues during implementation, the sum of logs is used rather than the product of the probabilities.

As stated before, a single keypoint can also be contained in multiple subgraphs. These cases have to be treated carefully as it is valid for those more than one of those multiple subgraphs to appear in the final lobster graph. An easy example of this is a body keypoint which has multiple subgraphs. One subgraph could contain the tail and back while another contains the arm and claw. In this case they are both valid because they could both be part of the final graph. Because of this, subgraphs in the pool cannot be discarded simply because they contain the same keypoint and label as another. Further, it is inevitable that multiple subgraphs with the same keypoint are used to be able to build a graph that is fully connected, otherwise additional rules will be need to define how two subgraphs should be connected.

With these considerations in mind, three different methods were used to build up the lobster graph from subgraphs, one of which gave poor results and was not used in the final evaluation.

(a) Keypoint method	(b) Label method	(c) Graph method
TODO images of different methods applied		

Figure 15: Comparison of the three different methods for rebuilding the complete lobster graph from matched subgraphs.

The three different methods are as follows:

1. **Keypoint method** - The initial method explored was to ensure every keypoint is used when rebuilding the subgraph. This will make sure that no keypoints are missed. For every keypoint that was detected and not filtered away, the subgraph with the highest combined probability is chosen. Some chosen subgraphs are removed to prevent overlaps where the same keypoint is given multiple labels. This removal is again based on probability where the subgraph with the highest probability is kept. The main issue with this method is it is very reliant on good keypoint detection and filtration. Any incorrectly detected keypoints will be included this process which leads to errors of labelling many irrelevant points. As such, more sophisticated methods were explored that do not rely so heavily on the keypoints detected.
2. **Label method** - In this method, a list of canonical required labels is used to choose the subgraphs for the final lobster graph. This ensures that the complete set of labels needed for the complete lobster is used and found where possible and very few additional labels past the canonical ones will be included. To build the complete graph, the most probable subgraph is chosen for each label in the canonical list of labels. Then, overlap is checked by comparing the keypoints and labels in each subgraph. This is done to make sure no keypoint has two different labels but will allow one keypoint to be contained in multiple subgraphs. Further, when a probably subgraph is chosen, the labels it contains are removed from the canonical list. The final output is the set of most probable subgraphs that contain as many of the canonical labels as possible without repetition.
3. **Graph method** - The final method explored takes into account graph properties of how nodes are connected rather than just choosing based on canonical labels. The weakness

of the label method is not taking into account any relations between the nodes. Here, a canonical *graph* is defined which specifies both the labels and the connections between them. For each edge in the graph, matched subgraphs are chosen based on whether they contain the same node connections as the canonical edge. Again the same method of choosing the subgraph with the highest probability and removing overlaps was used to prevent duplicate labelling.

In section 5, the results of using both the labelling and graph methods are compared and analysed to see how well they work.

# 5 Results

To evaluate how well this method of recreating lobster graphs performs, precision and recall metrics are used. The evaluation is split into two evaluations, one for the performance of identifying correct keypoints and the second for the performance of keypoint labelling. The evaluations are split up into two parts because defining false positives and false negatives when evaluating both aspects together is a difficult problem. For example, if a keypoint has been incorrectly identified, then how is the labelling of the keypoint dealt with? The label cannot be correct, but only because the keypoint itself is wrong and there is not defined correct label for them.

## 5.1 Keypoint identification

First, the precision and recall metrics were calculated for keypoint identification to see how many keypoints from the annotated images could be re-identified in the final graph. The labels of each keypoint and the edges between them are not taken into account for these results.

$$\text{Precision} = \frac{\text{Correctly detected keypoints}}{\text{Total keypoints detected}} \quad (4)$$

$$\text{Recall} = \frac{\text{Correctly detected keypoints}}{\text{Total keypoints in annotation}} \quad (5)$$

- True positive - Correctly detected keypoints
- False positive - Incorrectly detected keypoints
- False negative - Annotated keypoints that were not detected
- True negative -

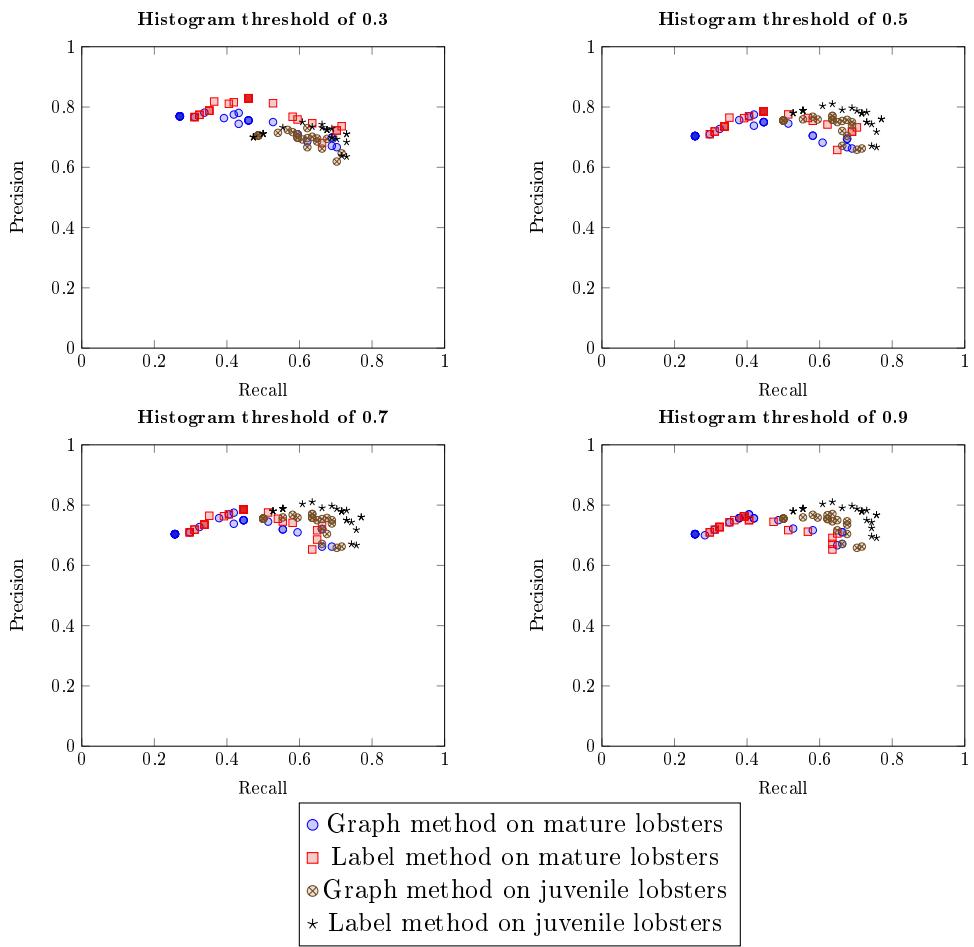


Figure 16: Precision/recall graphs with the mature model with varying label thresholds.

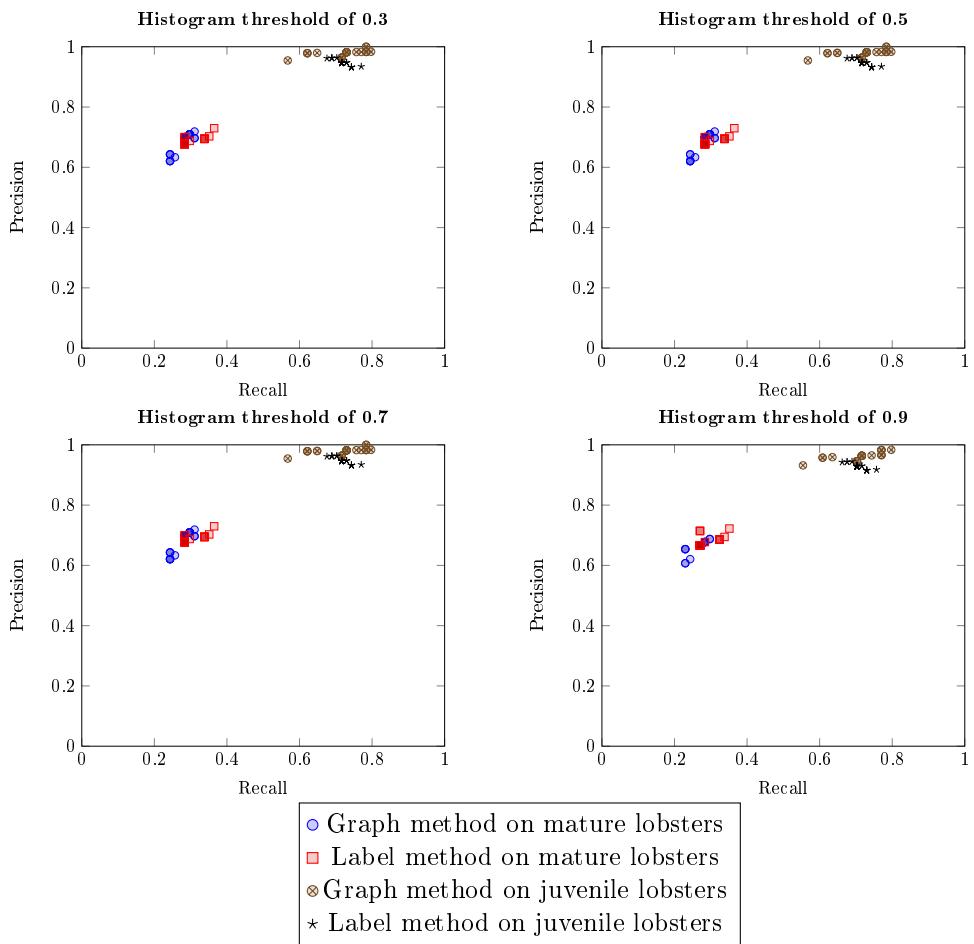


Figure 17: Precision/recall graphs with the juvenile model with varying label thresholds.

## 5.2 Keypoint labelling

- True positive - Correctly labelled keypoints
- False positive - Incorrectly labelled keypoints
- False negative - Missed labels, eg if 2 claws and only 1 was found-labelled
- True negative -

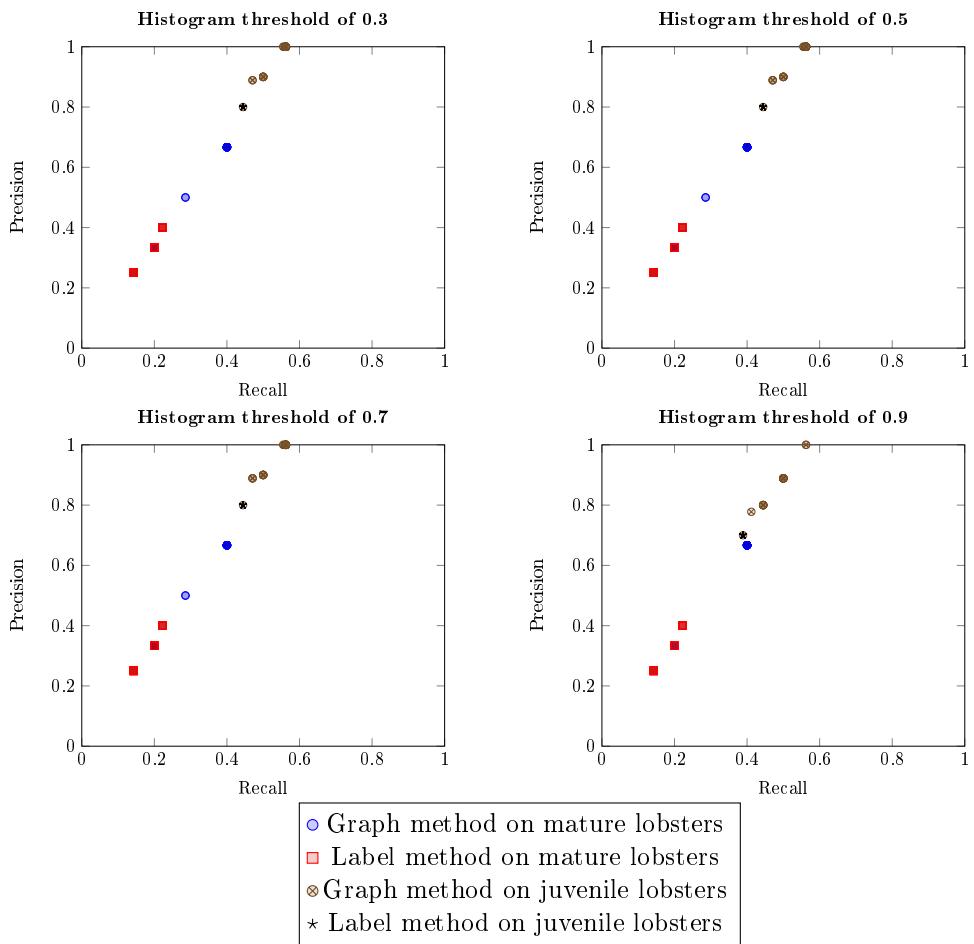


Figure 18: Precision/recall graphs with the juvenile model for label “claw”.

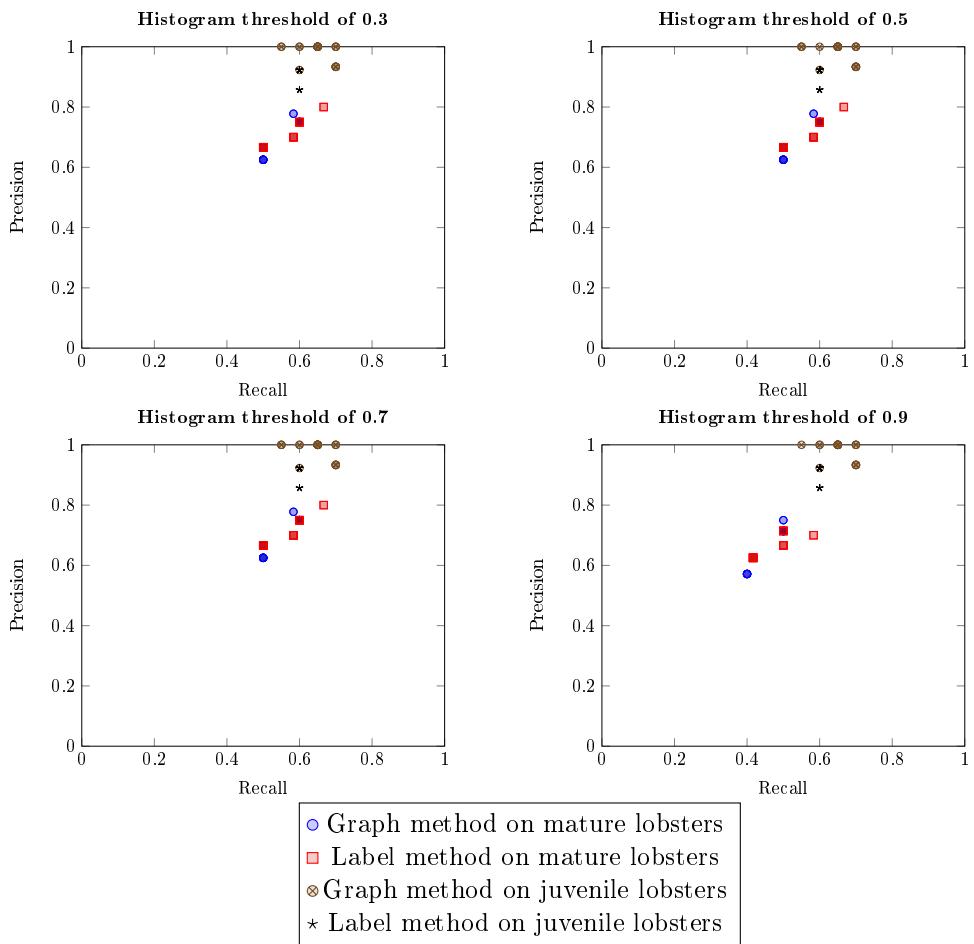


Figure 19: Precision/recall with juvenile model for label “arm”

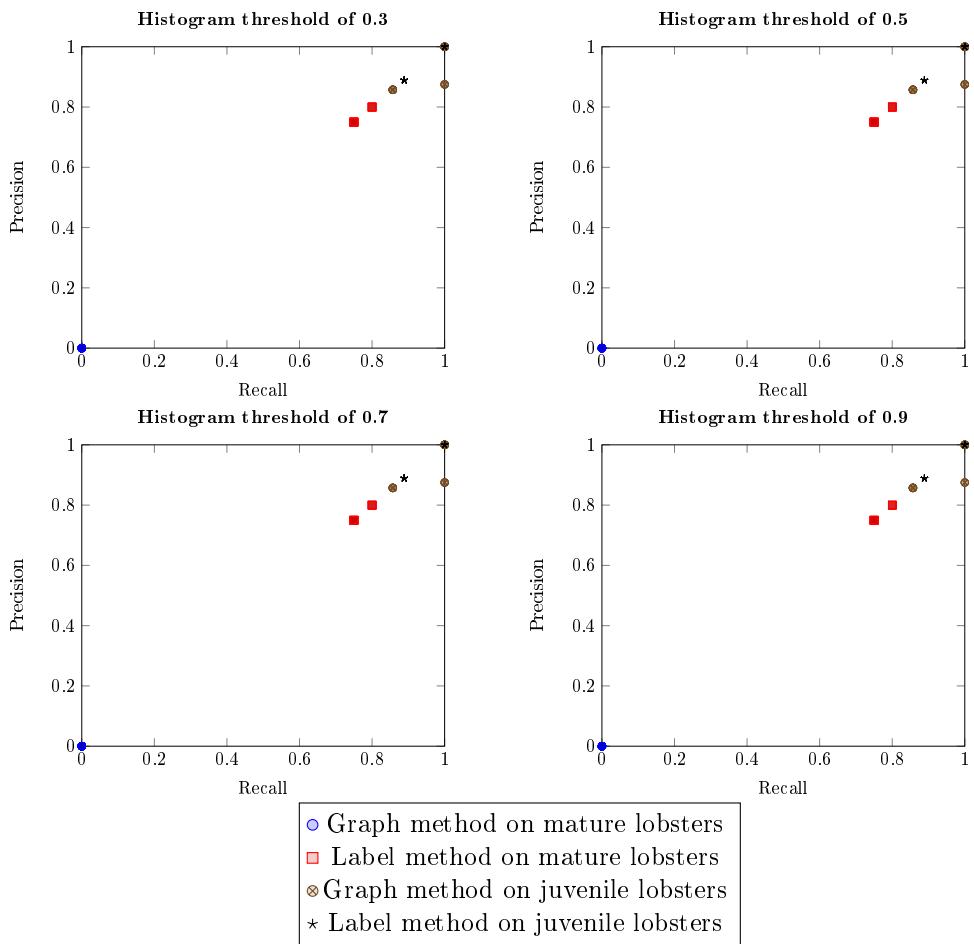


Figure 20: Precision/recall with juvenile model for label “tail”

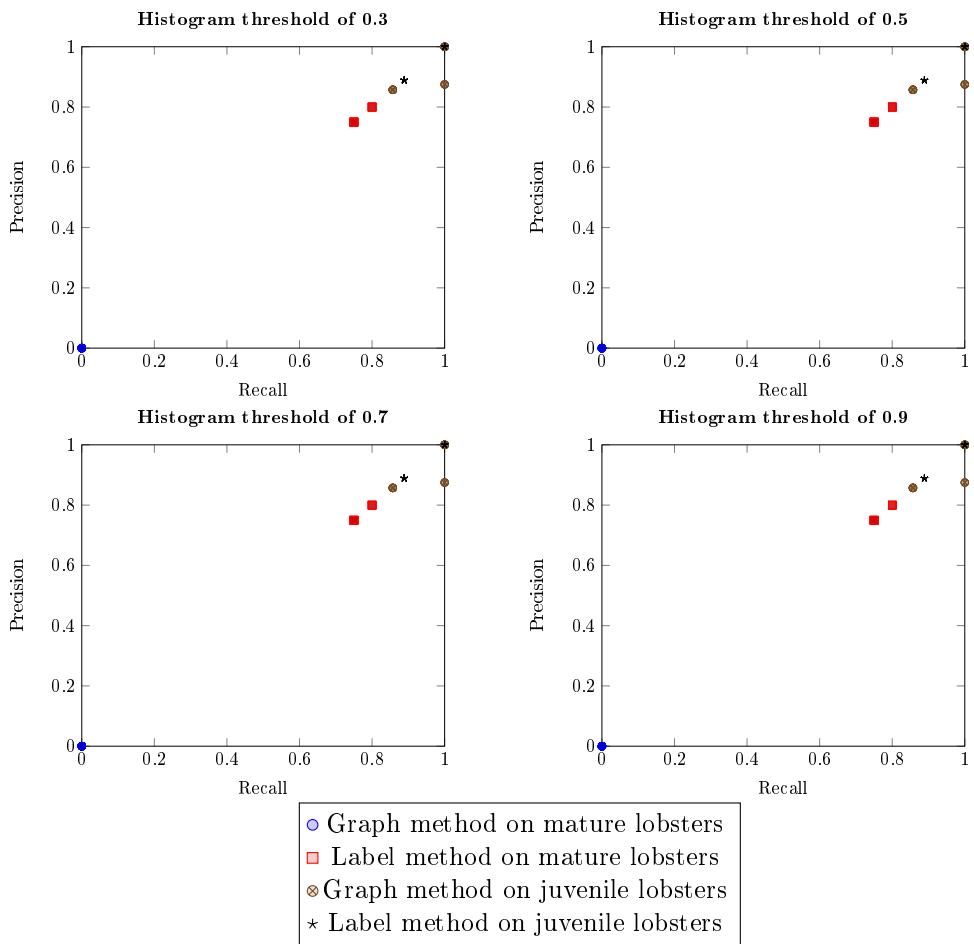


Figure 21: Precision/recall with juvenile model for label “head”

Problem with recall for labelling is false negatives very low as only 1 or 2 labels are in annotated set.

### 5.3 Classification

results why overlap classify [17]

## 6 Evaluation

## 7 Conclusion

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# Appendices

## Appendix A Comparison of feature detection algorithms

TODO imgs

TODO more imgs

## Appendix B Results of all keypoint labelling precision/recall

Claw labelling TODO

Head labelling TODO