

# Room Mapping Using Motion Vectors

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## ABSTRACT

In our project we deal with how to build a 3D point cloud of a closed room using only a drone and a camera. We learned about two important algorithms for doing so: orb, which is relatively slow, and motion-vectors, which is computed using some special hardware which makes it very fast and light in calculation. Motion vectors describe the translation of a pixel from one frame to the next, and we claimed to use this sort of information along with other formulas to calculate the  $(x, y, z)$  of the point represented by this pixel as we will explain in this report.

In this project, we experimented a new path for the drone to take in order to scan the room, which is vertical rotations.

## THE COMPUTATION

The inverse camera matrix is a matrix that recovers the points with normalized z coordinate.

$$\begin{pmatrix} \hat{x} \\ \hat{y} \\ 1 \end{pmatrix} = \begin{pmatrix} 1 & 0 & -c_x \\ f_x & 1 & -c_y \\ 0 & f_y & 1 \end{pmatrix} \begin{pmatrix} x_p \\ y_p \\ 1 \end{pmatrix} = \begin{pmatrix} \frac{x_p - c_x}{f_x} \\ \frac{y_p - c_y}{f_y} \\ 1 \end{pmatrix}$$

Let  $d$  be the depth of the point, then

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} = d \begin{pmatrix} \hat{x} \\ \hat{y} \\ 1 \end{pmatrix}$$

Consider the representation of the same point in two different frames as shown in figure 1.

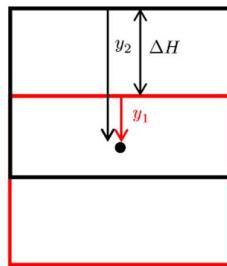


Figure1 : red frame is frame k-1, and black frame is frame k. we look at the y coordinate of the same point in two different frames, and calculate the depth using the distance

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Notice that:

$$\frac{\Delta H}{y_2} = \frac{y_2 - y_1}{y_2} = \frac{\hat{y}_2 - \hat{y}_1}{\hat{y}_2} = \frac{y_{p_2} - y_{p_1}}{f_y \hat{y}_2}$$

And therefore, we can conclude that:

$$d = \frac{\hat{y}_2}{y_2} = \frac{f_y \Delta H}{y_{p_2} - y_{p_1}} = f_y \frac{\Delta H}{\Delta y_p}$$

Therefore, we can conclude that:

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} = dC^{-1} \begin{pmatrix} x_p \\ y_p \\ 1 \end{pmatrix} = f_y \frac{\Delta H}{\Delta y_p} \begin{pmatrix} f_x & 0 & c_x \\ 0 & f_y & c_y \\ 0 & 0 & 1 \end{pmatrix}^{-1} \begin{pmatrix} x_p \\ y_p \\ 1 \end{pmatrix}$$

## INTIIAL ALGORITHM

We begin by defining what we can have from the drone. First of all, we have the motion vectors of each frame, meaning, we know where does every macro-block's center (of size  $16 \times 16$ ) moves in the next frame. We also have the height of each point frame, with accuracy of 10 cm. In addition, we are aware of the path, which is: rise, rotate  $60^\circ$ , fall, rotate  $60^\circ$ , rise again and so on until we scan the whole room. This means that we will convert each vertical movement into a cloud of points, and then rotate them according to their angle. Here is a pseudo-code of the algorithm we implemented in C++.

### Initial Mapping Algorithm

For each angle file,

1. For each frame in the file,
  - a. For each center  $c_p$  in the frame
    - i. If  $\Delta y_p = 0$ , ignore it.
    - ii. Else, add  $dC^{-1}c_p$  to the temporary cloud  $tmp$ .
  2. rotate  $tmp$  to the corresponding angle of the file around the axis  $\hat{y}$ .
  3. Concatenate  $tmp$  to the total cloud  $P$ .

## IMPROVEMENTS

### FPS Rate

One thing we noticed once we started working with the videos is that a high fps rate gives some very bad results. After debugging and looking directly at the data we realized that with a high fps, every movement is extremely decomposed into very small movements such that the motion vectors are mostly 0's. therefore we move to 10 fps which worked properly.

### Height Sensor Limitations

Our height sensor accuracy is limited to 10cm which made the results very discrete and not-obvious, besides making a lot of  $\Delta H = 0$ , meaning it cancels out points just because the height sensor didn't detect the change of height even though the camera did, so we looked at the

height function which seemed to be very linear if we ignore the sides of the function, thus we decided to first continuize the height function as follows.

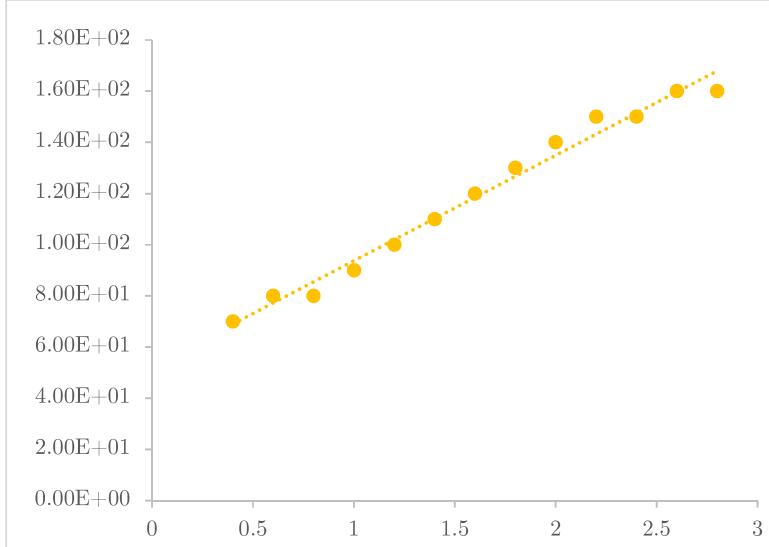


Figure 2: height function is almost linear

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### Continuation Algorithm

1. Set  $0 \rightarrow i$ .
2. Set  $0 \rightarrow j$ .
3. While  $i < heights.size$ 
  - a. While  $heights[i] = heights[j]$ , do  $i + 1 \rightarrow i$
  - b. Let  $\frac{hei_{[i]} - hei_{[j]}}{i - j} \rightarrow dif$
  - c. For  $j \leq k \leq i$ ,
    - i.  $heights[k] + dif \cdot (k - j) \rightarrow heights[k]$
  - d. set  $j = i$

and this way we have overcame the heights accuracy obstacle.

## Presenting the Results

### Depth Maps

We built depth maps which show how far a point is from the camera with the video playing in the background to recognize what points are problematic.

### OBJ Files

We built a "mesh model" in which each point is represented by a single triangle in the mesh model. This maybe wasn't the optimal choice, but it did work and help us use an interactive environment to represent the points without implementing a whole interactive mesh-viewer. We used Microsoft 3D builder, and Maya to show the mesh models, which was very easy and convenient to use and study the problems in our code and project in general.

### Matching y-Coordinate

Notice that the y-coordinates we get from the computation above is shifted, so we had to add the height of the frame to all y coordinates of the same frame.

## PRIMITIVE FILTERING POLICIES

Consider the results given by the above-described algorithm with all the above-mentioned improvements. We get the following results:

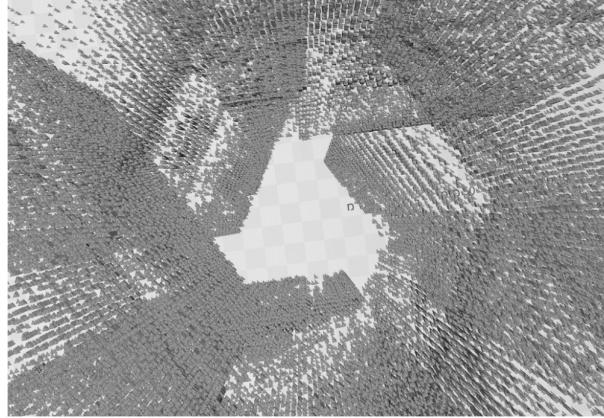


Figure 3: points we get from running the intial algorithm with the improvements

At first sight, this is incorrect, but actually, it is a correct map, just covered with a lot of outliers, thus our next part was to find policies to filter out outliers.

### 1. $\Delta x_p$ Filtering

We tried multiple  $\Delta x_p$  thresholds to filter out outliers, but they all failed.

### 2. SAD Filtering

SAD (Sum of Absolute Differences) is defined as the squared norm of the motion vector. We applied a binary search to find the "optimal" interval of SAD values to keep, which we found as [100,125], and gave the following results.

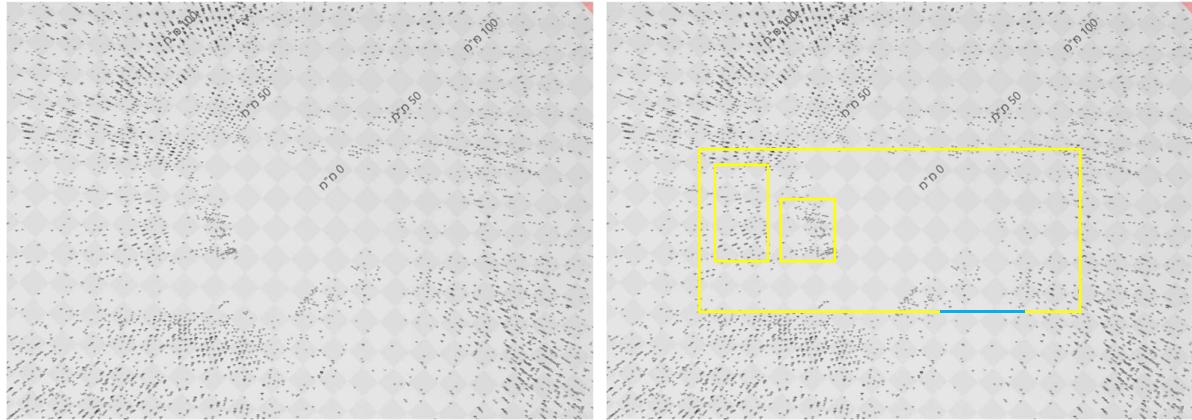


Figure 4: the results (left image), and how they should be interpreted. The yellow rectangles are a chair and a table that appeared in one of the videos.

## AVERAGE COLOR ALGORITHM

This algorithm aims to filtering the floor and white walls data using the block-average algorithm described below.

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## Average Color Algorithm

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For each macro-block  $y$  in the image:

1. sample 16 arbitrary (and not random) points, for instance, the diagonal of the macro-block.
2. Average their colors values: if  $c_1, \dots, c_{16} \in [255]^3$ , calculate  $\bar{c}_y = \frac{1}{16} \sum_{i=1}^{16} c_i$ .
3. If  $\frac{1}{8} \sum_{x \in \Gamma(y)} \|\bar{c}_x - \bar{c}_y\|_2 \leq f$ , where  $\Gamma(y)$  is all blocks adjacent (horizontally, diagonally, and vertically) to  $y$ , and  $f$  is some global constant, get rid of the point resulted by the center of  $y$ .

This is a useful filtering algorithm, since if two blocks have almost the same color average, meaning they're useless, the difference between their color-averages is very small, and therefore we get rid of them.

However, although the room maintains its shape, it loses lots of points, which makes it hard for us to see the shape of the room, and even harder for a computer to recognize. However, we can see that at the exit it is almost a clear area, which defines a tradeoff between how clear the room borders are and how clean the exit is.

Therefore, we could already see that the tradeoff we have is very extreme that we don't need to use the color average algorithm. Our explanation to this extreme tradeoff is that macro-blocks of the same color represent together an object, which is of some size. By applying our algorithm, we are only taking the "borders" of these objects, which makes it shallower and harder to recognize with a top-down view. Here are the results using this algorithm.



Figure 5: results of color-average algorithm

## MEDIAN COMPRESSING ALGORITHM

We begin by defining the algorithm which runs in  $\mathcal{O}(n \log n)$  time. We must mention that another group managed to get some very good results with it (using other tricks which we didn't implement since it's a whole another project) and therefore we wanted to implement it ourselves even though we had no time.

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## Median Compressing Algorithm

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1. Convert all points into polar representation with respect to the plane  $xz$ , and maintain the  $y$  coordinates, save this information into an array  $ps$ .
2. Build an array of buckets of size 360, and go over the points. Add each point with angle  $\theta$  into its corresponding bucket  $\lfloor \theta \rfloor$  with one linear scanning.
3. Remove all the points of with height  $y \in \mathbb{R} \setminus [50, 150]$ .
4. For each bucket, add the points of  $[5\%, 20\%]$  smallest radii in the bucket by sorting them in accordance to the radius.
5. Convert the points back to cartesian coordinates.

We got another tradeoff in the results. If we look at the radial line between the center and the wall on the left side of the picture, we can see that the desk hits this line, meaning it shares a bucket with the wall's points, thus taking a significant part of the  $[5\%, 20\%]$  smallest radii in the bucket, hence cancelling out the wall's points.



Figure 6: the results of 5-20% compression filtering algorithm, we can see a shallower room border.

## FINAL ALGORITHM

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### Final Mapping Algorithm

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For each angle file,

1. Continuize the height function using the algorithm above.
2. For each frame in the file,
  - a. For each center  $c_p$  in the frame
    - i. If  $\Delta y_p = 0$ , ignore it.
    - ii. If  $SAD \notin [100, 125]$ , ignore it.
    - iii. Else, add  $dC^{-1}c_p + (0, h, 0)$  to the temporary cloud  $tmp$ .
3. rotate  $tmp$  to the corresponding angle of the file around the axis  $\hat{y}$ .
4. Concatenate  $tmp$  to the total cloud  $P$ .

The running time of this algorithm is approximately one second on an average computer, thus approximately 10 seconds on an average drone micro-processor (particularly, raspberry-pi).

## FINAL RESULTS

The final results are satisfying. They are obviously not optimal and need more complex filtering policy, but we assume that by applying the median compressing algorithm we can achieve even better results. For the current time the best results we have are the results from the SAD filtering, which are the following.

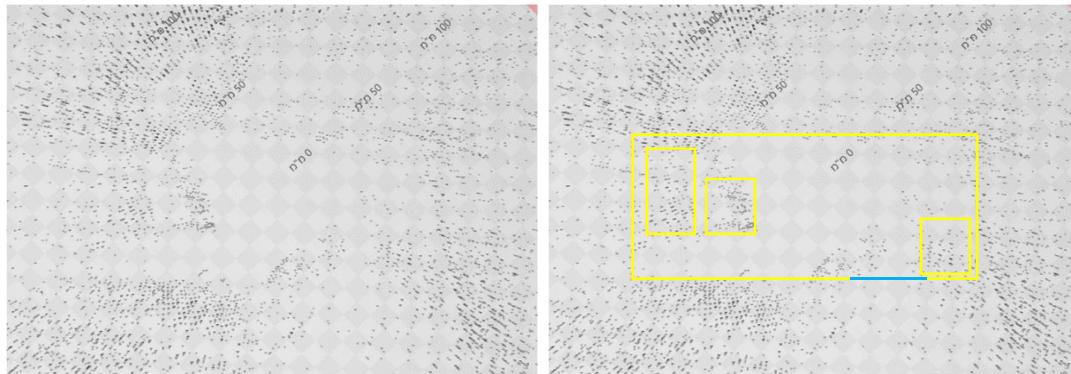


Figure 7: final results of our project for mapping the room.

We realized the "noise" on the entrance was not noise at all. By looking at the videos we can notice a chair next to the door, and a table on the other side, which made that much points next to the entrance, therefore we can conclude that the inner points cloud is correct and



Figure 8: objects located next to the entrance such as the chair, the shelves and the leader make the points which appeared to be noise, as shown in the presented frames from the videos before and after the entrance video ( $\pm 60^\circ$ )

works in a very good resolution, concluding that our project is a success.

## PROJECT SUMMARY

The project included multiple requirements of algorithmic, mathematical and geometric thinking, along with technical skills which we had to develop independently. We wrote our project in C++, while our instructor's language is python. We overcame the obstacle of how complex it is to build a C++ repository, link it with the needed libraries and download them, and eventually handling files just to start implementing algorithms. However, we managed to

achieve some very good results<sup>3</sup>, and paved the path for futuristic researchers and students to use C++ easily by following our instructions and tutorials we packed in our reports.

Additionally, we made sure to keep our code elegant, documented, and simple for a foreign reader to understand.

We can conclude our understanding of the results in the following points. On the positive side, we could see that our path is continuous and gives too much data, which makes it easier for us to deal with the data. Also, our path requires very simple calculations compared to other paths such as 360 up-down path where the mathematics went crazy. Additionally, we can notice that our model could recognize minor items like the desk, the chair, the leader, and others which according to our instructor were not recognizer before, which is a con and a pro of our model, since it could help not hit them, but they also made it harder for us to recognize the room's shape along with them being adjacent to the walls.

On the contrary, the path has a very noisy data which requires special filtering and made it harder for us to realize the results were actually correct. In addition, we had multiple representation of the same point since the intersection of multiple frames was not empty as was the case in the 360 up-down path, thus we got the same point multiple times, which made the picture a bit noisy. In total, we can conclude that our new path that we tried is not the ultimate solution to the room-mapping problem, but is a good trade-off to be taken into consideration for the future.

We must mention that as a continuation of our project, we sent the points cloud to our instructor for him to run smarter filtering algorithms which has been built by other teams, and check if it would work better than the filtering algorithms we have tried up until now.

## FUTURISTIC QUESTIONS

Can we use the data from some room to generalize the filtering policy to other rooms? And if so, what is the best model for learning this filtering policy? This sort of question cannot be solved using classical machine learning algorithms. Even with non-linear SVM, it would be at least very complex if not impossible to find the kernel that can make the features of the points  $(\Delta x, \Delta y, x, y, c)$  linearly separable, thus we will need some more complex model for this classification problem, for instance deep neural network whose final layer consists of the two neurons representing the answers "outlier" or "not outlier". Such a question requires more knowledge than we currently have, but can be left to futuristic research.

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<sup>3</sup> See the attachments to this file – data.obj, demo.mp4, code.zip, points.csv for further information on the results and the code: the mesh-model of the points, a demo of depth map, 3D cloud presentation and how the code works, and the code itself compressed into zip file, and the points cloud.