Termite Tracking in Collaboration with Harvard University

Nikolaj Aaes, Niklas Schalck Johansson, and Hildur Uffe Flemberg
{niaa, nsjo, hufl}@itu.dk

IT University of Copenhagen
Rued Langgaards Vej 7
DK-2300 Copenhagen S

Abstract. The Self-Organizing Systems Research Lab at Harvard University wants to physically track termites as well as being able to extract relevant statistics about them. At the moment there is no existing software to fulfill this function which is why this project was developed. Tracking termites could enable biologists to investigate how they collaborate and what behavioral patterns they express. This can in turn help the field of swarm robotics develop better collaboration between robots.

This project enables the user to control an XY-plotter and track ants and termites in a controlled enviroment and collect relevant data. While the solution is just a prototype it provides the foundation for further development towards real field equipment for biologists.

Keywords: Computer Vision, Image Processing, Termite Tracking, Biology, Computer Science.

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1 Introduction

This report is written at the IT University of Copenhagen (ITU) in the fall term of 2013 as a project supervised by Kasper Støy from ITU and with additional guidance from Kirstin Petersen from Harvard University. The project was developed from September 1st to December 16th 2013. The report is addressed to people interested in tracking ants or termites using image analysis.

The Self-Organizing Systems Research Lab at Harvard University has created an autonomous robot for tracking African termites in a lab environment but lacks the necessary software support. Working with and tracking these termites is cumbersome as they only thrive in environments that resemble their native environment and only when they are together with other termites. Therefore automatic tracking of specific termites is necessary, as tracking up until now has been done manually.

This project aims to develop software that is able to track both ants and termites in their native environment using a Hewlett-Packard XY-plotter provided by Harvard University. While it is already possible to communicate with the plotter using for instance Termite [1], there is a need for software that integrates tracking, plotter communication, statistics and a graphical user interface (GUI). The end product is to be used by biologists and this software will lay the foundation to enable them to track ants/termites with more precision and with better data being collected. Since biologists, who are the future end users of the product, would like to be able to stimulate the ants or termites with food or pheromones, we need a non-stationary part which is exactly what the plotter provides (the plotter arm).

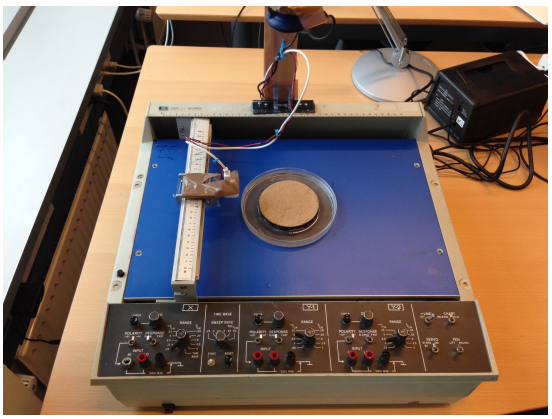


Fig. 1: Plotter with mobile camera, overhead camera and control panel

A team at Harvard University previously experimented with using the plotter to track a single ant on a white background with some success. While the details of this effort were unknown to us we decided to start this project from scratch. Since this team had some success with their approach we use their hardware setup as a starting point for this project. The focus of the project is mainly on the development of the software and the selected hardware has a secondary role.

Since tracking of ants is very hard to test systematically we have chosen to evaluate it by describing in which cases we expect the tracking to work as intended and in which cases we expect it not to. The results show that tracking of ants are both possible and satisfactory but still have cases where the it will fail. Both the results and possible improvements can be found in Section 4.2.

The project was undertaken as a substitute for the "Global Software Development" course at ITU and therefore has additional emphasis on the international collaboration and development process. Section 4.1 will describe the collaboration tools used as well as evaluate the overall process.

This report assumes that the reader has a basic knowledge of mathematics but any prior knowledge about computer vision is not required. We will first describe the requirements and scope of the project and the image analysis theory we either considered or used in the project. Then we will describe how we interacted with the XY-plotter and how we combined this with the tracking. Lastly will we describe the tests, analyze the results and conclude the project.

1.1 Project Proposal

The purpose of this project is to develop software, such that the provided hardware can be used to track ants or termites and extract relevant statistics. This includes a GUI that sends user input to the robot tracker.

There are three parts in this project:

1. Tracking ants using a low resolution camera. In order to track an ant, it is necessary to be able to determine its position and move the camera to its new position using image analysis on the camera output.
2. Interact with the plotter and update the camera's position with the result from the tracking software.
3. Design and develop a user interface that can be used to retrieve statistical data from the tracking.

2 Vision Based Insect Tracking

2.0.1 Scope

While the project lays the foundation for a fully usable solution we have chosen to narrow our scope to the essential functionality. This means that the project was designed and tested in a controlled environment where factors such as lighting, wind etc. are kept as stable as possible.

Because we did not have access to termites, our counselor at Harvard University suggested using ants instead. Minor adjustments, mostly to the blob detection code, should make the solution capable of tracking termites instead of ants since the main difference is the size.

We intent to experiment with colors that have a high degree of contrast with the background. Once a suitable color is found, we will not continue to investigate other possible colors.

The project will not focus on changing the hardware provided by Harvard University. The hardware had already been succesfully used in a controlled and simple environment, and this project focuses on implementing the software to handle a more complex environment. However if the current hardware is found to be too limited in our test environment, and if acquiring new hardware would improve the results of the developed software we will document any shortcoming and improvement suggestions.

While it could be interesting to track several ants with several cameras, we focus on tracking a single ant with a single camera. We do this because tracking several ants would require a significant modification of the hardware. Even if the optimal hardware was available before project start, controlling several cameras would be a substantial extension of the project as making sure that all cameras track one ant optimally without colliding and shadowing each others views requires special techniques. Thus tracking several ants would require more time than we have available.

Our counselor at Harvard University wanted the tracking and interfacing with the tracking device to be implemented in C++ to make further development easier. The graphical user interface (GUI) was not restricted to a certain programming langauge and so we ended up using C# and Windows Forms. The minimum requirement for supported platforms are Windows.

2.0.2 Requirements

To ensure the success of the project we compiled a list of the mandatory and optional requirements. This helped us plan our development process and align the expectations between us, our counselor at ITU and our counselor at Harvard University.

Mandatory requirements
The mandatory requirements of the project are listed below and must be fulfilled for the project to be considered a success.

1. Tracking of ants using a low resolution camera implemented in C/C++.
2. Ability to adjust tracking parameters before and during tracking.
3. Moving the camera in correspondance to the tracking.
4. A GUI containing two modes:
   - Calibration mode. Must contain a direct feed from the mobile camera, a proccessed feed and sliders to adjust the processing.
   - Tracking mode. Must contain a direct feed from the mobile camera, a direct feed from the overhead camera and statistics.
5. Ability to collect the following statistics:
   - Route of the ant over time.
   - Heatmap of where in the petri dish the ant tends to be.
6. Ability to save the collected statistics.

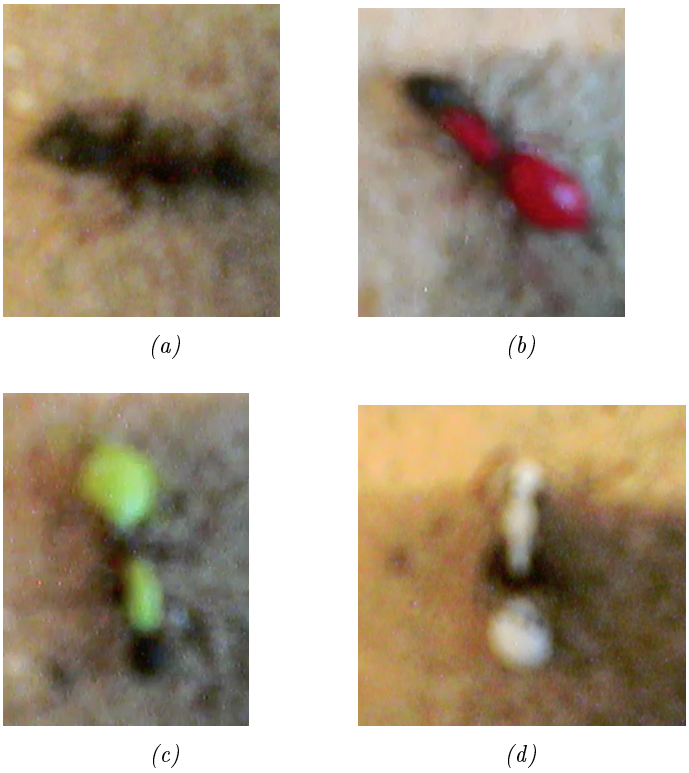
Optional requirements
The optional requirements are the so called "nice-to-have requirements". They are not mandatory for the project but features that could be desirable to implement if time and resources permit it.

1. An additional third mode in the GUI; bias mode. Bias mode adds the ability to select a certain point which the plotter will try to lure the ants towards using food or pheromones.
2. Ability to choose certain areas which should be avoided during tracking.
3. Collection of these additional statistics:
   (a) Average speed of the ant.
   (b) Amount of ants, the marked ant, meet during tracking. A way to adjust what defines a meeting.
   (c) Amount of time between each meeting. A way to adjust when a meeting starts and ends.
   (d) Duration of each meeting.
   (e) Area of the petri dish explored by the ant. A way to adjust the size of the area an ant will explore at any given time, also known as *headsize*.
   (f) How much area is explored over time.
   (g) Amount of time between each "stay".

Now that we have established the background, scope and goals for the project we continue with describing the central parts of the project. First we describe how to find the ant in an image, second, how we interacted with the plotter and third, how we created the GUI.

2.1 Experimentation with ants

During this project we had to decide whether to paint the ants or not, and if so, in what color. Figure 2 shows four examples of ants, with both their natural color, shown in image a, and painted versions shown in image b(red), c(green) and d(white). The images are recorded using the webcam from the plotter. We can see from these images that coloring an ant is preferred. Painting it white gives the best contrast compared to the background. Furthermore we suggest putting the ant to be painted in a freezer for 2-4 minutes as this will put it in a sedated state, making it much easier to paint. After a couple of minutes it will act normal again.



(a) *(b)* *(c)* *(d)*

Fig. 2: Coloring ants in different colors

A second problem were to keep the ant within the petri dish. The ant had no problem climbing the sides of the petri dish and escape. We therefore tried several different solutions to keep them. We were adviced to try teflon tape on the sides of the petri dish, as they should not be able to climb the slippery surface of that tape. This did not prove successful so we tried other types of slippery tape

versions like silicone and wax tapes. See the different types of tape in Figure 3. Unfortunately none of them were able to solve our problem. We were also adviced to use mineral oil, however we were unable to get a hold of any such oil. We tried with cooking oil instead such as sunflower oil and olive oil, however they did not have the desired effect.

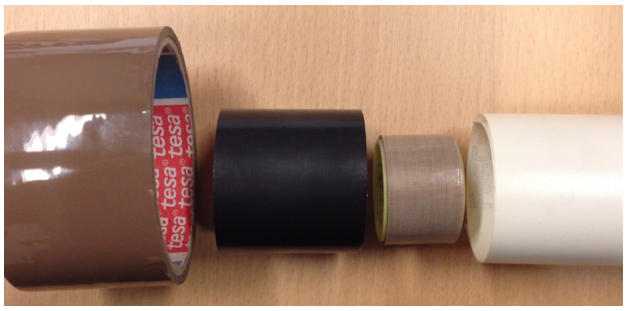


Fig. 3: Different types of slippery tape used

We followed up by trying to use natural ant repellents such as kitchen salt, however our tests did not prove fruitful as it did not have any effect.

Our solution was to eliminate all sides completely and create an "island" instead. We filled the petri dish with dirt until it was completely full, and placed it within a much larger petri dish full of water. We hoped that the ant would not cross the water, and thereby stay in the inner petri dish during our tests. The setup can be seen in Figure 4. This solution proved much more successful, as the ant did not move into the water immediately. However after some time it realized that it was completely surrounded by water, and tried to swim away. It would take a long time for the ant to try this, giving us enough time to test our software.

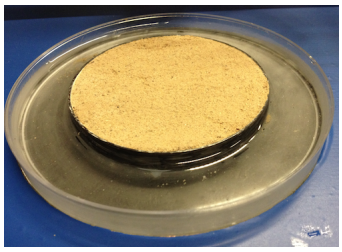


Fig. 4: Petri dish filled with dirt within a larger petri dish filled with water

2.2 Tracking

As mentioned in the project proposal the project was divided into three parts. The first part of the project was to be able to track termites. Since African termites are hard to come by and transport we settled for giant ants (Camponotus Ligniperdus), which are the largest ants found in Denmark [3], instead. While these are not as big as the termites, they behave in a similar way and the solution should be easily adaptable to termites. In the first part we started by implementing the tracking on a video. We received a video from Harvard University of a single ant capturing the entire petri dish with a white background. The ant itself was painted red and green. This was the simplest setup we could think of and acted as a good starting point. By recommendation we decided to use the OpenCV [2] framework. We will return to this framework in Section 2.2.2.

This chapter is divided into three subparts. First we will describe different image processesing techniques, and their use. Following this we will discuss the OpenCV framework, and finish off describing the implemented solution and design choices.

2.2.1 Theory

In this section we will use the *ternary if* notation which looks like the one shown in Equation 1.

$$value = Boolean\text{-}Condition?True\text{-}Evaluation : False\text{-}Evaluation \quad (1)$$

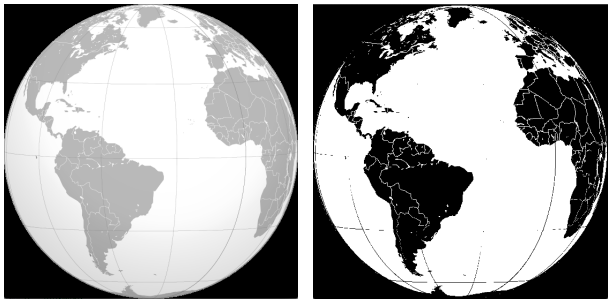
It works just like you would expect from many programming languages or mathematical expressions. It is also known as an inline *if-statement*.

Thresholding

Thresholding is an image processing technique used to make a final decision about each pixel in an image. Thresholding is most commonly used to find objects in images, e.g. finding an ant in an image [8]. During thresholding a decision is made based on the following; either a pixel value is one that we are interested in or it is not. This is usually done by assigning a specific pixel value to the pixel we want, and another to those that we do not want. In general we compare the *ith* pixel of the source image, *src*, to the threshold value, T, and save the result in a destination image, *dst* [8]. For instance, to create a binary image where we are interested in all pixels above the threshold T, the equation would look like the one shown in Equation 2,

$$dst_i = src_i \geq T?255 : 0 \quad (2)$$

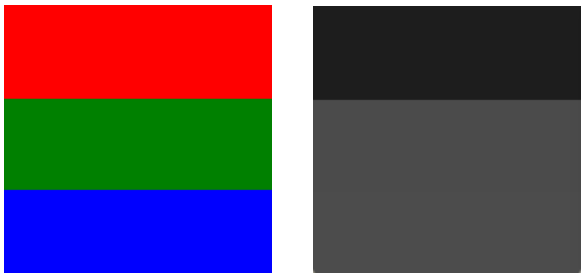
Most threshold operations are applied on grayscale images, where all pixel values range between 0 (black) and 255 (white). Sometimes these values are normalized to range between 0 and 1 instead. However for the rest of this report we will assume that grayscale images use the former convention. Figure 5 shows an example of applying thresholding to a grayscale image.



(a) Grayscale image *(b) Thresholded image*

Fig. 5: An example of applying a threshold on a grayscale image. This example use the threshold value $T = 200$

Now what happens if we are interested in a color? To use standard thresholding we first need to convert *src* to a grayscale image. However doing so might result in an image that has lost important information as can be seen in Figure 6. As shown, you have no way of differentiating the blue and green color.



(a) RGB image *(b) Grayscale image*

Fig. 6: Example of grayscaling a color image

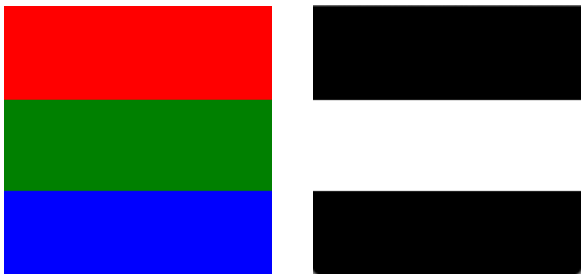
A step in the right direction would be to define the threshold value T as a scalar consisting of three values - one for each color channel. We will denote this threshold scalar as S and define it as shown in Equation 3.

$$S = \begin{pmatrix} S_R \\ S_G \\ S_B \end{pmatrix} \tag{3}$$

To apply it to an RGB image we need to change Equation 2 to the one shown in Equation 4.

$$dst_i = src_{iR} \geq S_R \wedge src_{iG} \geq S_G \wedge src_{iB} \geq S_B ? 255 : 0 \tag{4}$$

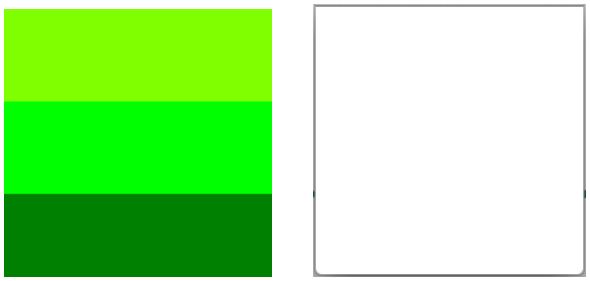
This makes it much easier to differentiate between colors. In Figure 7 a threshold attempt using this method directly on the RGB image is shown.



(a) RGB image *(b) Thresholded image*

Fig. 7: Example of thresholding a color image with Equation 4 using the scalar S=(0,100,0)

However one issue remains - what if you want to find a color among similar colors? The problem is illustrated in Figure 8 using the same scalar as in Figure 7.



(a) RGB image *(b) Thresholded image*

Fig. 8: Example of thresholding a color image with Equation 4 using the scalar S=(0,100,0). Unlike before the result is unsatisfactory.

The solution is to specify a *range* of acceptable values instead of just a threshold. We will specify two scalars; S Upper, SU, and S Lower, SL.

$$SL = \begin{pmatrix} SL_R \\ SL_G \\ SL_B \end{pmatrix} \tag{5}$$

$$SU = \begin{pmatrix} SU_R \\ SU_G \\ SU_B \end{pmatrix} \tag{6}$$

We will use the definitions in Equations 5 and 6 to update Equation 4. The changes can be seen in Equation 7.

$$dst_i = SU_R \geq src_{iR} \geq SL_R \wedge SU_G \geq src_{iG} \geq SL_G \wedge SU_B \geq src_{iB} \geq SL_B ? 255 : 0 \tag{7}$$

Using a range to specify a color instead will yield a much more satisfactory result as shown in Figure 9. In summary, both grayscale thresholding, and color thresholding can be used to find ants of certain colors in an image.

(a) RGB image *(b) Thresholded image*

Fig. 9: Example of thresholding a color image with Equation 7 using the range SL=(0,100,0) and SU=(1,150,10). We have sucessfully located the dark green color area.

Dilation and Erosion

When locating an ant, there might be many small bright dots that make the ant hard to see. This can be improved by using erosion or dilation, which are the basic concepts of *morphological transformations* [8], depending on the image in question. These concepts are mostly used to remove noise, isolating individual elements or joining disparate elements in an image [8]. Dilation and erosion are applied to either grayscale or binary images, and are often used to clean up after thresholding to make the them easier to analyze.

The way both erosion and dilation are applied to an image is by defining a kernel, denoted B, that will be applied to an image (or part of an image), denoted A. The kernel can be any shape or size, however it is often a square where the sides are uneven, e.g. 3x3, 5x5, 7x7 and so on [8]. A kernel has an *anchorpoint*, which is the pixel in A that erosion or dilation is applied to, and the result is stored in the corresponding point in the destination image, *dst(i,j)*. Figure 10 shows an example of a kernel and its anchorpoint in the center.

src(i-1,j-1)	src(i,j-1)	src(i+1,j-1)
src(i-1,j)	src(i,j)	src(i+1,j)
src(i-1,j+1)	src(i,j+1)	src(i+1,j+1)

Fig. 10: Given a pixel, src(i,j)*, the kernel covers the neighbouring pixels. Shown here is a 3x3 kernel.*

When transforming an image using dilation, whenever the kernel is applied to a new anchorpoint, the *local maximum* is used [8]. When eroding an image the *local minimum* is used [8]. Naturally, compared to the original image, bright areas are expanded when dilating, and dark areas are expanded when eroding. However one cannot say that e.g. eroding removes noise and dilating does not. It depends on the image which the transformation is applied to. Figure 11 shows an example of pixels used to determine the outcome of the anchorpoint in the destination image.

An example of how this applies to a real image is shown in Figure 12. It is clear from this example how erosion and dilation affect an image.

100	100	20
40	50	150
20	10	70

Fig. 11: An example of a kernel within a source image, src*, with pixel values inserted. The value assigned to the destination image,* dst(i,j)*, is 10 if erosion is chosen, or 150 if dilation is chosen.*

(a) Grayscale image *(b) Eroded image* *(c) Dilated image*

Fig. 12: Eroding and dilating an image. Eroding expands dark areas and dilation expands bright areas. This example uses a 7x7 kernel.

Unlike thresholding we cannot apply erosion or dilation to RGB images due to the nature of RGB values. Imagine the clear colors, red (255,0,0), green (0,255,0) and blue(0,0,255) - in this case we cannot argue which color is *greater* or *smaller* than the other. We can with grayscale and binary images since we can safely say that the pixel value 150 is smaller than 255, and 0 is smaller than 1. In summary, we have presented techniques to make ants much clearer in an image with a lot of noise, that might prevent us from properly finding an ant.

Contrast and Brightness

Where dilation and erosion sought to expand either dark or bright areas, contrast and brightness seek to change the overall brightness or darkness of an image or the absolute difference between dark and bright pixels. This can make it easier to find an ant in an image where the image is either too bright, or too dark.

To increase the absolute difference between two pixels, or increase the *contrast* of the image, each pixel in an image is multiplied with the same scalar, denoted

α. Since images are matrices this method is equal to *scalar multiplication* shown in Equation 8.

$$\alpha \times \begin{bmatrix} a & b & c \\ d & e & f \\ g & h & i \end{bmatrix} = \begin{bmatrix} \alpha \times a & \alpha \times b & \alpha \times c \\ \alpha \times d & \alpha \times e & \alpha \times f \\ \alpha \times g & \alpha \times h & \alpha \times i \end{bmatrix} \tag{8}$$

To increase the brightness, a scalar is added to each pixel, denoted β. This way the absolute difference between each pixel is kept, however all pixels get darker or brighter depending on the scalar. Similar to contrast this operation is equal to *scalar addition* as shown in Equation 9. To make the pixels brighter a positive scalar is added, to make it darker a negative scalar is added. Figure 13 shows the result of contrasting and increasing the brightness of an image. Contrast and brightness are used to make dark, bright and diffuse images easier to analyze. In summary, contrast and brightness can help improve the image quality, making it much easier to find an ant, or distinguish it from other parts of the image.

$$\beta + \begin{bmatrix} a & b & c \\ d & e & f \\ g & h & i \end{bmatrix} = \begin{bmatrix} \beta + a & \beta + b & \beta + c \\ \beta + d & \beta + e & \beta + f \\ \beta + g & \beta + h & \beta + i \end{bmatrix} \tag{9}$$

(a) Source image *(b) Brightened image* *(c) Contrasted image*

Fig. 13: Example of increasing the contrast and brigtness of an image. For this example $\alpha = 5$ *and* $\beta = 100$

Image Segmentation

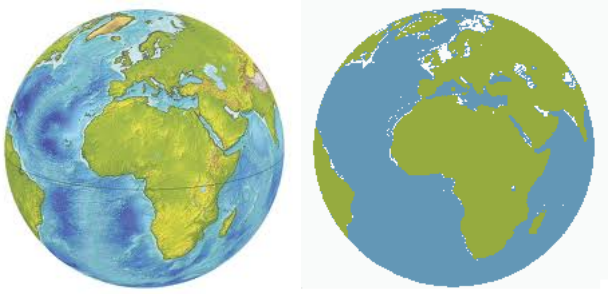
Image segmentation is the process of partitioning all the pixels in an image into S segments (or superpixels). The goal is to simplify or change the representation of an image such that it is easier to analyze. It is mostly used to locate objects that consist of a range of similar colors, that is combined into a single colored object after segmentation, thus making it easier to find [8]. Image segmentation is therefore the process of assigning a label to a pixel, such that pixels with the same label share certain visual characteristics. The result of image segmentation is a set of segments that covers the entire image. Thresholding, as described earlier, is the simplest method of segmenting an image. This can be an important

technique in finding the ant, should thresholding alone not be enough.

One of the most common algorithms to segment images is the *k-means* algorithm [9]. K-means is a *clustering algorithm* often used in *datamining*. K-means takes a set of unclassified data, and classifies it. It does so by assigning all the data to K different clusters, and iteratively assign each element to the cluster it is most similar to after new *centroids* have been assigned or created. The algorithm terminates when data no longer changes clusters or a predefined number of iterations have completed. Even though more robust classification algorithms exist, *k-means* is often used simply because each iteration is relatively fast. The algorithm works as follows:

1. Randomly select k objects in the dataset D, which initially represents the centroid for each cluster.
2. Each object in D, is then assigned to the centroid it is most similar to.
3. For each cluster, it computes a new centroid from the previously assigned object and repeats step 2.
4. If all clusters are unchanged between two iterations, the algorithm terminates.

An example of using k-means to cluster an image is shown in Figure 14. In summary, image segmentation provides a powerful way to easily simplify an image, which can make ant detection easier.



(a) Source image *(b) Segmented image*

Fig. 14: Example of segmenting an image. In this example the number of clusters specified is 3.

Background subtraction

Background subtraction (also known as foreground detection) is a process often used to detect moving objects with a static camera [8]. The idea is that the background remains roughly the same in every image in a video stream, while moving objects enter and leave the stream shortly after, or become part of the

background after some time have passed. The rationale is to have a background image (or reference point) and then subtract the image with the new object in it. This technique can be useful for tracking a moving ant, assuming the background remains roughly the same in the test setup. Computing the difference between the foreground and background will result in an image with only the moving object in it, that can be used for analysis. The absolute difference is computed almost like a standard *matrix subtraction* as shown in Equation 10. An example of background subtraction is shown in Figure 15.

$$\begin{bmatrix} a & b \\ c & d \end{bmatrix} - \begin{bmatrix} e & f \\ g & h \end{bmatrix} = \begin{bmatrix} abs(a-e) & abs(b-f) \\ abs(c-g) & abs(d-h) \end{bmatrix} \tag{10}$$

(a) Background image *(b) Foreground image* *(c) Object detection*

Fig. 15: Example of detecting a new object on a static background. In this example all differences greater than zero is set to 255.

2.2.2 Computer Vision Framework

The theory behind computer vision techniques is solid. However to track an ant in an image, theory and implementation is not enough. We have to keep in mind that we must locate the ant in several consecutive images, without delaying the entire process, allowing the ant to escape the camera. Therefore efficiency is a key aspect as well. Choosing an efficient framework to help us track ants is therefore of utmost importance. OpenCV is such a framework.

OpenCV is short for Open Computer Vision, and is an open source project started in 1999 and since maintained by Intel. It is written in C and C++ and runs on Linux, Windows and Mac OS X. OpenCV was designed from the beginning to be computationally efficient with a strong focus on real-time applications. Another goal is to provide a simple-to-use computer vision infrastructure. Since its initial creation, OpenCV has matured gradually, and along with it computer vision as well. Today, OpenCV and computer vision is used in a broad context from web applications to surveillance and aerial street maps.

Other computer vision frameworks exist but are limited on several parameters. As stated in the requirements, tracking had to be done in C/C++ which rules

out frameworks for higher level languages such as PyCVF for Python, imageJ for Java and OpenClooVision for C#. Furthermore several frameworks exist that extends OpenCV or creates a simpler abstraction layer such as SimpleCV and other frameworks offer a very limited amount of features such as VisionBlocks. As a result OpenCV was chosen to be the framework of choice, both because of maturity and efficiency, but also because of the amount of computer vision features offered to its users.

2.2.3 Realization

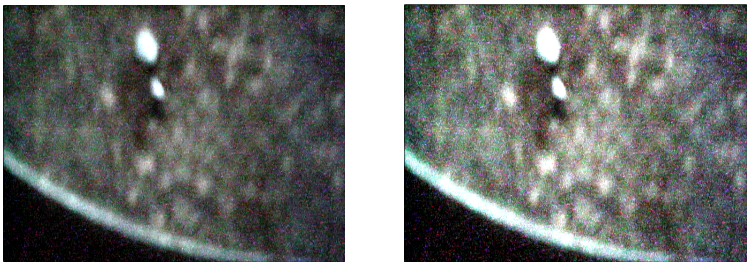
Having presented several computer vision techniques and the framework used, this section will focus on applying these techniques in a real world scenario to find an ant within an image from a webcam. To be able to track the ant of interest and make it distinguishable from other ants, we will paint it with a color that is easier to detect than the ant itself. We want to track the ants on real dirt, and not just an opaque background, and the ant available are either dark brown or black (as seen in image *a* in Figure 2) closely resembling dirt in their native environment. It is therefore important to choose a color that is easy to detect on such material. For this reason we have chosen white paint.

The image in Figure 16 will be used as a reference point when showing how a certain computer vision technique performs in locating the ant.

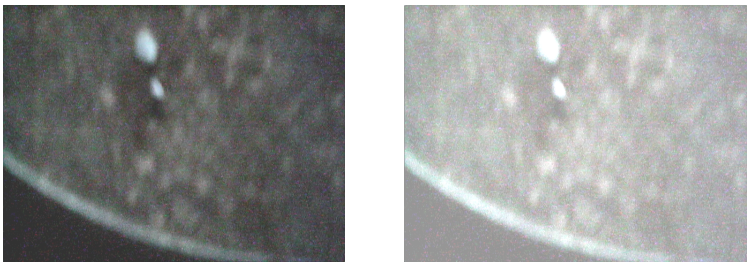
Fig. 16: Unprocessed image of an ant.

It is evident from the image in Figure 16, that the overall image is very dark. The ant itself is very hard to see, and even the white areas are dark. A way to improve this is to use the theory of *Contrast and Brightness*(Found in Section 2.2.1) to improve the lighting condition of the image. Figure 17 shows the result of applying contrast or brightness to Figure 16.

It is clear from Figure 17 that image *c* and *d* does not provide the best result. Even though the image is indeed brightened, differentiating between the ant and the background has not become much easier. Whether image *a* or *b* provides the



(a) $\alpha = 2$ *(b)* $\alpha = 3$



(c) $\beta = 50$ *(d)* $\beta = 150$

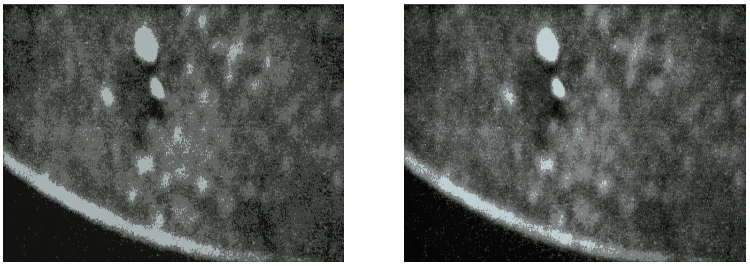
*Fig. 17: Applying brightness(*c *and* d*) or contrast(*a *and* b*) to the ant image.*

best result comes down to what we want the most - that the object we look for is as close to clear white as possible, or that it is the most distinguishable object in the image. In general, it is better for colors to be distinguishable than trying to make them match a specific color intensity. The result of image *a* is therefore preferable.

Now that we have improved the overall quality of the image, the next task is to isolate the ant in the improved image. For this task we have three techniques available; *thresholding*, *image segmentation* and *background subtraction*. Background subtraction requires that the background in any two compared frames are close to equal. Since the mobile camera is moving during tracking, this technique is not optimal. This leaves us with image segmentation and thresholding.

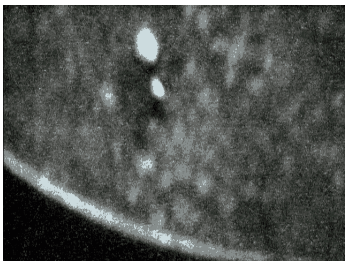
Figure 18 shows examples of running image segmentation with different numbers of segments, K, defined on image *a* from Figure 17. It is clear from these tests that a certain number of segments are neccessary to give a satisfactory result. $K = 8$ and $K = 10$ clearly gives the best results, however it comes at a cost; segmenting these images simply takes too much time for the camera to keep up with the ant. Even with only one segmentation attempt for each image, it takes around one second or more to produce a result. Considering this needs to be done *multiple* times within a second when using a live camera feed, this solution is simply not feasible or possible for tracking. An ant can easily move out of a

frame, simply because it is too slow or the ant is too fast.

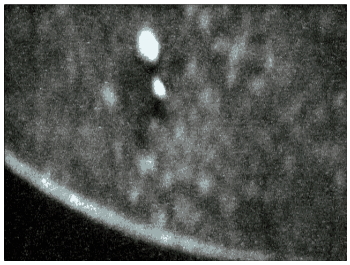


(a) K = 4

(b) K = 6



(c) K = 8



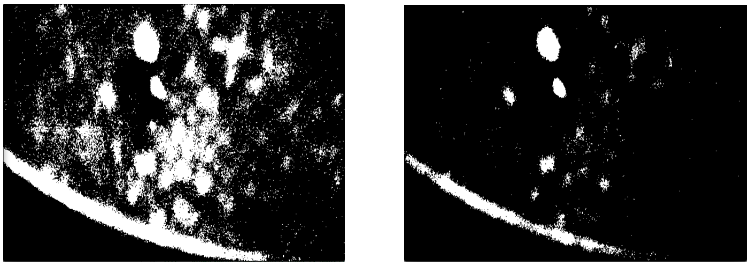
(d) K = 10

Fig. 18: Segmenting the ant image.

This leaves us with only one option; thresholding. Figure 19 shows thresholding attempts on a grayscale version of image *a* from Figure 17. The results of different thresholds shows two things; firstly that image *d* is a good threshold result and secondly that we need a rather high threshold value to get it. In contrast to segmentation, applying a threshold to our image is much faster and is usable with a mobile camera.

Now that we have a satisfactory binary image that clearly shows the position of the ant, the next step is to actually get the position of the ant within the image. For this purpose we use *blob detection*. In short, blob detection is a computer vision technique encapsulating mathematical methods that are aimed at detecting regions in a digital image. These regions can differ in properties such as brightness and color from the regions surrounding it. Where segmentation seeks to partition an image, blob detection seek to extract the partitions. All the pixels in a blob are considered to share similar properties.

The binary image *d* from Figure 19 clearly shows that we have two blobs available, that are rather large. This is of course ideal, but we might also have cases



(a) T = 100 *(b) T = 150*

(c) T = 200 *(d) T = 240*

Fig. 19: Thresholding the ant image.

where we have smaller blobs caused by reflections of the dirt or water. Therefore it is not enough to extract all blobs from the image and use the first one - we should always use the largest blob available in the image, which hopefully, is our ant. The result of finding the largest blob in our binary image is shown in Figure 20.

(a)
Detected blob drawn on binary image

(b)
Detected blob drawn on original image

Fig. 20: Final result of finding the ant in our image. The detected blob is found on both the thresholded image and the original ant image.

Concluding this chapter we summarize the process of going from a raw image input to a successfully detected ant, based on both the choices and experiments from this chapter. The process is as follows:

1. Increase the contrast of the raw image with an α value of at least 2.0.
2. Convert the contrasted image to grayscale.
3. Threshold the grayscale image with a threshold value of at least 240.
4. Run blob detection on the thresholded image.
5. Output the largest blob from the blob detection on the original image.

2.2.4 Optimizing the Realized Solution on Windows

During development we observed strange behavior with the OpenCV implementation. On OS X processing a single image took between 28 and 32 ms, however the same code performed much worse on our Windows test machine. This is strange considering that the computer running OS X has much older and much slower hardware than the Windows machine. In comparison, processing the same image on Windows, with the same implementation took between 200 and 300 ms and sometimes close to 500 ms for a single image. We ran several tests to find out why, and even when comparing the OpenCV installations we found no difference in what features were enabled and disabled. We also tested the implementation on another Windows machine with more powerful hardware, but the behavior was the same. To solve the problem we tried two things:

1. Compile the OpenCV source using CMake [10], instead of using the precompiled binaries available at the OpenCV download page.
2. Use the OpenCV CUDA [11] Graphical Processing Unit (GPU) module that can be used to optimize image processing on computers with NVidia GPU's.

After compiling the OpenCV source code on the machine where it should be used, we found no difference in performance at all. We therefore changed the implementation to use the enabled GPU module and moved some of the processing to the GPU. This greatly improved the performance. Processing time went down to a stable 27-30 ms on our test machine, allowing us to do processing in real time. We cannot say why Windows performs differently than OS X, however this is a satisfactory solution to the problem.

In conclusion we were able to use OpenCV to locate an ant in a frame using thresholding, contrasting and blob detection. The processing time of this were optimized using the OpenCV CUDA GPU module and enabled us to use this method in realtime when tracking an ant.

3 Camera and Plotter Integration

In Section 2.2, we introduced the theory and solution to the problem af locating ants in images. In this section, we describe how the PC, plotter and cameras cooperate, how we get our hands on a frame to process and how we use the techniques from Section 2.2 to turn a plotter, two standard web cameras and a PC into a tracking device.

3.1 Setup

The system as a whole contains four components:

- Hewlett Packard 7046A X-Y Recorder (An XY-plotter).
- Printed Circuit Board (PCB).
- Gigaware Web Camera 640x480 pixels (overhead camera).
- Pico iCubie Web Camera 640x480 pixels (mobile camera).

3.1.1 Plotter

The plotter is a 45x45cm table with a mechanical control panel on the side (see Figure 1). The plotter has a movable arm, moving along the X axis, consisting of a 30x3 cm metal bar that stretches all the way across the plotter table. On this, a piece of plastic is attached, able to move up and down the arm along the Y axis. Together, these units cover the entire area of the plotter table.

The control panel is divided into labeled regions with sets of controls to manipulate specific parts of the plotter. Specifically, there is a region with controls for adjusting the zero point of the X axis, one for the Y axis, one for power supply etc. Most important of these are the two buttons that is used to adjust the zero point (0,0), as the software will send only positive X and Y coordinates. Thus, the zero point must be located outside the area of the petri dish in order for the plotter arm to reach any possible location of the ant.

In order to connect the plotter to a PC, it provides an old-fashioned Line Print Terminal (LPT) parallel port interface. In this project, we use a printed circuit board (PCB) to convert between LPT and USB. The board has two diodes that will light up when signals arrive at the USB side of the board. One of them flashes green no matter what data is received, the other one toggles between blue and no light when *valid* data arrives. Together with a PC and an RS232 terminal like e.g. Termite [1], the diodes are useful for troubleshooting in case something is not working when running the tracking software.

3.1.2 Cameras

To track the ants present in the petri dish, the plotter is equipped with two low resolution standard web cameras connected directly to the PC through USB. One of the cameras is strapped on a piece of hard plastic holding the lens face-down, thus monitoring most of the plotter table from a height of approximately 30 cm. This camera is referred to as the overhead camera and is supposed to provide the user with the big overview, as well as a canvas to draw statistical overlays on, like heatmaps, the route of the ant etc. The second camera is mounted directly on the plotter arm and follows the ant as it moves around in the petri dish. We will refer to this camera as the mobile camera.

Both cameras have a resolution of 640x480 pixels (less than 1 megapixel) as opposed to modern digital cameras with a resolution of more than 15 megapixels. Choosing relatively low resolution cameras has been a deliberate decision, as processing is done on a per-frame basis, meaning there is good reason to believe that a higher pixel density would increase processing time and thus prevent the camera from keeping up with the ant. On the other hand, the resolution should be high enough for the software to be able to identify the ant and/or the painted marker on its body.

Another performance indicator for the mobile camera is the amount of frames it is able to record per second (FPS). To be able to maintain a stable tracking process, it is a key property that the ant is present in any two consecutive frames recorded by the camera. If this property is not held, it means that the ant is ahead of the camera, and the plotter will need to initiate a special procedure to relocate the ant. The camera needs at least as many FPS as needed for this to hold. On the other hand, more frames means more processing, which is also not good, but as long as the image quality is modestly low, this should not be a problem. Special techniques have been used to improve processing time, which we discussed in Section 2.2.4. The specific mobile camera that was used in this project has a suitable quality, but could use a higher FPS value.

It should be noted that the plotter is not new; the internal mechanics are sensitive and will some times cause the arm to do a fast wiggle. The effect of this is similar to taking a picture of a moving object with a DSLR camera whose shutter time is too large. The frame will be blurred and the pixels will "drag lines" (as shown in Figure 24 *d*) that may introduce blobs similar to the one representing the ant. Thus, the plotter is in danger of being biased in a wrong direction and lose track of the ant. This problem is also likely to be reduced by using a camera with a larger FPS rate - or a better plotter.

3.2 Communication with Plotter

In order to manipulate the plotter, we made a high level C++ API offering instructions like "Go to coordinate (x, y)", "move 10 units to the left" etc. Since the coordinate system axes of the plotter and the mobile camera grows in different directions, such an API is convenient to have in order to construct the logic that moves the camera when the ant leaves the center of the frame.

In order to implement this API, we needed to know the hardware protocol of the plotter. The plotter accepts commands in the pattern given in Equation 11.

$$0x01 + xxxx + yyyy \tag{11}$$

In this format, *xxxx* and *yyyy* are two 4-digit hexadecimal numbers representing the X and Y part of the target coordinate. 0x01 indicates that we are sending a command. Thus the plotter can receive coordinates between (0x0000, 0x0000) and (0xFFFF, 0xFFFF), however, any coordinate larger than (0x384, 0x12C) corresponding to (900,300) lies outside the table area and will overflow and come back at zero.

To transmit the coordinates through the USB connection, we use a light weight open source C library [12]. This library is implemented directly on top of the operating system specific calls for manipulating I/O resources, thus treating the plotter like it was manipulating a file. The library contains procedures for opening and closing the connection as well as transferring data. When sending commands in the format of Equation 11, one should note that both the X and the Y part needs to be split in two parts of two hexadecimal numbers each.

Using this library, we developed a high level plotter interface that takes coordinates in decimal format and converts them to appropriate arrays that are sent to the PCB. Furthermore, we added functions for moving the camera relatively to its own position. We even experimented with a special procedure for moving the arm in a soft fashion, as an attempt to keep the camera steady during movements to avoid blurry frames as mentioned earlier. In order to move the plotter a certain number of units from A to B, instead of going all the way at once, this procedure would start by first taking a small step of 2 units, then 4, 6, 8 and so on until it reaches a maximum step length (and stop in the same way with decreasing steps). Perhaps unsurprisingly, this did not solve much as the plotter can only move with one speed and will start and stop abruptly. However, any step smaller than a few units will be completed too fast for the camera to blur the frames.

We were succesfully able to implement an interface for communication with the plotter, exposing commands to move the camera in a relative and aboslute manner. We were however not able to make the acceleration and deceleration of the camera any smoother than initially.

3.3 Moving the camera

Being able to move the plotter, the question remains of how to respond to changes in video frames. In the current version of the software, the plotter will stay centered above the ant. Conversely, this means that the ant should be found in the

center of the frame - if this is not the case then it is either not in the frame at all (in which case manual interaction is needed) or it is somewhere along the edges, in which case we need to move the camera. To move the camera, the software locates the center of the frame along with the pixel coordinates of the ant, calculates the pixel difference in each direction, translates the distances to plotter units, adds the result to the current position of the plotter and issues a new `goto` command to move the camera. Unless the distance is smaller than approximately five units, the camera will blur when it starts to move, so we skip two frames, trusting that the third frame will be steady. The choice of skipping two frames is chosen by experimentation.

In order to know how many units we need to adjust the plotter in each direction when the camera has identified the ant, we need a way to convert a pixel distance to a unit distance. When doing this conversion, we need to consider that:

- The conversion depends on the height of the mobile camera and should be adjusted whenever the height is changed.
- The distance of 1 unit in millimeters is different on the X and Y axes of the plotter. Thus, we need separate conversions for each.
- From the cameras point of view, "right" points towards zero on the Y axis, and "down" points towards zero on the X axis.

To make the conversion, we turned on the camera while it was mounted on the plotter. Next we layed out a sheet of graph paper under the camera and measured the distance of one frame width (640 pixels) and one frame height (480 pixels). Next we measured the distance of an arbitrary amount of units on the plotter. The rest of the conversion can be done with simple arithmetic.

Because we skip two frames, if the ant leaves the center, heads straight for one of the frame edges and turns 180 degrees immediately after the camera begins to move, it gets harder for the camera to follow along due to processing time issues as discussed in Section 2.2.4. This event happens, though it is rare, but it motivates a discussion of which technique to choose for moving the camera. We chose to keep the ant locked in the center of the frame, but other options exist. One strategy could be to adjust the camera when the ant gets closer than a certain distance to the frame edges. Another one could be to take a chance and assume that whenever the ant moves in a certain direction, it probably won't make any sharp turns right away (say, bigger than 90 degreees). Thus, one could give the camera a head start by moving it along a straight line, headed for the new location of the ant, but instead of stopping when the ant is back in place at the center of the frame, we could continue moving the camera so that the ant ends up on the opposite side of the center. Unless the assumption does not hold[1], this should keep the ant in scope of the camera for a few extra frames.

[1] To make such an assumption would propbably require a thorough analysis of ant behavior. Since the system we are building is intended to provide exactly that, this is slightly paradoxical but could potentially make the system able to improve itself!

We experimented with the strategy of moving the camera when the ant reached the edges of the frame but speed combined with frequently changing directions rendered the technique infeasible to use. It is possible that this situation would change if one modified the plotter and increased the height of the camera so it would cover a bigger area on the table. In that way the ant would stay in scope of the camera for a longer duration. We chose not to consider this option as keeping the ant in the center of the frame seemed to be relatively stable in the current setup.

3.4 Graphical user interface

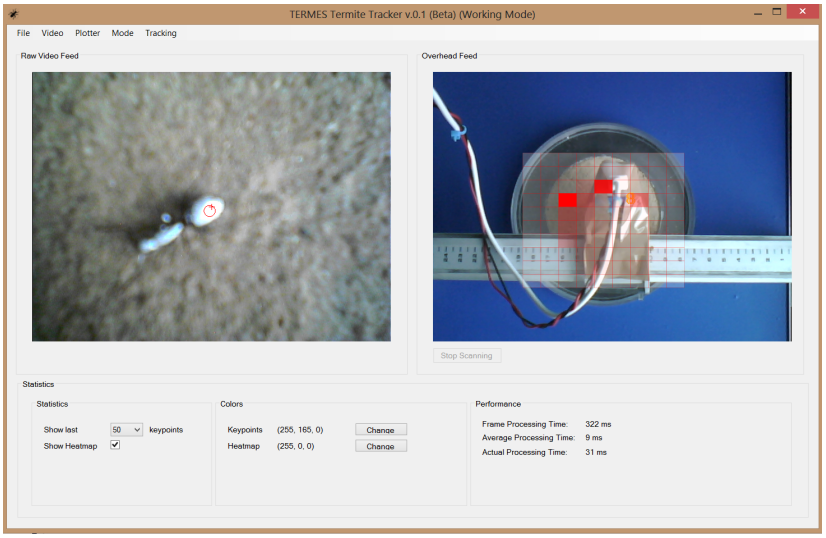


Fig. 21: GUI in tracking mode with heatmap statistic.

In order to use the system to track ants, we needed a user interface. The requirements for the user interface are the following:

- It should be able to show the camera feed from both the mobile and the overhead camera.
- It should be able to calibrate the system before initiating the tracking procedure.
- It should provide a way to gather statistics during the process of tracking.
- It should provide a set of controls to manipulate the plotter manually.

We chose to implement the GUI in Windows Forms using C# because it was a requirement that all software would run at least on Windows but preferably on other platforms as well. We experimented with a Swing GUI in Java, however

we experienced problems with calling into C++ code on Windows using Java Native Interface (JNI) [13] so we chose to switch to C# in order to save time.

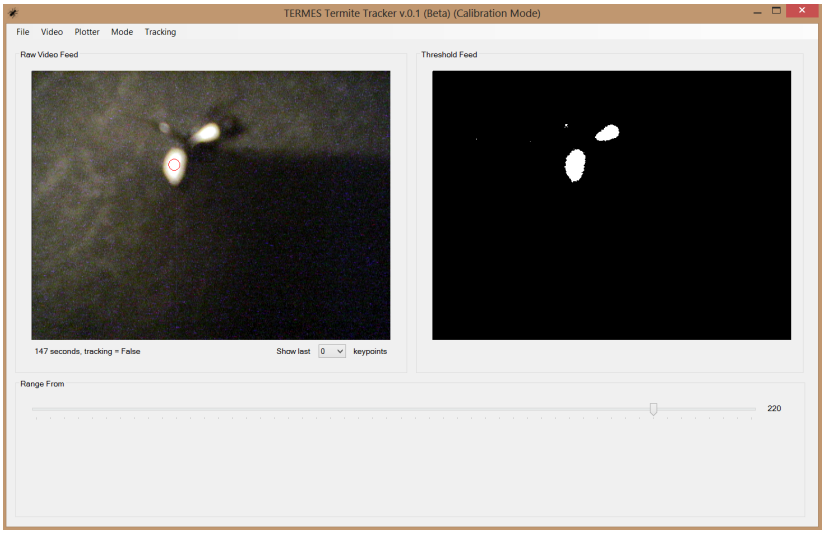


Fig. 22: GUI in calibration mode.

Furthermore, it is easy to integrate C++ code with .NET as no libraries like JNI are needed. All C++ logic is published as a DLL with an interface represented in the GUI. The GUI is shown in Figure 21 and Figure 22.

As seen from the figure, the GUI consists of a horizontal menu bar in the top, a video feed for the mobile camera on the left and a video feed for the overhead camera on the right. In the bottom, a panel is placed to display various statistics about the tracking process and the current performance of the system such as processing time, etc.

The GUI provides two modes - one for calibration and one for tracking. Switching between tracking and calibration mode is done through the `Mode` menu point in the top menu. When in calibration mode, the right camera feed will switch and show a thresholded version of the mobile view instead. Likewise, the lower panel will reveal a slider for setting the threshold value. Thresholding is one of the key techniques behind the tracking and the quality varies with the light and general surroundings of the camera, so it is important to be able to adjust it between and during sessions. The result of changing the threshold value is visible in real time in the right camera feed, thus, it is possible to stay in calibration mode while tracking.

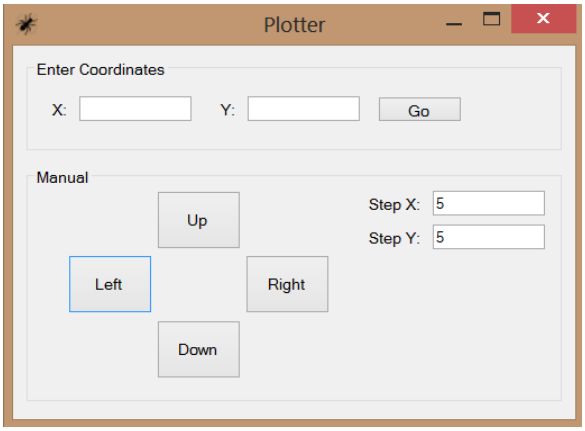


Fig. 23: Manual Steering.

Ideally, the camera should be located above the ant when setting the threshold value, as we are essentially telling the system how to identify the ant. To do this, open the manual steering panel by selecting `Manual Steering` from the plotter menu in the top bar. This panel provides controls similar to the arrow keys on a keyboard for manipulating the plotter. Using the keys and the camera feeds and provided that the ant is not moving too quickly, it is possible to adjust the plotter so the camera is located above the ant. This process might require leaving the ant in the freezer for a couple of minutes beforehand. By default, the plotter will move 5 units each time a button is clicked. This number can be adjusted for each axis individually by setting the textfields in the right side of the window. Alternatively, use the controls in the top of the window, as shown in Figure 23, to go directly to a specific coordinate.

When the camera is in place, return to the slider and adjust it until the ant is the largest white blob on screen. Ideally, the ant should be the only white object, but the system will look for the largest object so a reasonable amount of minor objects or noise are allowed to be visible as well.

When thresholding is in place, tracking is started by choosing `Start` under `Tracking` in the top menu. The camera will track the ant and show statistics in the panel until the user presses `Stop` or the ant is lost in the picture. In either case, the process can be repeated to start tracking again.

3.4.1 Statistics

One of the requirements to the GUI is that it is able to present relevant statistics to the user in a natural way. We chose to focus on the statistics that have a somewhat graphical presentation, we decided to implement the following statistics:

- The route of the ant.
- A heatmap.
- Performance indicators.

Since the purpose of the software is to enable users to track ants, it seems natural to provide a graphical view of the route. In the current version, when tracking is enabled, the user can choose to display the last x locations of the ant where x can be adjusted from the drop down menu in the statistics panel. Whenever a number greater than zero is chosen, the locations appear as small circles in the overhead frame. The color of the circles can be adjusted in the GUI as well.

The second statistic is a heatmap. The heatmap is visualized as a 2D array of rectangles drawn in the overhead frame. While the route statistic provides location information, the heatmap provides this information over time. When tracking is started, the program will capture the location of the ant, find the encapsulating rectangle and keep incrementing the intensity of the color in that rectangle until the ant enters a neighbouring rectangle. After a few minutes of tracking, the color intensities of the heatmap will reveal the preferred location of the ant during those minutes.

The three performance indicators that we provide are located in the lower statistics panel to the right. These indicate the overall performance of the system in terms of frame processing time, image processing time and average image processing time in milliseconds. Frame processing time indicates how much time is spent on each frame in total including image processing, updating statistics etc. Image processing time covers time spent exclusively on image processing. This includes thresholding, blob extraction, copying frames to and from the GPU etc. Average image processing is simply an average of time spent on image processing of frames. We believe these last statistics are useful especially for troubleshooting.

In order to be able to keep the results gathered from tracking, the program saves all statistics in a log file which is placed next to the programs executable file when the user stops the tracking in the GUI.

4 Testing and evaluation

4.1 Process

The development process in this project required more planning than usual because of the long distance collaboration with our counselor at Harvard University. This meant that we, at an early stage agreed on a time plan, a preliminary table of contents for the report and which tools we would use for communication and tracking of our progress.

For communication we used regular email, Skype and the Github [4] wiki and issue tracking system. Email allowed us to easily communicate with our counselor at Harvard University even when either part was too busy for a Skype meeting. It also helped to express the more formal questions about the project and the email correspondance was a good reference throughout the development of the solution and writing of this report. We made sure to update our counselors weekly via email to inform them on our progress and problems.

Skype enabled us to have face-to-face meetings several times in the project. A summary of each meeting was created on the wiki both for our own sake but also to make it easy for us, our counselor at ITU and our counselor at Harvard University to track our agreements and progress. The Skype meetings were more sparse than the email correspondance, since it was harder to agree on a time because of the time difference, and because they took more time which reduced the time spent coding. Since Danish culture is a low-context culture (defined by Halls [5]) Skype meetings were not greatly advantageous compared to pure email correspondance but it was nice to be able to discuss certain aspects. When a bundle of questions presented themselves at the same time it would save time to ask them in bulk. The fact that both we and our counselor at Harvard University shared the same culture (specifically work culture) made the collaboration quite a lot smoother. This made the expectations of work hours, work load and final product align more easily along with avoiding any confrontations as a result of surprising holdidays or customs etc.

The issue tracking system on Github was something we started out using but quickly abandoned. Since most of our work was done in the same location with all group members present the issue tracking system's primary function was to help our counselors track our progress easily. We quickly discovered that we were using a lot of time documenting these issues and that our counselors were satisfied with the weekly email update we provided.

In general we were satisfied with the tools we used. The combination of verbal and written communication provided us with good channels to fulfill our needs and we feel that all of our questions were answered in a satisfactory way. Additionally we feel that our tools have helped us to inform our counselors of our progress and problems along the process in a satisfactory way. The fact that

email is an asynchronus form of communication also helped us deal with the time difference between Copenhagen and Boston. We did not experience any problems with this.

The learning outcome of this project regarding the process has been mostly about when to change direction when encountering a technical roadblock. When we encountered problems using JNI and communication with the PCB we should have been quicker to search for alternate solutions or abandon the cross platform design. This could have given us more time to implement more features in the final solution instead of struggling with technical problems.

4.2 Testing the tracking software with real ants

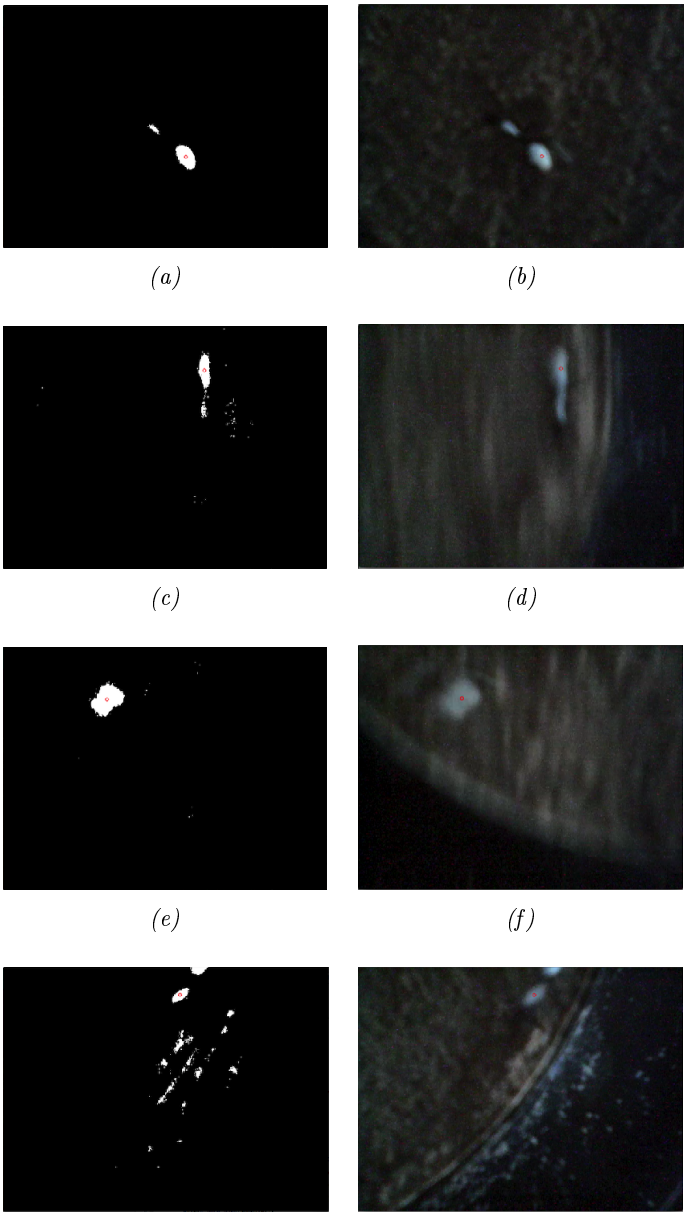
Having solved the problem of finding an ant in a single image and integrated our software with the XY-plotter and cameras, this section focuses on testing how the solution works with a video feed of an ant moving around in a controlled environment.

The goal of these tests, was to test ant tracking in an environment that was as close to a real environment as possible, but still controlled enough to be able to track the ant. The tests were performed in an ordinary office environment, with the plotter placed on a table. The room was only lit by daylight, and we used the setup explained in Section 3.1, with a petri dish filled with dirt surrounded by water, as can be seen in Figure 4. According to our experimentation described in Section 2.1 we painted our ant with a white color to have the best possible color for tracking.

In the following we will show several results of running the solution, both where the tracking works as intented, but also situations where the solution does not work. We will end this section with a summary of the challenges presented by this real time testing and suggest possible solutions to the problems and an overall evaluation of how the software together with the plotter and camera performs. We will also comment on the important observations made during testing.

We will begin by showing several images from the test where tracking works. Examples can be seen in Figure 24. We are showing both the final thresholded image, as well as the original image. For this test, we used the following values $\alpha = 2.0$ for contrasting and $T = 240$ for thresholding.

We can see from the images in Figure 24 that the software is able to handle different situations where a) the image is very blurry, b) there is noise in the thresholded image and c) the ant is clearly visible. In general, we can say that it is possible to track the ant in situations where it is distinguishable from anything else in the image, or when it is the largest object present after image processing. However our tests also showed that we were unable to track the ant when certain



(a) *(b)*

(c) *(d)*

(e) *(f)*

(g) *(h)*

Fig. 24: Examples of real time ant tracking.

conditions were met, as shown in Figure 25.

In image *b* and *d* in Figure 25, tracking fails because the ant is no longer the largest object in the thresholded images *a* and *c*. In image *b* it is because the dirt reflects too much light, and in image *d* it is because the water reflects too much light. One might wonder why, especially in image *c*, the ant is considered smaller than the reflection. This is because the blob detector in OpenCV, assumes blobs are *circular* and the size of a blob is actually the radius of that circle. Because the blob is lengthy but slim the radius of the circle surrounding the entire blob becomes very large, and as such the radius reported by the blob detector is so as well. This leads to the problem that our software interprets the water reflection to be the largest blob in the image.

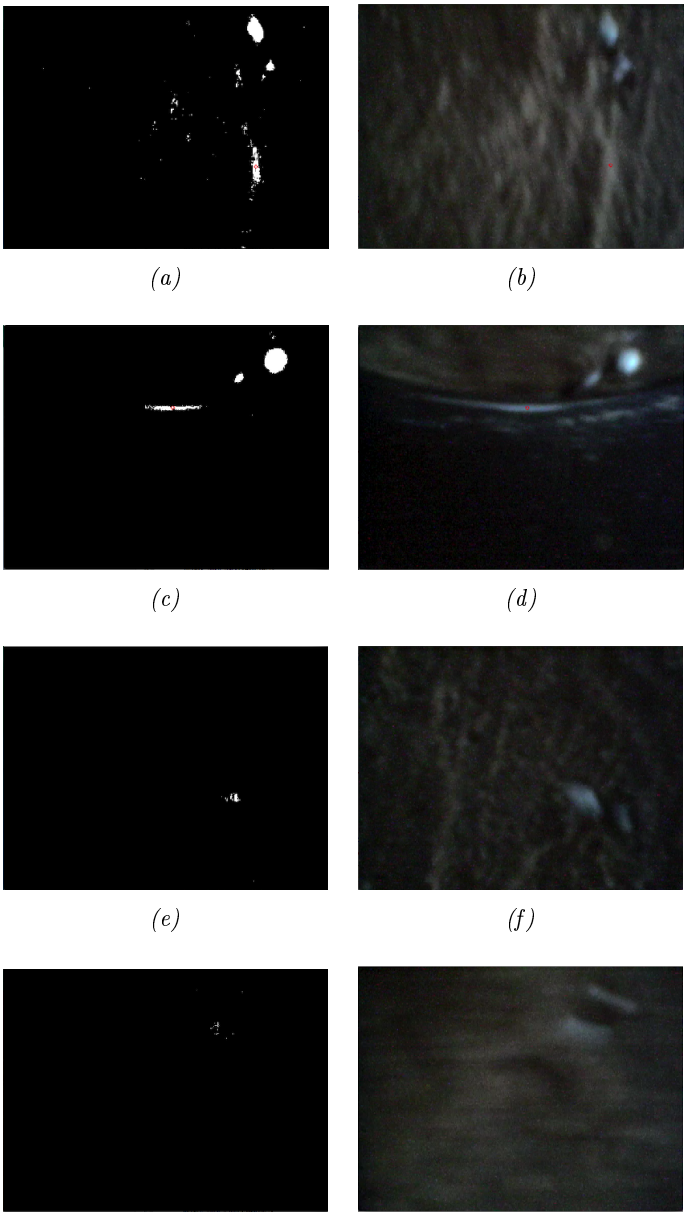
In image *f* the problem arises because the image is too dark. Even with the given contrast, most of the white color does not exceed the threshold boundary, and the pixels that makes it past the threshold is considered noise by the blob detector. In image *h* the image is simply too blurry (the ant is in the upper right corner), which makes both the ant and the white color "disappear" into the background.

In summary the problems found throughout our tests can be generalized to cover the following issues:

- Background reflections.
- Bad lighting of test area.
- Camera blurryness.
- Ant speed.

To solve the issues of background reflections and lighting conditions a lab environment could be established where there would be no daylight involved, and the entire test area lit by diffuse light. We tried using the two small diodes attached to the camera to improve the lighting conditions in the image, however the light was too bright making both the ant and dirt/water appear white in the image. A proper test environment would ensure both a much better lit ant, and possibly also a solution to track an ant using other colors than white. Furthermore, reflections would not be as apparent due to the lack of a strong single light source, and would further reduce shadows from the arm of the plotter.

During the tests we noticed that the ants moved very fast, and every so often they would move out of the cameras view in a second or two. Most of the time the camera could keep up with the ant, but because of the speed many of the images produced by the camera were very blurry, and at some point tracking would fail because the ant could not be located in the blurry images as shown in Figure 25. To solve this issue, one could use ants that moved slower, or move the camera further up from the petri dish, such that it did not have to move as much between every frame as in our case and capture a larger part of the petri



(a) *(b)*

(c) *(d)*

(e) *(f)*

(g) *(h)*

Fig. 25: Examples of tracking failues.

dish in each frame.

We do not know if termites move as fast as the ants available to us. If not, then they would be easier to monitor and follow with this setup. We also noticed that the increased speed of the ants were often triggered when they were frigthened. We noticed this when painting the ants, and releasing them into the test environment. They would however slow down over time.

During our test, the XY-plotter would stutter from time to time, making loud noises and shake the petri dish for a brief moment. This probably caused a frightened reaction with the ant, seing as it started to move very fast, escaping the camera due to blurry images.

Another observation is that the unpainted parts of the ant were almost never visible in the images (at least not to the human eye) and completely disappeared in blurry images, where the white color would still be visible. It is worth noting that this would really complicate tracking of *multiple ants* in the same frame if the others are not painted. If they were painted, this would also complicate the solution as the software would need to account for multiple colors at the same time.

We conducted five independent tracking tests, with a length of 5 minutes each. For the five different tests we measured how long we were unable to track the ant. The result of these tests is shown in the following:

Test 1: 00:40 minutes out of 05:00 minutes.
Test 2: 01:41 minutes out of 05:00 minutes.
Test 3: 02:54 minutes out of 05:00 minutes.
Test 4: 01:10 minutes out of 05:00 minutes.
Test 5: 01:22 minutes out of 05:00 minutes.

On average we were unable to track the ant for 01:34 minutes out of 05:00 minutes or 31.13% of the time..
In conclusion, we argue that the software itself works as intended, with only a few situations where it causes the tracking to fail. The failures can mostly be credited to a poor test setup, test environment, hardware difficulties and the animals themselves moving much faster than anticipated.

4.3 Threats to validity

4.3.1 Threats to internal validity

While we believe our results to be purely causal there are always some threats to internal validity that questions which factors could have an impact on the results. We describe the important ones here:

Behavior of the ants This project had a development period spanning six months. In this period the season changed and so did the temperature. The ants could have altered behavioral patterns, movement patterns and speed during the project essentially making the ants we tested during the last part of the project, behave completely different from the ants we started out with.

Painting We painted our first ant relatively early in the development process and the ants could have had some reaction to the paint. We did use acrylic paint as recommended by our counselor, and we did not observe any noticeable changes but it could still be present.

Hardware Getting the camera in the same start position every time is not something that can be done with 100% accuracy. The small margin of error during positioning might have had a miniscule impact on each tracking session.

Light As we tried to do all tests at the same time of day with the same types of light each time, it was very hard to keep the environment completely identical. Since light does have a significant impact on the tracking, this threat to validity might be the greatest, but it is also something that can be hard to control.

4.3.2 Threats to external validity

The outcome of this project is highly dependent on the environment around the hardware and the ants or termites. This makes it hard to replicate the results even with slight changes in things like light or camera resolution. This has the repercussion that while the software works in theory and in a controlled environment it is unlikely to work in the natural habitat of any ants or termites. The following list contains the environmental factors we consider to be important for the results:

Light The tracking relies on thresholded images which can be deteriorated by different levels of light that makes the tracking more inaccurate and more likely not to find the ant.

Reflections Keeping a lid on the petri dish or filling the outer rim of the petri dish with water, like described in Section 2.1, generates a lot of reflections. This is somewhat tied to the lighting factor and if the lights are positioned in such a way that the camera catches the reflections, it can deteriorate the thresholded image used for tracking.

Camera resolution The camera used had a low resolution of 640x480 pixels. While it could be nice to have a larger resolution, the low resolution enables us to process each frame fairly quickly. The threat to validity is mostly tied to performance. If a better camera is chosen one might need to skip more

frames or upgrade the connected PC since each frame will have a longer processing time.

Camera weight The camera attached to the plotter during our development and testing was very light. This made the plotter stutter less when it moved and thereby generated less noise. Both sudden movements and loud noises can have an effect on the movements of the ants and if the camera is exchanged for a heavier one, it could amplify the noise and thereby impact the movement of the ants further.

Movement of the ants In our testing phase we observed that whenever we placed an ant in our petri dish the first thing it would do would be trying to escape. It would immediately seek the edges of the dish regardless of whether we had the rim filled with water or not. If the petri dish was bigger or if the ant species was different this might not have been the case.

Temperature, wind and humidity Ants, like any other animals, react to temperature, wind and humidity. If any of these factors are changed it could impact how the ants move and how they behave which in turn can impact the tracking.

Ants and termites Ants are not termites. This fact is something of a gap in the testing and the results of the project. We did not have the opportunity to test the software with real African termites and therefore settled for ants. While our counselor assured us that they behave in a very similar way we do not have any data supporting that this project will work with real termites, only a strong indication that it should.

All in all we are quite certain that the outcome of this project can be quite hard to replicate. This makes the project more useful as a base for further development than an actual tool to take into the field in its current state.

4.4 Reflection

In this section we will discuss and reflect upon issues that we believe have had a potential influence on the outcome of the project. These include a discussion of how the situation would have looked if we could have removed the requirement of using a mobile camera and how the project could have benefitted from using a different plotter.

Using a mobile camera is a requirement because users would potentially like to be able to stimulate the ant using food or a pheromone stick attached to the camera. However, excluding this requirement, we have no reason to believe after this project that it should not be possible to reach the same goals using only the overhead camera. This would of course require an overhead camera with a suitable resolution and tests to verify that frames with the chosen resolution can be

processed in a satisfactory amount of time. The relation between the resolution of the current cameras and processing times leads us to believe that it would indeed be possible to increase resolution without increasing the processing time to an unacceptable level. However, it requires testing to know exactly how much.

On the positive side, using only an overhead camera would get rid of the mechanical wiggles that cause the frames to become blurry, remove sounds that might affect the behavior of the ant and remove shadows from the mobile camera on the plotter table. Furthermore, it will increase (but not remove) the upper bound we need to put on processing time per frame as there is no mobile camera to lose track of the ant between frames. With only an overhead camera, it would even be possible to do tracking based on video files instead of a live camera input and thus eliminate all bounds on processing time (because all frames could be recorded beforehand).

Ignoring reflections from the water could be a useful addition to the software. Whenever a blob would be detected, we could convert its pixel position to a camera coordinate, and based on this, measure the distance to the center of the petri dish. If the distance is greater than the radius of the petri dish the blob must be a reflection from the water and can be safely ignored. A corner case where this would fail is if the ant is close to the edge, causing the reflection to merge with the ant and create a single blob where ant and reflection is indistinguishable.

Reducing the sounds from the plotter is also something we could have achieved by exchanging the plotter for a different model. Choosing a different plotter would also open possibilities for choosing a better model that has smoother moving arms.

5 Conclusion

5.1 Related Work

TERMES: An Autonomous Robotic System for Three-Dimensional Collective Construction
Paper by Kirstin Petersen, Radhika Nagpal and Justin Werfel [6]. This paper presents a hardware system and high-level control scheme for autonomous construction of 3D structures. The hardware system consists of mobile autonomous robots and a collection of passive marked blocks. The general idea is to use swarm robotics to enable efficient construction even in extraterrestrial or disaster areas. The behavior of the robots is much like ants and termites in that sensing is entirely onboard and each robot acts independently of each other. Our contribution to the field can help enhance this project in the long run through analysis of the collaborational patterns of nature's own swarms: ants and termites. By analyzing how termites build their large hives one could potentially find a great way for swarm robots to collaborate when building structures.

Distributed Multi-Robot Algorithms for the TERMES 3D Collective Construction System
Paper by Kirstin Petersen, Radhika Nagpal and Justin Werfel [7]. This paper presents the algorithmic part of the TERMES 3D collective construction system described in the paper above [6]. It describes algorithms for autonomous robots to build 3D structures both alone and in collaboration with additional identical robots. Our contribution can potentially help enhance these algorithms. The movement of ants and termites could provide the key to better collaboration between the robots. Especially conflict resolution when two ants or termites need to occupy the same space on a path could be interesting to transfer into the robots' behavior.

5.2 Future Work

Because time was a limited resource for our team there were features we did not implement and ideas for additional functionality that could have been included. This section describes a short list of the possible extensions to the project we might have worked towards, were we given more time.

The first task would be to implement the optional requirements listed in Section 2.0.2. While some of these requirements are relatively easy to implement, given the right amount of time, some of them are more challenging. For example tracking multiple ants can be difficult unless all ants are marked, however this is something the current solution cannot solve.

When all optional requirements were fulfilled it could be beneficial to support multiple types of XY-plotters. The plotter we used was a little dated and being able to switch to another XY-plotter could be very practical. Of course this would also imply testing with a number of different plotters to see whether or not the same result could be reproduced. To support multiple plotters one could implement plotter control as an external API to make it easy for other applications to control the plotter.

One of the things we really wanted to do, but did not have the opportunity to, was to test with real termites. The solution was designed to be able to switch between different insects of different sizes and to test with real termites would be a strong indicator of how well this switch would work.

5.3 Project Conclusion

In this report we have presented software for tracking ants and termites in a controlled environment using the OpenCV computer vision framework and an HP 7046A XY-plotter. Additionally we have developed a GUI to control the tracking as well as extract statistics of the ants' and termites' movement. We have tested the software and found that we were unable to track the ant in 31.13% of the

time, and that the tracking works in most cases but still have a small amount of cases where it fails, mostly due to the testing environment.

We argue that although the project has potential for further development, it contributes to the field in general and has potential to help biologists analyze the behavior of termites in a more precise way than before. This analysis can in turn help the field of swarm robotics to develop better collaboration algorithms for robots in the future.

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