# Track an Object in 3D Space

## FP.1 Match 3D Objects

| | |
|---|---|
| Implement the method "matchBoundingBoxes", which takes as input both the previous and the current data frames and provides as output the ids of the matched regions of interest (i.e. the boxID property). Matches must be the ones with the highest number of keypoint correspondences. | Code is at camFusion_Student.cpp (lines 351:391). |

## FP.2 Compute Lidar-based TTC

| | |
|---|---|
| Compute the time-to-collision in second for all matched 3D objects using only Lidar measurements from the matched bounding boxes between current and previous frame. | computeTTCLidar function is at camFusion_Student.cpp (lines 321:348).<br><br>There are other helper functions called by computeTTCLidar as well. |

## FP.3 Associate Keypoint Correspondences with Bounding Boxes

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|---|---|
| Prepare the TTC computation based on camera measurements by associating keypoint correspondences to the bounding boxes which enclose them. All matches which satisfy this condition must be added to a vector in the respective bounding box. | clusterKptMatchesWithROI function is at camFusion_Student.cpp (lines 195:208). |

## FP.4 Compute Camera-based TTC

| | |
|---|---|
| Compute the time-to-collision in second for all matched 3D objects using only keypoint correspondences from the matched bounding boxes between current and previous frame. | computeTTCCamera function is at camFusion_Student.cpp (lines 212:273). |

## FP.5 Performance Evaluation 1

| | |
|---|---|
| Find examples where the TTC estimate of the Lidar sensor does not seem plausible. Describe your observations and provide a sound argumentation why you think this happened. | Pls see the sheet named “TTC_Lidar”<br><br>in the enclosed Excel file named “TTCLidar_TTCCamera_Performances.xlsx” |

| Frame (From/To) | Original Xmin values | | Xmin values after removing noise | | TTC LIDAR | Xmin Diff. (Original) | Xmin Diff. (After noise removal) |
|---|---|---|---|---|---|---|---|
| | Xmin prev. | Xmin curr. | Xmin prev. | Xmin curr. | | | |
| 1-2 | 7.97 | 7.91 | 8.05 | 7.98 | 12.28 | -0.06 | 0.06 |
| 2-3 | 7.91 | 7.85 | 7.98 | 7.92 | 13.20 | -0.06 | 0.06 |
| 3-4 | 7.85 | 7.79 | 7.92 | 7.87 | 17.12 | -0.06 | 0.05 |
| 4-5 | 7.79 | 7.68 | 7.87 | 7.80 | 10.54 | -0.11 | 0.07 |
| 5-6 | 7.68 | 7.64 | 7.80 | 7.77 | 26.80 | -0.04 | 0.03 |
| 6-7 | 7.64 | 7.58 | 7.77 | 7.73 | 18.85 | -0.06 | 0.04 |
| 7-8 | 7.58 | 7.55 | 7.73 | 7.68 | 15.36 | -0.03 | 0.05 |
| 8-9 | 7.55 | 7.47 | 7.68 | 7.61 | 10.87 | -0.08 | 0.07 |
| 9-10 | 7.47 | 7.43 | 7.61 | 7.56 | 13.74 | -0.04 | 0.06 |
| 10-11 | 7.43 | 7.39 | 7.56 | 7.47 | 8.49 | -0.04 | 0.09 |
| 11-12 | 7.39 | 7.20 | 7.47 | 7.41 | 13.00 | -0.19 | 0.06 |
| 12-13 | 7.20 | 7.27 | 7.41 | 7.33 | 9.65 | 0.07 | 0.08 |
| 13-14 | 7.27 | 7.19 | 7.33 | 7.24 | 7.87 | -0.08 | 0.09 |
| 14-15 | 7.19 | 7.13 | 7.24 | 7.17 | 10.40 | -0.06 | 0.07 |
| 15-16 | 7.13 | 7.04 | 7.17 | 7.10 | 9.86 | -0.09 | 0.07 |
| 16-17 | 7.04 | 6.83 | 7.10 | 7.02 | 8.78 | -0.21 | 0.08 |
| 17-18 | 6.83 | 6.90 | 7.02 | 6.95 | 9.79 | 0.07 | 0.07 |
| 18-19 | 6.90 | 6.81 | 6.95 | 6.87 | 8.48 | -0.09 | 0.08 |
| | | | | | 4.58 | | |

**hedey:**
In the pink highlighted cells, because of the relatively lower than normal difference between Xmin values (after noise removal), I doubt the corresponsding frames the most as the candidates for Lidar TTC inaccurate calculation. That's because I think the preceding vehicle was decelerating at a relatively steady rate.

**hedey:**
Regarding the Green Highlighted cells, which has abnormal Xmin difference values, the noise removal helped to bring the TTC Lidar calculation to be more accurate and avoid the effect of these abnormal differences.

| Frame (From/To) | Manually estimated Xmin values | | |
|---|---|---|---|
| | Xmin prev. | Xmin curr. | TTC |
| 1-2 | | | #DIV/0! |
| 2-3 | | | #DIV/0! |
| 3-4 | | | #DIV/0! |
| 4-5 | 7.80 | 7.76 | 19.40 |
| 5-6 | 7.68 | 7.64 | 19.10 |
| 6-7 | 7.64 | 7.60 | 19.00 |
| 7-8 | | | #DIV/0! |
| 8-9 | | | #DIV/0! |
| 9-10 | | | #DIV/0! |
| 10-11 | | | #DIV/0! |
| 11-12 | | | #DIV/0! |
| 12-13 | | | #DIV/0! |
| 13-14 | | | #DIV/0! |
| 14-15 | | | #DIV/0! |
| 15-16 | | | #DIV/0! |
| 16-17 | | | #DIV/0! |
| 17-18 | | | #DIV/0! |
| 18-19 | | | #DIV/0! |

These are the 3 examples that I estimated manually.

## FP.6 Performance Evaluation 2

| CRITERIA | MEETS SPECIFICATIONS |
| --- | --- |
| Run several detector / descriptor combinations and look at the differences in TTC estimation. Find out which methods perform best and also include several examples where camera-based TTC estimation is way off. As with Lidar, describe your observations again and also look into potential reasons. | Pls see the sheet named “TTC_Camera”<br>in the enclosed Excel file named “TTCLidar_TTCCamera_Performances.xlsx”<br>Based on my findings, I see that FAST and SHITOMASI are the best performing detectors.<br>Together with AKAZE, they have the 10 lowest TTC standard deviation values.<br>In my opinion AKAZE/AKAZE is the most consistent detector/descriptor combination.<br>It gave the most consistent illustration of how the preceding vehicle is steadily decelerating<br>from frame to frame.<br>ORB and HARRIS on the other hand gave unreliable results with lots of negative, inf,<br>and nan TTC values. |

| Detector | FAST | | | | | |
|---|---|---|---|---|---|---|
| Descriptor | BRISK | BRIEF | ORB | FREAK | AKAZE | SIFT |
| 1-2 | 12.11 | 11.14 | 11.47 | 11.08 | N/A | 11.06 |
| 2-3 | 12.23 | 10.60 | 10.55 | 11.06 | N/A | 11.20 |
| 3-4 | 12.90 | 12.74 | 12.40 | 11.30 | N/A | 13.68 |
| 4-5 | 12.63 | 12.87 | 12.88 | 13.30 | N/A | 12.72 |
| 5-6 | 16.97 | 15.05 | 15.12 | 15.77 | N/A | 18.76 |
| 6-7 | 13.04 | 12.67 | 12.46 | 12.04 | N/A | 12.70 |
| 7-8 | 11.43 | 11.78 | 11.29 | 12.04 | N/A | 12.06 |
| 8-9 | 11.09 | 12.21 | 11.53 | 10.86 | N/A | 13.74 |
| 9-10 | 11.86 | 12.00 | 11.71 | 11.11 | N/A | 12.02 |
| 10-11 | 13.15 | 12.51 | 13.42 | 12.58 | N/A | 13.66 |
| 11-12 | 12.38 | 14.45 | 13.18 | 11.70 | N/A | 14.22 |
| 12-13 | 11.53 | 10.83 | 11.71 | 12.00 | N/A | 10.91 |
| 13-14 | 11.71 | 11.79 | 12.44 | 11.56 | N/A | 12.32 |
| 14-15 | 11.35 | 11.11 | 10.68 | 11.31 | N/A | 11.14 |
| 15-16 | 10.77 | 10.52 | 9.90 | 10.21 | N/A | 10.77 |
| 16-17 | 11.93 | 11.25 | 10.69 | 10.87 | N/A | 11.49 |
| 17-18 | 9.14 | 7.49 | 9.29 | 7.15 | N/A | 7.87 |
| 18-19 | 11.28 | 9.47 | 11.01 | 10.18 | N/A | 10.69 |
| Standard Deviation | 1.50 | 1.67 | 1.35 | 1.62 | | 2.15 |

| Detector | BRISK | | | | | |
|---|---|---|---|---|---|---|
| Descriptor | BRISK | BRIEF | ORB | FREAK | AKAZE | SIFT |
| 1-2 | 12.39 | 11.70 | 11.24 | 10.76 | N/A | 12.32 |
| 2-3 | 19.76 | 16.59 | 17.61 | 23.80 | N/A | 14.10 |
| 3-4 | 11.12 | 11.57 | 11.30 | 13.18 | N/A | 14.60 |
| 4-5 | 13.78 | 20.16 | 13.98 | 13.19 | N/A | 10.84 |
| 5-6 | 19.14 | 18.33 | 17.35 | 20.39 | N/A | 22.44 |
| 6-7 | 15.77 | 13.66 | 17.32 | 12.90 | N/A | 11.34 |
| 7-8 | 15.48 | 14.67 | 14.44 | 13.38 | N/A | 12.72 |
| 8-9 | 15.37 | 17.08 | 14.86 | 16.05 | N/A | 14.62 |
| 9-10 | 13.96 | 15.19 | 14.74 | 13.97 | N/A | 15.50 |
| 10-11 | 12.29 | 10.99 | 10.25 | 13.23 | N/A | 13.03 |
| 11-12 | 11.92 | 12.77 | 12.99 | 11.97 | N/A | 12.85 |
| 12-13 | 10.70 | 12.70 | 11.37 | 10.82 | N/A | 10.03 |
| 13-14 | 11.20 | 11.94 | 11.03 | 11.34 | N/A | 12.65 |
| 14-15 | 11.62 | 10.25 | 11.22 | 10.94 | N/A | 9.90 |
| 15-16 | 12.07 | 10.55 | 11.16 | 12.60 | N/A | 11.79 |
| 16-17 | 10.77 | 10.28 | 10.11 | 9.40 | N/A | 10.39 |
| 17-18 | 9.18 | 10.77 | 9.21 | 8.86 | N/A | 8.94 |
| 18-19 | 9.92 | 9.38 | 9.72 | 10.59 | N/A | 11.36 |
| Standard Deviation | 2.89 | 3.02 | 2.66 | 3.61 | | 2.93 |

| Detector | ORB | | | | | |
|---|---|---|---|---|---|---|
| Descriptor | BRISK | BRIEF | ORB | FREAK | AKAZE | SIFT |
| 1-2 | 14.31 | 20.18 | 18.77 | 12.18 | N/A | 14.31 |
| 2-3 | 11.25 | 34.24 | 9.65 | 20.12 | N/A | 10.52 |
| 3-4 | 12.12 | 81.34 | 14.24 | 12.03 | N/A | 10.94 |
| 4-5 | 26.68 | 15.12 | 17.47 | 10.94 | N/A | 293.96 |
| 5-6 | 32.55 | 22.81 | 12.65 | 67.96 | N/A | 21.34 |
| 6-7 | 11.11 | 15.13 | 12.50 | 11.54 | N/A | 20.22 |
| 7-8 | 15.96 | 13.04 | 174.77 | 127.59 | N/A | 12.72 |
| 8-9 | 10.31 | 24.85 | 10.07 | 8.96 | N/A | 8.80 |
| 9-10 | 12.87 | 70.71 | 13.09 | 13.33 | N/A | 11.60 |
| 10-11 | 19.47 | 11.40 | 15.29 | -272.52 | N/A | 10.01 |
| 11-12 | 7.86 | 14.53 | 8.29 | 7.25 | N/A | 9.20 |
| 12-13 | -inf | 14.12 | 26.04 | 47.57 | N/A | -inf |
| 13-14 | 9.26 | 13.04 | 9.48 | 6.62 | N/A | 9.45 |
| 14-15 | 7.85 | 9.71 | 9.63 | 57.39 | N/A | 13.72 |
| 15-16 | 8.73 | 8.94 | 9.26 | 8.61 | N/A | 11.28 |
| 16-17 | 13.38 | 8.97 | 8.87 | 9.34 | N/A | 9.54 |
| 17-18 | 11.32 | 11.18 | 6.66 | 11.32 | N/A | 17.23 |
| 18-19 | 28.04 | 11.37 | 18.52 | 7.52 | N/A | 7.83 |
| Standard Deviation | 7.82 | 20.09 | 37.36 | 74.84 | | 64.83 |

| Detector | AKAZE | | | | | | TTC |
|---|---|---|---|---|---|---|---|
| Descriptor | BRISK | BRIEF | ORB | FREAK | AKAZE | SIFT | LIDAR |
| 1-2 | 11.74 | 13.08 | 12.14 | 11.94 | 12.14 | 12.26 | 12.28 |
| 2-3 | 15.13 | 14.69 | 14.12 | 13.74 | 13.57 | 14.11 | 13.20 |
| 3-4 | 12.58 | 13.32 | 12.93 | 13.79 | 12.69 | 12.98 | 17.12 |
| 4-5 | 14.38 | 13.82 | 13.51 | 13.99 | 14.22 | 14.22 | 10.54 |
| 5-6 | 14.17 | 14.11 | 14.85 | 15.03 | 14.21 | 15.05 | 26.80 |
| 6-7 | 13.32 | 13.64 | 13.52 | 13.20 | 13.20 | 12.99 | 18.85 |
| 7-8 | 15.64 | 15.88 | 15.44 | 14.97 | 14.92 | 15.39 | 15.36 |
| 8-9 | 13.66 | 14.18 | 14.07 | 13.56 | 13.99 | 13.74 | 10.87 |
| 9-10 | 13.08 | 13.29 | 12.86 | 12.88 | 13.30 | 13.96 | 13.74 |
| 10-11 | 11.88 | 11.64 | 11.62 | 11.79 | 11.60 | 11.64 | 8.49 |
| 11-12 | 11.84 | 12.38 | 11.89 | 11.51 | 12.05 | 11.99 | 13.00 |
| 12-13 | 10.37 | 11.57 | 11.32 | 10.77 | 10.40 | 10.95 | 9.65 |
| 13-14 | 9.92 | 9.94 | 9.98 | 10.86 | 11.08 | 10.86 | 7.87 |
| 14-15 | 9.70 | 9.43 | 9.66 | 9.14 | 10.05 | 9.96 | 10.40 |
| 15-16 | 9.53 | 9.12 | 9.43 | 9.63 | 9.68 | 9.52 | 9.86 |
| 16-17 | 10.24 | 9.67 | 9.67 | 10.28 | 9.45 | 9.66 | 8.78 |
| 17-18 | 9.48 | 9.09 | 8.83 | 8.71 | 8.87 | 8.99 | 9.79 |
| 18-19 | 8.77 | 8.96 | 8.87 | 8.59 | 8.74 | 8.73 | 8.48 |
| Standard Deviation | 2.08 | 2.17 | 2.07 | 2.04 | **1.94** | 2.07 | 4.58 |

| Detector | SHITOMASI | | | | | |
|---|---|---|---|---|---|---|
| Descriptor | BRISK | BRIEF | ORB | FREAK | AKAZE | SIFT |
| 1-2 | 13.05 | 12.95 | 13.18 | 12.85 | N/A | 12.99 |
| 2-3 | 12.72 | 12.84 | 12.10 | 11.87 | N/A | 12.42 |
| 3-4 | 12.88 | 11.00 | 10.35 | 10.09 | N/A | 10.05 |
| 4-5 | 12.40 | 12.53 | 11.63 | 12.44 | N/A | 12.67 |
| 5-6 | 12.35 | 10.98 | 11.92 | 11.45 | N/A | 12.28 |
| 6-7 | 12.49 | 11.75 | 12.51 | 12.51 | N/A | 12.35 |
| 7-8 | 12.47 | 16.50 | 11.75 | 12.23 | N/A | 12.34 |
| 8-9 | 12.55 | 11.88 | 12.15 | 12.84 | N/A | 12.14 |
| 9-10 | 10.48 | 11.64 | 11.28 | 11.36 | N/A | 11.99 |
| 10-11 | 13.53 | 12.17 | 12.42 | 11.87 | N/A | 12.25 |
| 11-12 | 11.33 | 11.79 | 11.33 | 10.69 | N/A | 12.23 |
| 12-13 | 11.52 | 11.20 | 10.46 | 11.29 | N/A | 10.89 |
| 13-14 | 12.24 | 12.10 | 12.65 | 12.61 | N/A | 11.76 |
| 14-15 | 10.57 | 9.79 | 10.02 | 9.10 | N/A | 9.21 |
| 15-16 | 8.62 | 11.45 | 10.23 | 8.69 | N/A | 12.00 |
| 16-17 | 9.98 | 11.12 | 7.59 | 7.74 | N/A | 9.35 |
| 17-18 | 11.14 | 10.02 | 8.67 | 10.63 | N/A | 9.06 |
| 18-19 | 7.60 | 7.56 | 7.57 | 7.53 | N/A | 9.18 |
| Standard Deviation | 1.54 | 1.70 | 1.62 | 1.66 | | 1.33 |

| Detector | HARRIS | | | | | |
|---|---|---|---|---|---|---|
| Descriptor | BRISK | BRIEF | ORB | FREAK | AKAZE | SIFT |
| 1-2 | 10.91 | 10.91 | 10.91 | 10.91 | N/A | 10.91 |
| 2-3 | 0.03 | 10.20 | 11.01 | 11.01 | N/A | 11.01 |
| 3-4 | -80.85 | -11.47 | -11.47 | 0.09 | N/A | -80.85 |
| 4-5 | 11.77 | 11.77 | 11.77 | 12.51 | N/A | 11.77 |
| 5-6 | -inf | 12.88 | 35.38 | 44.92 | N/A | 13.64 |
| 6-7 | 0.29 | 15.25 | 13.62 | 14.20 | N/A | 35.19 |
| 7-8 | 11.73 | 14.27 | 13.50 | 12.40 | N/A | 13.50 |
| 8-9 | 25.12 | 25.12 | 25.12 | 12.92 | N/A | 25.12 |
| 9-10 | 0.01 | 3.90 | -nan(ind) | -nan(ind) | N/A | 3.90 |
| 10-11 | -inf | -inf | -inf | 0.05 | N/A | -inf |
| 11-12 | 11.81 | 11.81 | 11.81 | 0.02 | N/A | 11.81 |
| 12-13 | 11.69 | 11.69 | 11.69 | 11.69 | N/A | 11.69 |
| 13-14 | -inf | 44.33 | 44.33 | 44.33 | N/A | 44.33 |
| 14-15 | 12.14 | 5.66 | 5.66 | 12.44 | N/A | 5.66 |
| 15-16 | -inf | -14.78 | -14.78 | -12.64 | N/A | -16.03 |
| 16-17 | 6.66 | 6.76 | 6.72 | 6.72 | N/A | 7.29 |
| 17-18 | 11.10 | 12.58 | 12.58 | 0.09 | N/A | 0.23 |
| 18-19 | -inf | -inf | -inf | -nan(ind) | N/A | -inf |
| Standard Deviation | 21.21 | 12.51 | 13.94 | 14.07 | | 24.82 |

| Detector | SIFT | | | | | |
|---|---|---|---|---|---|---|
| Descriptor | BRISK | BRIEF | ORB | FREAK | AKAZE | SIFT |
| 1-2 | 10.93 | 11.77 | OOM | 11.00 | N/A | 10.44 |
| 2-3 | 11.52 | 11.79 | OOM | 12.25 | N/A | 11.62 |
| 3-4 | 13.54 | 15.09 | OOM | 13.54 | N/A | 13.15 |
| 4-5 | 18.65 | 19.68 | OOM | 19.93 | N/A | 16.35 |
| 5-6 | 14.17 | 14.21 | OOM | 13.56 | N/A | 12.50 |
| 6-7 | 11.57 | 11.72 | OOM | 11.98 | N/A | 10.76 |
| 7-8 | 14.05 | 12.70 | OOM | 13.94 | N/A | 12.70 |
| 8-9 | 14.82 | 15.14 | OOM | 11.18 | N/A | 10.84 |
| 9-10 | 12.08 | 12.25 | OOM | 13.55 | N/A | 10.85 |
| 10-11 | 10.66 | 10.22 | OOM | 8.01 | N/A | 9.77 |
| 11-12 | 12.76 | 10.66 | OOM | 10.16 | N/A | 10.46 |
| 12-13 | 9.33 | 8.99 | OOM | 8.21 | N/A | 10.67 |
| 13-14 | 9.30 | 8.70 | OOM | 8.82 | N/A | 8.99 |
| 14-15 | 9.64 | 9.03 | OOM | 8.58 | N/A | 8.54 |
| 15-16 | 9.60 | 10.27 | OOM | 8.67 | N/A | 9.88 |
| 16-17 | 8.40 | 8.38 | OOM | 8.63 | N/A | 8.16 |
| 17-18 | 8.95 | 8.71 | OOM | 7.56 | N/A | 7.71 |
| 18-19 | 8.78 | 8.91 | OOM | 8.80 | N/A | 8.87 |
| Standard Deviation | 2.61 | 2.89 | | 3.04 | | 2.03 |