Sensor Fusion Nanodegree

3D Object Tracking: Final Project Report

FP.1 Match 3D Objects

This task was implemented as follows:

1. For each keypoint match, the keypoints in the previous and the current frames were extracted.
2. Looping over all bounding boxes in the previous and the current frames, the previous and current keypoints are each matched to a bounding box
3. If both keypoints were successfully matched to a bounding box, the IDs of the corresponding bounding boxes are saved in an array bbMatches
4. After all keypoint matches are processed, recurring bounding boxes are matched in a new array bbMatchesCnt
5. For every bounding box in the previous frame in bbMatchesCnt, the bounding box in the current frame with the highest count of matches is found. The results are saved to the bbBestMatches array

FP.2 Compute Lidar-based TTC

A helper function getMinX() was implemented to get the lidar point with the minimum distance in x direction. Outliers are filtered based on the standard deviation of the distance values in x direction. Lidar points with distances exceeding 3 x the standard deviation are therefore excluded. In computeTTCLidar(), the TTC is calculated.

FP.3 Associate Keypoint Correspondences with Bounding Boxes

For every keypoint match, the corresponding keypoint in the current frame is extracted and is checked to see if it lies within the given bounding box. If so, the keypoint match is added to the matchesROI array. For the matches lying in the bounding box, the standard deviation of the distances values is calculated and all matches exceeding 3 x the standard deviation are excluded. The rest is saved in the kptMatches array within the bounding box and the corresponding box is saved to the keypoints array of the bounding box.

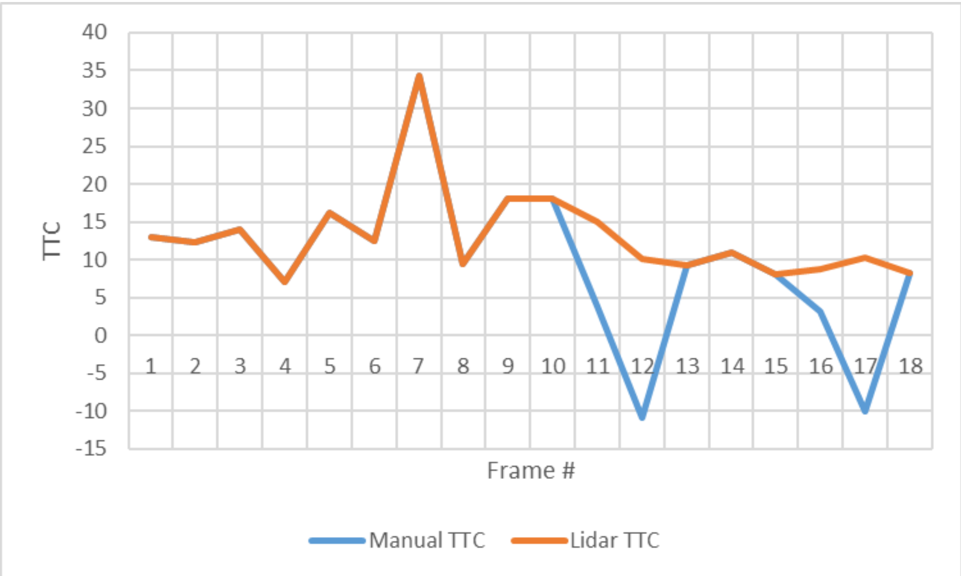
FP.4 Compute Camera-based TTC

In the current and the previous bounding boxes, the distance between the keypoints is calculated. The ratio of the distance values of corresponding pairs of keypoints in the current and previous frames is calculated and the median of the distance ratios is determined. The median distance is then used to calculate the TTC.

FP.5 Performance Evaluation I

For this task, the TTC values generated by the *computeTTCLidar* function were compared to TTC values manually calculated using the minimum distance values from the top view of the point cloud. It can be seen in the table below and in the following plot that the TTC values are identical in all but four frames. The difference in the TTC values is caused by the lidar point clustering, which, in these frames, does not associate the closest point on the preceding vehicle to the bounding box. Since the *computeTTCLidar* function only considers the points within the bounding box, the minimum distance to the preceding vehicle is different and, therefore, also the TTC value. For example, the minimum distance value to the preceding vehicle in frame 11 (within the bounding box) is 7.344 m, while the actual minimum distance was 7.205. This led to an incorrect TTC value in frame 11 and consequently also in frame 12. The same applies to frames 16 and 17.

Frame	Lidar TTC	Manual distance	Manual TTC
0	-	7.974	-
1	12.9722	7.913	12.9721311
2	12.264	7.849	12.2640625
3	13.9161	7.793	13.9160714
4	7.11572	7.685	7.11574074
5	16.2511	7.638	16.2510638
6	12.4213	7.577	12.4213115
7	34.3404	7.555	34.3409091
8	9.34376	7.475	9.34375
9	18.1318	7.434	18.1317073
10	18.0318	7.393	18.0317073
11	14.9877	7.205	3.83244681
12	10.1	7.272	-10.8537313
13	9.22307	7.194	9.22307692
14	10.9678	7.129	10.9676923
15	8.09422	7.042	8.09425287
16	8.81392	6.827	3.17534884
17	10.2926	6.896	-9.9942029
18	8.30978	6.814	8.3097561



<u>FP.6 Performance Evaluation II</u>

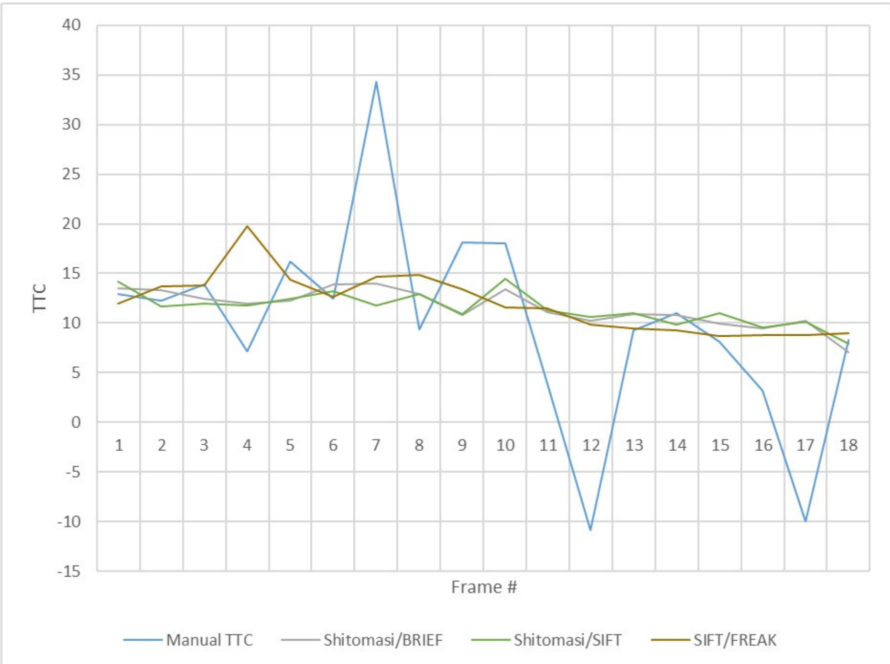
For this task, the camera TTC values were calculated for each detector/descriptor combination and the results can be seen in the spreadsheet in the following page. Additionally, the mean, minimum and standard deviation of the TTC values were calculated. Although there is actually no way of knowing the correct TTC values, we can use the manually calculated TTC values as a benchmark for this task, since they are based on the actual minimum distance to the preceding vehicle as measured by the lidar. Therefore, the difference between each TTC value and the corresponding manual TTC is also included.

First of all, several detector/descriptor combinations resulted in (negative) infinite values for the TTC in several frames (these are indicated as -1000 in the spreadsheet to ease calculations in Excel). Since the TTC is calculated based on the following formula, the infinite values correspond to a median distance ratio of 1. This means that these detectors/descriptors failed to detect any change in the distance between the keypoints in two subsequent frames. While the frame rate could be reduced so that a more significant change between the frames can be detected, this is a clear disadvantage in the robustness of these detector/descriptor combinations and they will therefore be excluded from the comparison as indicated in red in the following table.

$$TTC = \frac{d_1}{v_0} = \frac{-\Delta t}{\left(1 - \frac{h_1}{h_0}\right)}$$

For the rest of the combinations, the sum of squared "errors" (SSE) (compared to the manual TTC) was calculated, as shown in the table below. Using this metric, we can see which combination delivered TTC values that are closest to the manual TTC values. The combinations with the least SSEs were also plotted in the following graph.

		Descriptor					
		BRISK	BRIEF	ORB	FREAK	AKAZE	SIFT
Detector	Shi-Tomasi	1593.93112	1499.47611	1615.66718	1616.67235		1604.88304
	Harris						
	FAST		7602.48613	2033.40959			1905.61883
	BRISK	1670.82637	1920.92263	1664.88497	1649.90052		1944.09529
	ORB						
	AKAZE					1471.15478	
	SIFT	1548.11606	1584.96903		1522.39719		1557.69136



As can be seen in the plot, there are distinctive differences between the camera TTC values and the manual TTC values, regardless of the detector/descriptor combination, especially in frames with sudden changes in the TTC, such as frames 7, 12 and 17. This indicates that the distance ratios might need further filtering beyond the calculation of the median.

Descriptor Type / Detector Type		BRISK					BRIEF					ORB				
	Img#	TTC	mean TTC	min TTC	std TTC	TTC -manual TTC	TTC	mean TTC	min TTC	std TTC	TTC -manual TTC	TTC	mean TTC	min TTC	std TTC	TTC -manual TTC
	0	-	11.55	7.71	2.08		-	11.57	7.08	1.84		-	11.19	7.31	1.79	
	1	13.27				0.30	13.47				0.49	13.65				0.68
	2	12.35				0.09	13.33				1.06	11.06				-1.20
	3	14.24				0.32	12.42				-1.49	12.75				-1.17
	4	11.60				4.48	11.93				4.82	11.27				4.15
	5	13.35				-2.90	12.22				-4.03	12.44				-3.82
	6	14.46				2.04	13.91				1.48	13.91				1.48
	7	11.85				-22.49	13.97				-20.37	10.88				-23.46
	8	14.52				5.18	12.94				3.60	13.07				3.73
Shi-Tomasi	9	11.04				-7.09	10.82				-7.31	10.03				-8.11
	10	13.38				-4.66	13.46				-4.58	13.76				-4.27
	11	10.77				6.94	11.10				7.27	10.73				6.89
	12	10.08				20.93	10.21				21.07	10.06				20.91
	13	11.43				2.21	10.94				1.72	11.20				1.98
	14	9.62				-1.34	10.81				-0.16	10.43				-0.54
	15	8.03				-0.06	9.94				1.85	8.94				0.85
	16	9.56				6.39	9.45				6.28	10.23				7.06
	17	10.56				20.55	10.20				20.20	9.75				19.74
	18	7.71				-0.60	7.08				-1.23	7.31				-1.00
	0	-	-139.74	-1000.00	404.92		-	-151.37	-1000.00	390.87		-	-151.88	-1000.00	390.53	
	1	-0.20				-13.17	-1000.00				-1012.97	43.47				30.49
	2	10.60				-1.66	26.39				14.13	43.83				31.57
	3	365.18				351.27	32.68				18.76	32.68				18.76
	4	11.93				4.82	11.93				4.82	11.93				4.82
	5	40.94				24.69	48.38				32.13	-1000.00				-1016.25
	6	11.76				-0.66	44.70				32.28	34.15				21.73
	7	10.84				-23.50	13.06				-21.28	14.87				-19.47
	8	-1000.00				-1009.34	53.02				43.68	32.61				23.27
Harris	9	9.91				-8.22	6.89				-11.24	6.95				-11.18
	10	-45.11				-63.14	3.61				-14.42	3.80				-14.23
	11	7.67				3.83	7.21				3.38	5.62				1.79
	12	-1000.00				-989.15	-1000.00				-989.15	-1000.00				-989.15
	13	27.25				18.03	11.55				2.33	11.55				2.33
	14	-1000.00				-1010.97	-1000.00				-1010.97	-1000.00				-1010.97
	15	7.14				-0.95	5.71				-2.38	5.23				-2.86
	16	12.52				9.34	10.55				7.37	10.55				7.37
	17	7.06				17.06	-3.12				6.87	7.33				17.33
	18	7.10				-1.21	2.80				-5.51	1.57				-6.73
	0	-	-44.39	-1000.00	238.49		-	12.39	7.67	2.89		-	13.43	8.79	6.55	
	1	13.50				0.53	12.51				-0.46	12.40				-0.57
	2	12.87				0.60	10.76				-1.50	11.41				-0.86
	3	11.62				-2.29	12.14				-1.78	12.00				-1.91
	4	14.00				6.88	19.32				12.21	16.48				9.37
	5	-1000.00				-1016.25	18.07				1.82	38.58				22.33
	6	13.39				0.97	15.43				3.01	12.62				0.20
	7	11.95				-22.39	12.98				-21.37	14.15				-20.19
	8	10.46				1.11	11.20				1.85	10.83				1.48
FAST	9	12.17				-5.96	13.50				-4.63	12.70				-5.43
	10	14.42				-3.61	12.61				-5.42	14.12				-3.91
	11	12.61				8.78	13.70				9.86	13.99				10.16
	12	11.82				22.68	10.13				20.98	10.68				21.54
	13	11.17				1.95	11.56				2.34	11.69				2.46
	14	10.27				-0.70	10.42				-0.55	10.30				-0.66
	15	10.09				1.99	10.77				2.67	9.86				1.77
	16	11.57				8.39	10.32				7.14	10.42				7.24
	17	8.33				18.32	7.67				17.66	8.79				18.79
	18	10.67				2.36	9.97				1.66	10.67				2.36
	0	-	14.75	8.64	4.41		-	14.37	10.08	3.23		-	14.68	9.10	3.51	
	1	14.13				1.15	13.79				0.81	17.46				4.49
	2	24.56				12.30	17.29				5.02	20.14				7.87
	3	13.33				-0.58	12.65				-1.27	14.49				0.57
	4	16.90				9.78	19.45				12.33	17.85				10.73
	5	23.76				7.51	20.07				3.82	19.57				3.32
	6	18.89				6.47	17.49				5.07	19.27				6.85
	7	18.81				-15.53	17.14				-17.20	18.77				-15.57
	8	15.12				5.78	17.72				8.37	16.89				7.54
BRISK	9	14.63				-3.50	15.57				-2.56	14.78				-3.35
	10	15.55				-2.48	11.84				-6.19	12.59				-5.44
	11	12.40				8.57	13.82				9.99	13.39				9.56
	12	12.09				22.94	15.68				26.54	12.00				22.86
	13	11.91				2.69	11.97				2.75	11.58				2.36
	14	11.63				0.66	11.36				0.40	12.90				1.93
	15	12.12				4.03	11.22				3.12	11.42				3.32
	16	10.69				7.51	10.96				7.78	11.19				8.01
	17	8.64				18.63	10.08				20.07	9.10				19.10
	18	10.26				1.95	10.63				2.32	10.80				2.49
	0	-	-151.25	-1000.00	390.87		-	-83.11	-1000.00	337.18		-	-133.01	-1000.00	405.73	
	1	12.54				-0.43	17.49				4.52	16.77				3.80
	2	14.41				2.14	28.91				16.65	12.05				-0.21
	3	13.44				-0.47	54.92				41.00	17.54				3.62
	4	28.69				21.57	11.76				4.64	18.64				11.52
	5	-1000.00				-1016.25	17.82				1.57	326.47				310.22
	6	12.79				0.37	223.12				210.70	-1000.00				-1012.42
	7	68.77				34.43	-1000.00				-1034.34	-1000.00				-1034.34
	8	11.23				1.89	29.72				20.37	10.87				1.53
ORB	9	40.95				22.82	-1000.00				-1018.13	-1000.00				-1018.13
	10	-1000.00				-1018.03	25.28				7.24	35.14				17.11
	11	8.33				4.50	16.24				12.40	7.50				3.67
	12	-1000.00				-989.15	12.95				23.80	81.78				92.64
	13	7.71				-1.51	13.24				4.01	9.27				0.04
	14	9.42				-1.54	8.58				-2.38	13.57				2.61
	15	8.76				0.66	8.76				0.66	13.22				5.13
	16	12.70				9.52	9.26				6.08	9.56				6.39
	17	9.79				19.79	13.99				23.99	11.91				21.91
	18	18.03				9.72	12.01				3.70	21.51				13.20
	0															
	1															
	2															
	3															
	4															
	5															
	6															
	7															
	8															
AKAZE	9															
	10															
	11															
	12															
	13															
	14															
	15															
	16															
	17															
	18															
	0	-	11.87	8.41	2.89		-	12.12	8.38	3.10						
	1	12.12				-0.86	12.47				-0.50					
	2	13.01				0.74	14.64				2.38					
	3	13.86				-0.06	14.92				1.00					
	4	19.26				12.14	19.67				12.55					
	5	14.81				-1.44	14.62				-1.63					
	6	12.38				-0.04	13.82				1.39					
	7	14.52				-19.82	13.97				-20.37					
	8	14.36				5.02	14.34				4.99					
SIFT	9	13.07				-5.06	13.55				-4.58					
	10	11.11				-6.92	10.69				-7.34					
	11	11.65				7.82	12.35				8.52					
	12	10.45				21.30	10.45				21.30					
	13	8.92				-0.30	9.19				-0.03					
	14	9.01				-1.96	9.00				-1.97					
	15	8.86				0.76	8.94				0.84					
	16	8.41				5.23	8.38				5.21					
	17	8.94				18.93	8.52				18.52					
	18	8.87				0.56	8.69				0.38					

Descriptor Type / Detector Type		FREAK					AKAZE					SIFT				
	Img#	TTC	mean TTC	min TTC	std TTC	TTC -manual TTC	TTC	mean TTC	min TTC	std TTC	TTC -manual TTC	TTC	mean TTC	min TTC	std TTC	TTC -manual TTC
	0	-	11.89	7.34	2.66							-	11.48	7.92	1.63	
	1	13.67				0.69						14.20				1.23
	2	13.15				0.88						11.67				-0.59
	3	11.55				-2.37						11.92				-1.99
	4	11.31				4.19						11.80				4.69
	5	12.86				-3.39						12.47				-3.79
	6	19.61				7.18						13.22				0.80
	7	13.31				-21.03						11.79				-22.55
	8	13.73				4.38						12.91				3.56
Shi-Tomasi	9	11.27				-6.86						10.88				-7.25
	10	13.83				-4.20						14.47				-3.56
	11	9.92				6.08						11.31				7.48
	12	11.82				22.67						10.59				21.44
	13	12.03				2.81						11.05				1.82
	14	9.61				-1.36						9.81				-1.16
	15	9.05				0.96						10.97				2.88
	16	10.29				7.11						9.56				6.39
	17	9.75				19.74						10.15				20.15
	18	7.34				-0.97						7.92				-0.39
	0	-	-161.00	-1000.00	387.44							-	-211.43	-1000.00	433.95	
	1	7.04				-5.93						-7.77				-20.74
	2	-10.03				-22.29						10.50				-1.76
	3	17.10				3.19						12.56				-1.35
	4	11.43				4.32						-1000.00				-1007.12
	5	40.94				24.69						48.38				32.13
	6	15.61				3.19						36.22				23.80
	7	11.72				-22.63						14.51				-19.83
	8	9.39				0.05						36.30				26.96
Harris	9	7.01				-11.13						8.27				-9.87
	10	-1000.00				-1018.03						-1000.00				-1018.03
	11	8.20				4.36						8.80				4.97
	12	-1000.00				-989.15						-1000.00				-989.15
	13	-1000.00				-1009.22						11.48				2.26
	14	63.18				52.22						-1000.00				-1010.97
	15	7.29				-0.80						5.93				-2.17
	16	12.66				9.48						10.14				6.97
	17	-106.69				-96.69						-5.14				4.86
	18	7.22				-1.09						4.03				-4.28
	0	-	-43.58	-1000.00	238.73							-	13.43	7.70	4.98	
	1	11.93				-1.04						12.67				-0.30
	2	28.84				16.58						12.19				-0.07
	3	12.77				-1.15						13.25				-0.67
	4	15.34				8.22						23.81				16.69
	5	-1000.00				-1016.25						28.47				12.22
	6	12.20				-0.22						13.64				1.22
	7	12.38				-21.96						12.93				-21.41
	8	10.97				1.63						12.60				3.26
FAST	9	12.25				-5.88						13.37				-4.76
	10	13.48				-4.55						13.20				-4.83
	11	12.82				8.99						14.24				10.41
	12	11.48				22.34						11.01				21.87
	13	10.53				1.30						11.99				2.76
	14	10.20				-0.76						10.60				-0.37
	15	9.73				1.63						10.54				2.44
	16	11.17				7.99						9.94				6.76
	17	7.95				17.94						7.70				17.69
	18	11.60				3.29						9.61				1.30
	0	-	14.39	8.84	4.08							-	15.30	9.10	5.00	
	1	14.66				1.69						14.84				1.86
	2	23.51				11.25						17.65				5.39
	3	13.65				-0.26						18.06				4.15
	4	16.35				9.24						13.98				6.86
	5	21.82				5.57						32.27				16.01
	6	18.89				6.47						17.49				5.07
	7	17.23				-17.12						15.68				-18.66
	8	15.89				6.55						16.96				7.62
BRISK	9	16.16				-1.97						17.38				-0.75
	10	13.32				-4.71						14.94				-3.10
	11	12.77				8.94						14.81				10.98
	12	11.49				22.34						12.71				23.57
	13	11.07				1.84						12.77				3.55
	14	11.17				0.20						10.85				-0.12
	15	11.74				3.65						13.42				5.33
	16	9.85				6.68						10.50				7.33
	17	8.84				18.83						9.10				19.09
	18	10.64				2.33						11.97				3.66
	0	-	-153.57	-1000.00	389.67											
	1	11.51				-1.46										
	2	38.81				26.55										
	3	15.64				1.73										
	4	10.34				3.22										
	5	-1000.00				-1016.25										
	6	11.00				-1.42										
	7	-1000.00				-1034.34										
	8	8.88				-0.47										
ORB	9	15.30				-2.83										
	10	-1000.00				-1018.03										
	11	7.11				3.27										
	12	47.57				58.42										
	13	6.33				-2.90										
	14	26.05				15.08										
	15	8.51				0.42										
	16	6.98				3.81										
	17	9.85				19.84										
	18	11.85				3.54										
	0						-	12.40	8.73	2.26						
	1						12.48				-0.50					
	2						14.12				1.85					
	3						12.92				-1.00					
	4						15.19				8.07					
	5						16.21				-0.04					
	6						14.44				2.02					
	7						15.45				-18.89					
	8						13.82				4.48					
AKAZE	9						13.94				-4.19					
	10						11.87				-6.16					
	11						12.03				8.20					
	12						11.38				22.23					
	13						11.19				1.97					
	14						10.42				-0.55					
	15						10.35				2.26					
	16						9.75				6.57					
	17						8.73				18.72					
	18						8.92				0.61					
	0	-	12.00	8.66	2.98							-	11.75	8.14	2.80	
	1	11.95				-1.02						11.95				-1.02
	2	13.69				1.42						12.70				0.44
	3	13.78				-0.14						12.92				-0.99
	4	19.79				12.68						18.29				11.17
	5	14.40				-1.85						15.38				-0.87
	6	12.62				0.20						12.17				-0.25
	7	14.71				-19.63						13.85				-20.49
	8	14.88				5.54						14.54				5.20
SIFT	9	13.43				-4.70						14.30				-3.83
	10	11.55				-6.48						10.58				-7.45
	11	11.49				7.65						11.24				7.40
	12	9.87				20.73						11.02				21.87
	13	9.44				0.22						8.61				-0.61
	14	9.27				-1.70						9.29				-1.67
	15	8.66				0.57						9.15				1.06
	16	8.74				5.57						8.83				5.66
	17	8.77				18.76						8.53				18.53
	18	9.01				0.70						8.14				-0.17