HD vs. 4K Driven Remote Tower Optical Systems

What is the better Optical Sensor?

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Abstract—**The purpose of this study was to investigate the rationale performance in between of 4K versus Full HD cameras in the context of a Remote Tower Optical System. Live videos from operational traffic at a German regional airport were recorded with both sensor types under different visibility condition. 23 air traffic controllers and aerodrome flight information officers compared and rated the different videos with respect to perceived video quality, detection and recognition range performance. Results show that, at least in this setting, in some situations, the 4K camera performs significantly better than the Full HD camera, but the effects are small and a clear decision without considering any other configuration parameters cannot be made unrestricted. The number of pixels of the sensor for instance is just one of many other parameters, which have to be considered in order to provide a well-tuned video stream, which supports an appropriate detection and recognition rate as well as a high-quality appearance.**

Keywords-HD; 4K; Camera; RemoteTower.

I. INTRODUCTION

A. Characteristics of Full HD and 4K Cameras

Remote Tower is a prospering concept to provide aerodrome Air Traffic Services (ATS) more efficiently. The out-of-the-window view from the Air Traffic Control (ATC) tower is captured via video cameras and relayed to a controller working position in a Remote Tower Center (RTC), which is located independent of the location of the actual airport. Out of such RTCs many airports can be operated, which creates synergies in terms of flexibility, efficiency and cost-effectiveness. In order to continue to handle the traffic safely and efficiently as from a conventional ATC tower, the quality of the video stream is of central importance. Particular attention is paid to the choice of the best camera sensor. 4K sensor cameras are increasingly entering the Remote Tower market, as the latest generations can compensate for the disadvantages compared to the currently used Full HD sensor cameras and thus, bring the 4K advantages into focus. But is the 4K really the better sensor for an Remote Tower Optical System (RTOS)?

Finally, all is about to find a well-tuned RTOS set-up, providing an optimal video performance to meet the operational needs as well as infrastructure and cost constraints. For that purpose and in accordance to [1], many "glass-to-glass" (from the sensor lens to the display) parameters have to be considered, including but not limited to:

- number of pixels (e.g., HD vs 4K),
- sensor size,
- Field of View (FoV) (set by focal length),
- angular resolution (pixel/degree),
- color depth,
- video compression in terms of maximum bitrate and bit per pixel
- CODEC implementation, e.g., H.264 or H.265,
- light sensitivity,
- contrast,
- video update rate (fps),
- network latency,
- jitter,
- noise,
- packet loss,
- display resolution,
- size of the display and
- distance of the display from operator.

The aim of outweighing these factors is to deliver best possible user experience and the required detection and recognition range performance by using today's video technology [1]. Increasing the performance of one parameter does not necessarily increase the overall performance of the entire RTOS. The ideal output is often achieved by wisely orchestrating multiple parameters. More specifically, it does not help to rely solely on high resolution (pixel per degree) to increase detection performance, when other parameters like light sensitivity or video compression rate do not promote the higher resolution. Typical parameters to be taken into consideration are described in the following sub chapters.

1) Sensor Size and Light Sensitivity

4K cameras have four times more pixels than HD cameras, but often still the same sensor size because the size of the sensor is limited by the housing size of the cameras. This results in the fact that a 4K pixel has only ¼ of the area of an HD pixel at the sensor (Figure 1). The detection capability of very small details is highly dependent on the number of photons of this detail, which are reaching the sensor (Figure 2).

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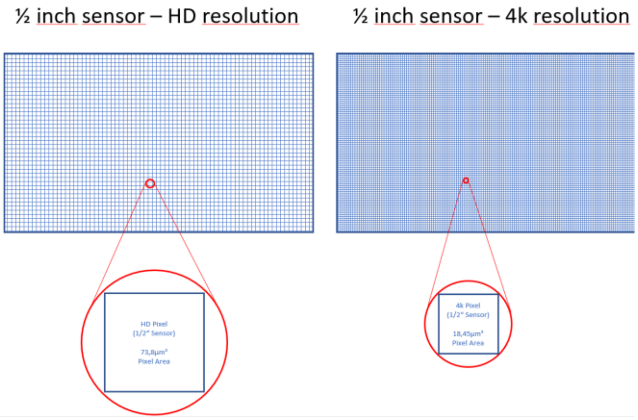

Figure 1. Pixel Sizes of HD vs. 4K Sensors.

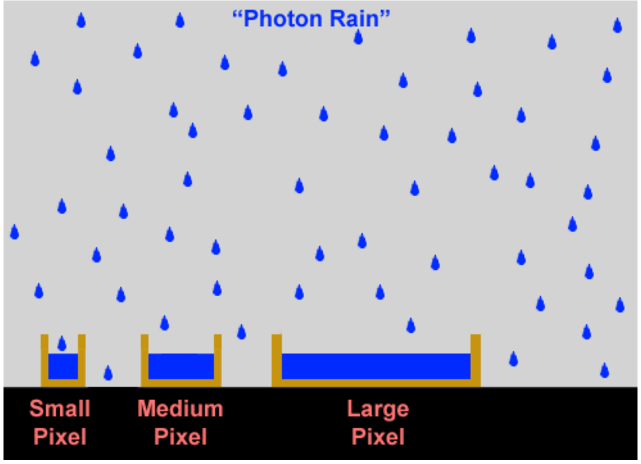

Figure 2. Photon Rain on different Pixel Sizes.

A larger pixel size guarantees a collection of a larger number of photons, which increases the visibility of the specific detail/object. Therefore, the following general rule to detect small details apply: The larger the pixel size, the higher the visibility/detection rate. However, technologies evolve over the time and from sensor generation to sensor generation the 4K sensor size increased from 1/2 to 4/3 inches and further the number of photons needed to detect an object/detail could be lowered.

This means that newer 4K sensor generations need fewer photons to detect an object than older sensor generation and so reaches similar light intensity as the current HD cameras, but with a four times higher resolution (by the same FoV).

2) *Bandwidth and Processing Resources*

Due to the circumstance that 4K resolution contains four times the amount of pixels HD resolution does, using 4K technology in an environment that requires video processing would result in the fourfold demand of processing power of the video processing infrastructure, and thus also in the fourfold amount of bandwidth required for transmitting the video data from the camera at the airport to the Remote Tower center. Today the power needed to process and encode large 4K video streams is provided on System-on-Chip (SoC) processors, which can cope with this large bitrate demand, but only up to a certain performance limit, to avoid the overheating of the processor inside the camera. Such powerful 4K-generation processors with an extended processing power are relative cheap nowadays, which results into the fact, that the same powerful processors are used in modern HD cameras too. Hence, in practice the same maximum processing performance is facilitated in HD and 4K cameras, resulting in a very similar performance referring to maximum bitrate and bandwidth consumption. But the 4K delivers four times more pixels, thus the bit per pixel rate of the 4K camera is usually lower. As a consequence, given the same pixel per degree resolution in between of 4K and HD videos (4K in contrast to HD with fourfold FoV), the quality of the 4K video is poorer than the quality of the HD video – it contains more artefacts, which makes it more difficult to detect specific objects (e.g., aircraft) in the 4K image compared to the HD image (see Figure 3).

However, in practice this effect will usually be compensated by adapting the FoV of the 4K camera to gain more pixel per degree (= higher angular resolution) to exploit the advantage of having the fourfold number of pixels.

3) *High Dynamic Range*

Current industry standards use High Dynamic Range (HDR) to improve the detection of moving objects, both in the sky and on the ground. HDR combines overexposed, ideally exposed, and underexposed images into one resulting image. While underexpose images are well suited to detect objects in the sky, overexposed images are better suited to detect objects on the ground. Combining these images into one provides an ideal basis for object detection. Until recently, HDR was a feature, which was only supported by HD cameras, but by today is also common standard for 4K cameras.

B. *Performance Criteria*

1) *Detection and Recognition Range Performance*

The operator using an RTOS typically is an Air Traffic Control Officer (ATCO) or an Aerodrome Flight Information Service Officer (AFISO) who provides ATS to the airspace and aerodrome user (usually pilots). ATCOs/AFISOs aim for preventing collisions, organizing and expediting the flow of air traffic either by granting instructions and clearances or only by traffic information. For that purpose, on their video screens they have to have the traffic in sight in terms of detection and recognition of aircraft arriving and departing from the airport, in order to monitor landings and take-offs, as these are the most safety critical flight phases. So, the required

Figure 3. Artefacts in 4K vs Full HD compressed video streams with same pixel per degree resolution.

performance of the camera(s), which is the crucial part of the overall RTOS, is mainly driven by *what* (w.r.t. the object size) and *where* (w.r.t. the distance) the operator has to be able to "see" something to provide the required ATS [1]. Such operational requirements are aerodrome and use case specific and are further split into *detection* and *recognition* range performance requirements. The terms are seen in the sense of Johnson's definition [2], who distinguished in between of "an object is discernible by the operator" (detection) and "main features of the object can be determined, sufficient to discern its object class" (recognition). Both constructs are crucial elements of an RTOS and mainly drives its performance requirements.

Reuschling et al. [3] investigated detection and recognition range performances by comparing infrared and visual spectrum cameras in an RTOS context. Also Jakobi & Hagl [4] applied the EUROCAE [1] strategy to evaluate detection and recognition range performances in relation to different video update rates but so far, the detection and recognition range performances related to 4K sensors compared to HD sensors has not been investigated systematically in an RTOS context.

2) Quality of video streams

Another parameter to decide about the performance of an RTOS performance is the quality of the video stream. There are subjective and objective assessments methods, but it has been shown that objective quality assessments, such as Peak Signal-to-Noise Ratio (PSNR), correlate poorly with subjective ratings [5]. However, since a subjectively perceived quality of the video is the method of choice to get high operational acceptance and values from the operators, a subjective assessment seems to be more informative. If the operator is not convinced of the system quality, errors can emerge by expressed mistrust in the system. Confidence in a system plays a mediator role in the system reliability [6]. Particularly, flickering and low-resolution streams were barely accepted in past research [4] [7] [8]. Furthermore, video quality parameter like noise, color appearance, and sharp or blurry edges and textures play a role in perceived video quality.

C. Research Question and Hypothesis

The introduction showed which HD and 4K technologies can be found today, and what advantages, disadvantages, opportunities, risks and limitations exist. In a nutshell, today 4K sensor technologies almost equal levels of light intensity of the HD technology in the range of 0.05 for color images and 0.01 lux for black-and-white images with an aperture of 1.5. Furthermore, the latest 4K camera models also support HDR. 4K cameras delivers four times more pixels than a Full HD sensor, so the FoV of a 4K camera is four times larger with the same pixel/degree resolution or vice versa, with the same FoV the horizontal x vertical resolution is four times larger than a Full HD camera (or a combination of both parameters). However, standard 4K images are usually compressed heavier by the internal camera processing, in the sense of lower bit per pixel rates, which then in turn leads to poorer image quality (see Figure 3). This effect can probably be compensated by a higher pixel per degree resolution. Common RTOS 4K camera settings work with a combination of slightly higher FoV and a slightly higher pixel per degree resolution to compensate the poorer pixel quality of 4K compared to HD cameras to bring the detection range in 4K footage to a similar or (preferably) to a slightly higher level compared to the HD footage.

One can therefore postulate that with such typical configurations the same detection and recognition performance are to be gained and further, very similar operator assessments of the video quality are to be expected in between of 4K and HD technology. The substantive hypotheses are therefore formulated as follows:

$H_{0,1}$: There are no differences between HD and 4K cameras in terms of their detection range performance.

$H_{0,2}$: There are no differences between HD and 4K cameras in terms of their recognition range performance.

$H_{0,3}$: There are no differences between HD and 4K cameras in terms of their perceived video quality.

II. METHOD

A. Participants

Overall goal of this study was the comparison of HD versus 4K camera technology in the operational context of ATS provided by ATCOs or AFISOs using an RTOS. Since detection and recognition of traffic is not only a mere perception test but also highly affected by the operator's expertise and situation awareness, operator experts, being ATCOs and AFISOs, had to be selected as test subjects for the experiment. They were recruited directly from airports and air navigation service providers asking if anyone would be interested in taking part in such an experiment.

In total 23, two female and 14 male ATCOs between the ages of 22 and 60 years (M = 36.14, SD = 11.73) as well as 7 male AFISOs between 27 and 66 years (M = 46.67, SD = 15.03), all of German nationalities, participated in the experiment. 1 male ATCO was excluded from the data analysis, as the experiment failed mid-way by technical reasons, resulting in 22 valid participants in the end.

The ATCOs participated voluntarily and they were compensated for their travel and accommodation expenses and their working hours. The study was performed in accordance with the General Data Protection Regulation (EU) 2016/679.

B. Design and Material

1) Camera Specs

The different cameras should prove themselves in different operational areas of interest, different visibility conditions and with different aircraft (object) sizes. Three different network cameras were selected:

- AXIS Q1647-LE (called: "HD"),
- AXIS Q1798-LE (called: "4K-1")
- Sony SNC-VB770 (called: "4K-2")

The first two AXIS cameras are commercial off-the-shelf cameras and very representative, because they are used by the Remote Tower supplier industry for today's RTOS installations. Both are from the same manufacture (AXIS) and therefore will serve as well-suited candidates for this study.

The Sony 4K-2 is an older 4K type from the year 2016, which was chosen to see how much 4K camera technology has progressed over the past seven years. All cameras have been configured by engineers of the supplier industry in the best possible way as they would be used as one of several fixed composite cameras to gain a single panoramic image, usually 360°, in an operational implementation. Depending on the operationally required vertical FoV and the required pixel/degree resolution, the cameras are positioned vertical or horizontal ranging from usually 7 up to 16 cameras for a 360° panorama. Therefore, the camera types slightly vary in between with respect to the pixel/degree resolution and they also slightly vary with all other specification and configuration, since each camera type is tuned in a way to get a high-quality image and best detection and recognition performance out of it. TABLE I. shows the main technical specifications and settings of the three used cameras HD, 4K-1 and 4K-2.

2) *Camera Set up & Selection and Processing of Video Material*

The three cameras were set up at the research airport Braunschweig-Wolfsburg (EDVE) on the roof of a building at the German Aerospace Center (DLR) campus, very close to and in similar height like the operational Tower cabin (Figure 4). They were attached to an aluminum extruded profile for easy parallel alignment. The cameras were powered and networked using Power over Ethernet (PoE). The origin out-of-the-camera video streams were relayed to and recorded on a Linux-based file server.

TABLE I. TECHNICAL SPECIFICATIONS AND CONFIGURATIONS OF THE THREE CAMERAS "HD", "4K-1", AND "4K-2"

	HD	**4K-1**	**4K-2**
Lens	F1.4	F1.7	F1.4
HDR	yes	yes	yes
Image sensor size	1/2 inch (12,7 mm)	4/3 inches (33,9 mm)	$1\,{}^{3}/_{8}$ inches (35 mm full frame)
FoV [p]	1920 x 1080 Full HD	3840 x 2160 UHD	3840 x 2160 UHD
FoV [°]	43° x 24°	60° x 33°	54° x 32°
Resolution in pixel per degree [ppdeg]	45	65	68
Total number of pixels	2,073,600	8,294,400	8,294,401
Target frame rate (fps)	30	30	30
Total number of pixels per second (pps)	62,208,000	248,832,000	248,832,001
Video compression	H.264 High	H.264 High	H.264 High
Max bitrate [Mbit/s]	50	50	32
Average max bit per 1000 pix per camera	804	201	129

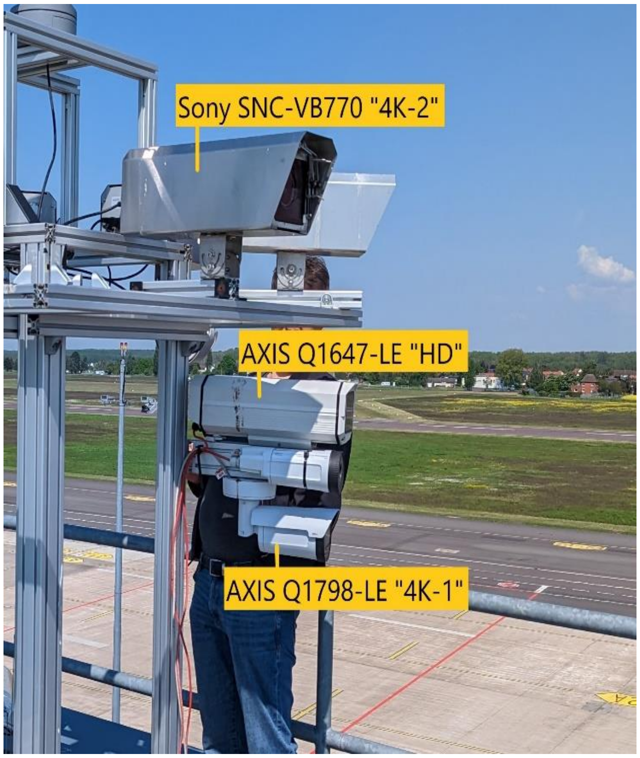

Figure 4. Camera mounting.

Two different viewing conditions (areas of interest) were decided for: one facing east to capture the Instrumental Flight Rules (IFR) traffic approaching and landing on runway (RWY) 26 via its Instrument Landing System (ILS) approach and the second one facing north to capture incoming Visual Flight Rule (VFR) traffic, entering the ATC control zone (CTR) via the mandatory reporting points NOVEMBER 1 and 2. To ensure consistency among the aircraft sizes, the same type of aircraft was chosen within each camera position. For the east facing position, a medium sized aircraft Dornier 328, and for the north view small sized aircraft like a Diamond Aircraft DA40 and a Piper PA-28 became the matter of choice. Seven different weather and visibility conditions for the camera facing east (see Figure 5 to Figure 11 (METAR of the selected time in brackets)) were decided for.

Figure 5. **Opposite Sun** (23th April 2023 METAR EDVE 110550Z 25009KT 9999 VCSH SCT024 OVC037 07/04 Q1008=).

Figure 6. **Rain** (20th April 2023 METAR EDVE 200550Z 08006KT 050V110 9999 -RA SCT008 BKN010 OVC034 05/04 Q1020=).

Figure 7. **Dusk** (28th April 2023 METAR EDVE 281850Z 12005KT 8000 BKN028 11/10 Q1010=).

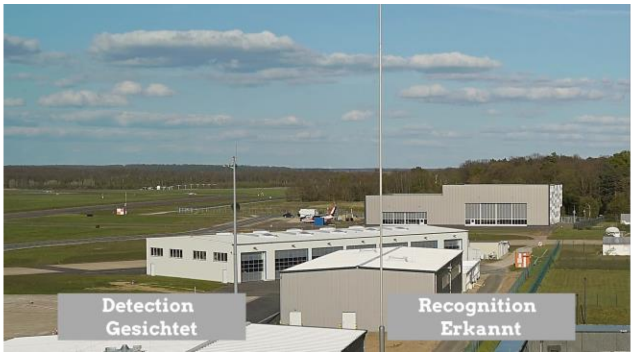

Figure 8. **CAVOK with Clouds** (27th April 2023 METAR EDVE 271550Z VRB03KT CAVOK 12/M04 Q1020=).

Figure 9. **Significant Clouds** (2nd May 2023 METAR EDVE 020550Z 28008KT 9000 SCT010 OVC012 10/08 Q1018=).

Figure 10. **Low Visibility** (2nd May 2023 METAR EDVE 020620Z 30008KT 5000 -DZ BKN005 BKN007 OVC014 10/09 Q1019=).

Figure 11. **Blue Sky** (3rd May 2023 METAR EDVE 030550Z VRB01KT 9999 BKN035 04/02 Q1029=).

For the camera position facing North opposite sun is not relevant. Also, low visibility and dusk does not play a role because the incoming traffic being VFR traffic, which is exclusively flying under visual meteorological conditions (VMC), which excludes low visibility and dusk conditions. Therefore, only three different visibility conditions for the camera facing north were decided for (see Figure 12 to Figure 14 (METAR of the selected time in brackets)).

For both camera positions, recordings were gathered over a period of six weeks lasting from April until June 2023. Afterwards with the support of historical METAR data [9] the desired visibility conditions were scanned and watched for suitable traffic and selected when appropriate.

Figure 12. **Sun-yes_clouds-no** (13th May 2023 METAR EDVE 130950Z 11012KT CAVOK 19/05 Q1021=).

Figure 13. **Sun-yes_clouds-yes** (18th May 2023 METAR EDVE 181450Z 09003KT 020V180 CAVOK 15/02 Q1027=).

Figure 14. **Sun-no_clouds-yes** (22nd May 2023 METAR EDVE 221520Z 10008KT 070V130 CAVOK 25/13 Q1012=).

Multiplying the number of cameras with the number of visibility conditions for each camera position sums up to a total of 3 x 7 (east) + 3 x 3 (north) = 30 video streams. Each file was watched individually by the experimenter to capture the exact moment when the first pixel of the aircraft appeared in the video in order to set objectively the earliest time, when something can be detected phenomenologically. When assessed these time stamps, the distances from the camera to the aircraft's position at this time stamp was calculated. For this purpose, datasets from the OpenSky Network [10] for the medium sized aircraft and with surveillance data delivered by the DLR owned local ADS-B/MLAT/FLAM Jetvison surveillance system [11] in combination with Google Earth for the small sized aircraft were retrieved. For calculating the distances for aircraft, formulae like the Pythagorean theorem [12] were applied in which the very small effect of the curvature of the earth was neglected to keep it simple. Also, the altitude of the building (21m), where the cameras were located on, was discarded for the distance calculation for the small aircraft due to neglectable accuracy gains.

Besides the video material, corresponding audio files with ambient aerodrome sound and with all relevant pilot/ATCO radio communication were retrieved from the long-time recordings. Finally, the video files were cut and merged with the corresponding audio files.

As the used 4K camera settings had a greater FoV compared to the HD camera (see TABLE I. , the 4K FoV presentation would need a bigger screen, when using a pixel per pixel presentation. In order to present the 4K and HD video streams on the same screen in full screen mode, the 4K videos were cropped to align them to the same size as the HD videos, yet maintaining the quality and pixel per pixel presentation.

To process the video material, FFmpeg multimedia framework [13] was used to cut the videos and merge them with the corresponding audio files. Also, for cropping the merged 4K files, the FFmpeg bitstream filter was the matter of choice. Furthermore, Audacity [14] and the Python module MoviePy [15] were applied to cut and merge the audio files.

3) Experimental set up

The experiment was set up via PsychoPy [16] and split into two parts. Part one assessed the test subjects' detection and recognition range performance, part two assessed the perceived video quality. In total the test subjects watched 3 x 7 + 3 x 3 = 30 video streams, whereas the order was randomized. All videos and corresponding audio files are presented pixel-true (pixel-per-pixel) in landscape orientation with Full-HD resolution size of 1920 x 1080 pixels on a 27-inch display with Quad HD (QHD) resolution of 2560 × 1440 pixel (see Figure 15). Via headset the test person could hear the ambient sound and the radio communication between ATCO and pilot.

They were instructed to click the “detection” button via mouse, when the aircraft was spotted, and secondly, on the “recognition” button, when the object was recognized as a medium or small aircraft. When they clicked by mistake, they could click again because only the last click was considered for later analysis. In order to avoid learning effects for the test subjects, the video's starting point of the scene was slightly different in every video.

After having the aircraft detected and recognized, the test subject was requested to judge about the general perceived video quality on a Likert scale ranging from 1 to 5. At last, the test subjects should rate the legibility of a lettering sign situated in a distance of 240 m, again on a Likert scale ranging from 1 to 5. Afterwards, they could click "next" and move on to the next video stream.

With part two of the experiment, the test subject moved to a 43-inch display with a 3840 × 2160 (4K UHD) resolution. On this display video streams of all three cameras (HD, 4K-1 and 4K-2) were presented simultaneously and pixel-true, and the test subject was instructed to compare the videos against each other with respect to five different video quality parameters in the sense of:

- **Motion**: Movements smooth vs. flickering
- **Noise**: noise vs. noise-free
- **Color**: colors bleeding vs. natural
- **Edges**: blurring vs. sharp
- **Textures**: blurring vs. sharp.

Sliders from minimum to maximum without any value scaling were used. When all five parameters for each of the three cameras had been rated (5 x 3 = 15 in total), the test person could go on to the next three-way comparison out of a total of 7 + 3 = 10 aircraft approach scenarios (see Figure 16).

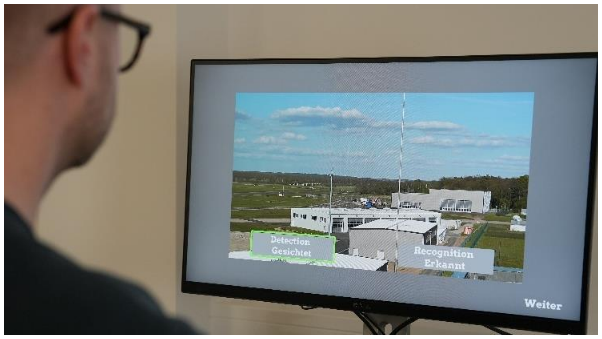

Figure 15. Test Subject conducting the detection and recognition task.

Figure 16. Test Subject conducting the perceived video quality evaluation task comparing three video streams out of the three cameras.

4) *Planned Statistical Tests*

As the test subjects should undergo all test conditions, a two-way repeated measures ANOVA were planned to conduct for both the detection and the recognition rate performance. Where sphericity is not met, the Greenhouse-Geisser adjustment will be performed. Following the recommendation of Bakeman [17], the effect size will be reported as the generalized eta squared (η^2_G) [18]. Post-tests were planned to determine the differences between the cameras, should they prove to be significant. For each video quality parameter, a pairwise comparison of the cameras was foreseen to conducted. This should be done via a paired-samples t-test. Should the data not meet the necessary assumptions for ANOVAs and t-tests, nonparametric solutions were intended to be used. Values are to be treated as outliers when they are above quartile Q2 + 1.5*IQR or below Q1 – 1.5*IQR.

III. RESULTS

A. *Detection Range Performance*

For the RWY26 approaches (cameras facing east) the test subjects watched video streams from seven different weather/visibility conditions each with three different camera recordings, in total 21 in a randomized sequence, and decided about the detection time, when the DO328 aircraft was spotted. Figure 17 depicts the detection range performance distances in a graphical bar chart diagram. Distances are in nautical miles (nmi) from the sensor lens to the aircraft. Standard deviations are shown as error bars.

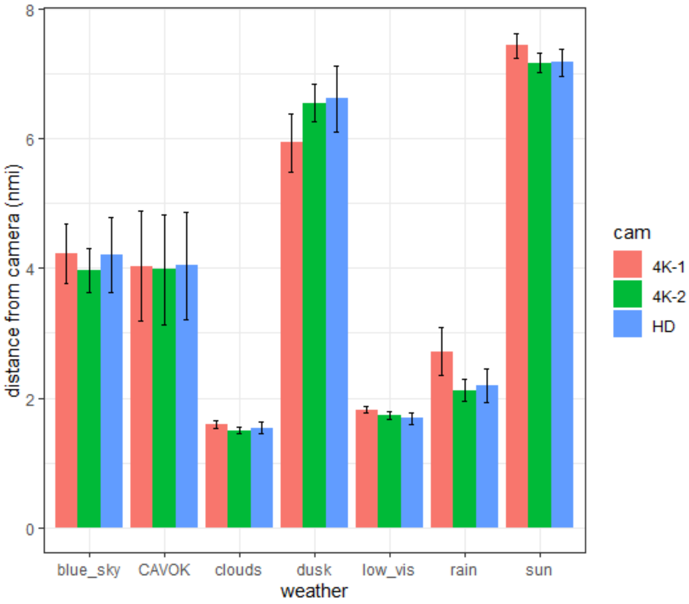

Figure 17. RWY26 Detection Range Performance - bar chart statistics for distances [nmi] via “Cam” and “Weather” condition.

To prove for significant differences, a 3 x 7 two-way repeated measures ANOVA with the two Independent Variables (IV) “Cam” (3 cameras) and “Weather” (7 different visibility conditions) and the Dependent Variable (DV) “distance” revealed a significant result for IV “Weather” but not for IV “Cam” as it was postulated by hypothesis $H_{0,1}$. However, the main factor effects are hard to interpret since also the Cam*Weather interaction became significant (TABLE II.).

In average, over the different weather/visibility condition the cameras do not differ with respect to the detection range performance. However, there are significant differences between the cameras for each single weather/visibility condition. TABLE III. shows the post-hoc tests differences and their significance values: Within the IV “Weather” categories “Opposite-Sun”, “Rain”, “Dusk”, “Significant Clouds” and “Low Visibility” the detection range performances differ significantly between the cameras. The 4K-1 is significantly worse in “Dusk” and significantly better in “Opposite-Sun”, “Rain”, “Significant Clouds” and “Low Visibility”. Within “CAVOK with Clouds” and “Blue Sky” there are no significant differences.

TABLE II. 3 X 7 TWO-WAY REPEATED MEASURES ANOVA FOR DETECTION DISTANCES (DF = DEGREES OF FREEDOM, F = F-VALUE, P = ERROR PROBABILITY, *** HIGHLY SIGNIFICANT; D= DIFFERENCE; η^2_G = EFFECT SIZE ETA SQUARE)

	df_n	df_d	F	p		η^2_G
Cam	2.00	14.00	2.017	0.170		0.027
Weather	1.57	10.97	489.115	0.000	***	0.965
Cam*Weather	12.00	84.00	6.434	0.000	***	0.208

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TABLE III. PAIRWISE T-TEST COMPARISON OF THE CAMERAS FOR DETECTION DISTANCES WITH BONFERRONI ADJUSTMENT (T = T-VALUE; *** EXTREMELY SIGNIFICANT; ** HIGHLY SIGNIFICANT; * SIGNIFICANT; D= DIFFERENCE (NMI); CI = CONFIDENCE INTERVALL)

Group 1	Group 2	n1	n2	t	df	p	p-adjusted		D	95% CI
Sun										
4K-2	HD	12	12	0.0389	11	0.970	1.000		0.002	[-0.102, 0.106]
4K-2	4K-1	12	12	-4.4417	11	0.001	0.003	**	-0.292	[-0.437, -0.147]
HD	4K-1	12	12	-4.7897	11	0.001	0.002	**	-0.294	[-0.429, -0.159]
Rain										
4K-2	HD	17	17	-1.1857	16	0.253	0.759		-0.073	[-0.204, 0.058]
4K-2	4K-1	17	17	-8.0395	16	0.000	0.000	***	-0.605	[-0.764, -0.445]
HD	4K-1	17	17	-6.8933	16	0.000	0.000	***	-0.532	[-0.695, -0.368]
Dusk										
4K-2	HD	15	15	0.0283	14	0.978	1.000		0.003	[-0.222, 0.228]
4K-2	4K-1	15	15	5.6031	14	0.000	0.000	***	0.642	[0.396, 0.888]
HD	4K-1	15	15	4.5887	14	0.000	0.001	**	0.639	[0.340, 0.938]
CAVOK										
4K-2	HD	16	16	-0.0650	15	0.949	1.000		-0.018	[-0.610, 0.574]
4K-2	4K-1	16	16	-0.0314	15	0.975	1.000		-0.008	[-0.562, 0.546]
HD	4K-1	16	16	0.0394	15	0.969	1.000		0.010	[-0.524, 0.544]
Clouds										
4K-2	HD	16	16	-2.0835	15	0.055	0.164		-0.040	[-0.080, 0.001]
4K-2	4K-1	16	16	-7.0150	15	0.000	0.000	***	-0.104	[-0.135, -0.072]
HD	4K-1	16	16	-3.1882	15	0.006	0.019	*	-0.064	[-0.107, -0.021]
Low Visibility										
4K-2	HD	17	17	2.5877	16	0.020	0.059		0.045	[0.008, 0.082]
4K-2	4K-1	17	17	-5.0577	16	0.000	0.000	***	-0.093	[-0.132, -0.054]
HD	4K-1	17	17	-7.2145	16	0.000	0.000	***	-0.138	[-0.179, -0.098]
Blue Sky										
4K-2	HD	13	13	-1.5676	12	0.143	0.429		-0.243	[-0.580, 0.095]
4K-2	4K-1	13	13	-2.1447	12	0.053	0.159		-0.290	[-0.585, 0.005]
HD	4K-1	13	13	-0.1946	12	0.849	1.000		-0.047	[-0.579, 0.484]

The small aircraft approaching via mandatory reporting point November 1 and 2 (camera facing north) were usually spotted in 2-3 nmi (TABLE IV.), but since the aircraft made a turn downwind at N2 flying west the distances increased again out of physical recognition range. Figure 18 shows the approach path of a small VFR aircraft incoming from the North (cyan line). The red line (from camera to the church of the village in the north of the airport) served as orientation line to match times in the video and Google Earth. Further, a calculated line in yellow, with respect to the first pixel appearance, is shown.

TABLE IV. shows the objectively measured detection distances, when the first pixel appeared. Differences are not significant, so do not vary over “Cam” or “Weather”. TABLE V. shows a pie chart matrix for the subjective detection performance, in which grey symbolizes “detected”, white symbolizes “not detected”.

There are no main differences in between of the cameras, just the visibility conditions show severe differences. The small aircraft was hardly detected in blue sky (Sun-yes / Clouds-no) but therefore almost every time detected in cloudy conditions with shaded sun (Sun-no / Clouds-yes). For each of the three visibility conditions, a Cochran's Q test was conducted to detect possible camera differences within a certain visibility condition. Only the test for one of the three conditions (Sun-yes / Clouds-yes) revealed a significant camera difference, $Q(2) = 11.46$, $p = 0.003$. Descriptively, detection rates were highest for the 4K-2 camera.

B. *Recognition Range Performance*

Figure 19 depicts the recognition range performance distances in a graphical bar chart diagram for RWY26 approaches (cameras facing east). There are significant differences in between of the “cameras”, in between of the “Weather” conditions, but also significant interaction effects, that is, main effects “Cam” and “Weather” cannot be interpreted unambiguously (see TABLE VI.).

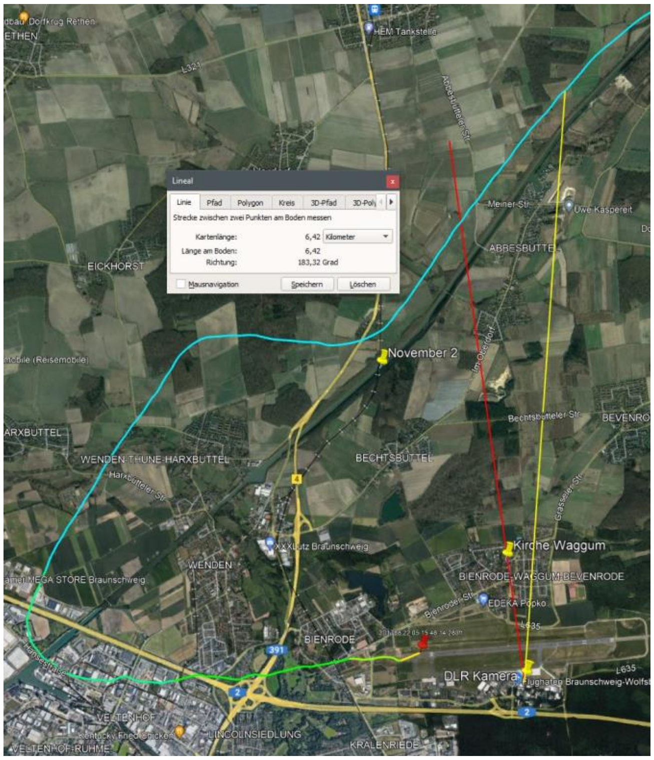
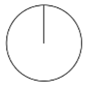


Figure 18. Approach path of small VFR aircraft from the North.

TABLE IV. DISTANCES FIRST PIXEL APPEARANCE FOR SMALL AIRCRAFT APPROACHING FROM THE NORTH

Weather	Cam	nmi
CAVOK Sun-yes_clouds-no	4K-1	2,74
	4K-2	2,18
	HD	1,97
CAVOK Sun-yes_clouds-yes	4K-1	3,33
	4K-2	3,18
	HD	3,66
CAVOK Sun-no_clouds-yes	4K-1	3,37
	4K-2	3,46
	HD	3,39

TABLE V. PIE CHART MATRIX FOR DETECTION PERFORMANCE FOR SMALL AIRCRAFT (GREY = “DETECTED”, WHITE = “NOT DETECTED”)

<table>
<tr><td></td><td></td><th colspan="3">Cameras</th></tr>
<tr><td></td><td></td><th>4K-1</th><th>4K-2</th><th>HD</th></tr>
<tr><th rowspan="3">V
i
s
i
b
i
l
i
t
y</th><th>CAVOK
Sun-yes
Clouds-no</th><td></td><td></td><td></td></tr>
<tr><th>CAVOK
Sun-yes
Clouds-yes</th><td></td><td></td><td></td></tr>
<tr><th>CAVOK
Sun-no
Clouds-yes</th><td></td><td></td><td></td></tr>
</table>

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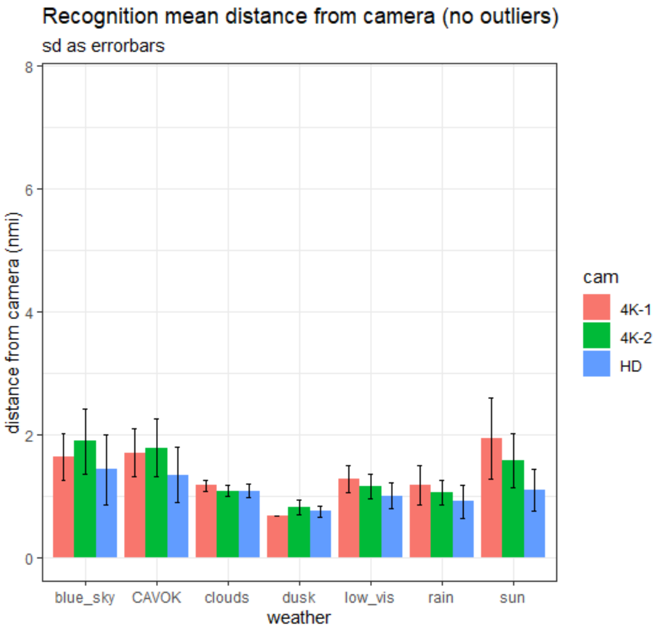


Figure 19. Descriptive bar chart statistics for RWY26 Recognition Range Performance via IV "Cam" and "Weather".

TABLE VI. 3 x 7 TWO-WAY REPEATED MEASURES ANOVA FOR RECOGNITION DISTANCES

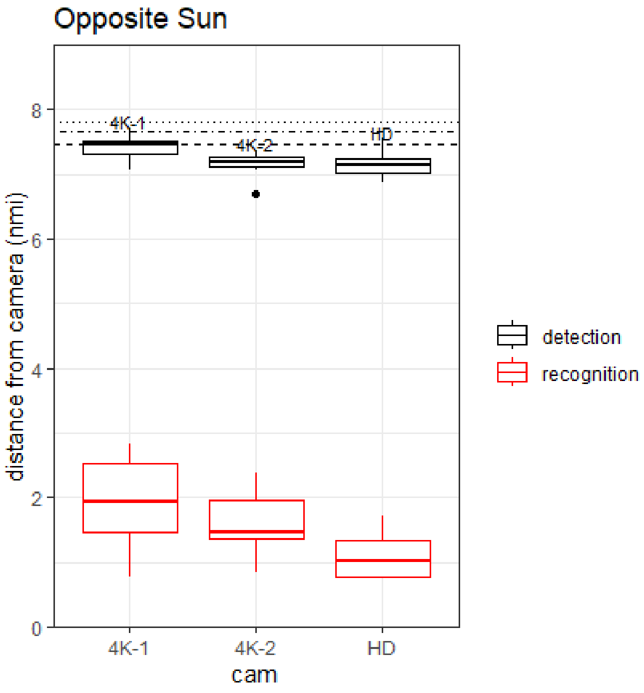
	df_n	df_d	F	p		η^2_G
Cam	2	10	12.720	0.002	**	0.136
Weather	6	30	29.801	0.000	***	0.644
Cam*Weather	12	60	5.286	0.000	***	0.224

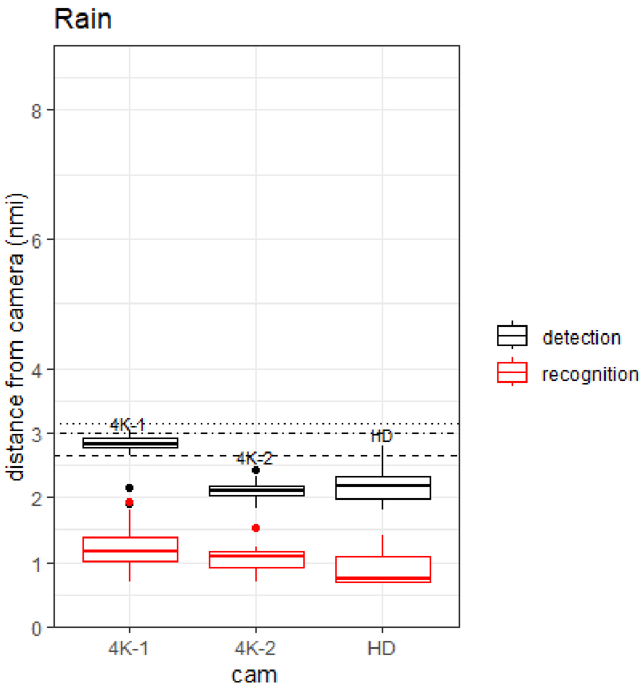
TABLE VII. shows the post-hoc tests differences and their significance values: Rather identically to the detection results, the 4K-1 is significantly worse in "Dusk", but significantly better in "Opposite-Sun", "Rain", "Significant Clouds" and "Low Visibility", and "CAVOK with Clouds". In "Blue Sky" conditions there are no significant camera differences.

TABLE VII. PAIRWISE T-TEST COMPARISON OF THE CAMERAS FOR RECOGNITION DISTANCES WITH BONFERRONI ADJUSTMENT (T = T-VALUE, D= DIFFERENCE; CI = CONFIDENCE INTERVALL).

	Group 1	Group 2	n1	n2	t	df	p	p-adjusted		D	95% CI
Sun											
	4K-2	HD	16	16	6.0218	15	0.000	0.000	***	0.436	[0.282, 0.580]
	4K-2	4K-1	16	16	-3.9825	15	0.001	0.004	**	-0.397	[-0.609, -0.184]
	HD	4K-1	16	16	-6.3142	15	0.000	0.000	***	-0.833	[-1.110, -0.552]
Rain											
	4K-2	HD	15	15	3.3314	14	0.005	0.015	*	0.211	[0.075, 0.348]
	4K-2	4K-1	15	15	-1.6355	14	0.124	0.372		-0.124	[-0.286, 0.039]
	HD	4K-1	15	15	-5.1496	14	0.000	0.000	***	-0.335	[-0.475, -0.195]
Dusk											
	4K-2	HD	15	15	0.0283	14	0.978	1.000		0.003	[-0.222, 0.228]
	4K-2	4K-1	15	15	5.6031	14	0.000	0.000	***	0.642	[0.396, 0.888]
	HD	4K-1	15	15	4.5887	14	0.000	0.001	**	0.639	[0.340, 0.938]
CAVOK											
	4K-2	HD	15	15	3.7923	14	0.002	0.006	**	0.410	[0.178, 0.643]
	4K-2	4K-1	15	15	0.5594	14	0.585	1.000		0.057	[-0.160, 0.274]
	HD	4K-1	15	15	-3.0866	14	0.008	0.024	*	-0.354	[-0.599, -0.108]
Clouds											
	4K-2	HD	13	13	0.6653	12	0.518	1.000		0.018	[-0.041, 0.077]
	4K-2	4K-1	13	13	-3.8178	12	0.002	0.007	**	-0.094	[-0.148, -0.040]
	HD	4K-1	13	13	-4.1448	12	0.001	0.004	**	-0.112	[-0.171, -0.053]
Low Visibility											
	4K-2	HD	17	17	4.7938	16	0.000	0.001	***	0.149	[0.083,0.215]
	4K-2	4K-1	17	17	-3.8858	16	0.001	0.004	**	-0.119	[-0.184, -0.054]
	HD	4K-1	17	17	-5.8124	16	0.000	0.000	***	-0.268	[-0.366, -0.170]
Blue Sky											
	4K-2	HD	16	16	3.9000	15	0.001	0.004	**	0.482	[0.218, 0.745]
	4K-2	4K-1	16	16	1.7166	15	0.107	0.321		0.194	[-0.047, 0.435]
	HD	4K-1	16	16	-2.3452	15	0.033	0.100		-0.288	[-0.549, -0.026]

The following boxplots descriptively depict all RWY26 detection and recognition distances, one boxplot diagram for each "Weather", seven in total (Figure 20). The dashed lines show the objective detection time, pre-assessed by the experimenter by replaying the video streams back and forth to objectively decide for, when the first pixel truly appeared. Within the boxplots, there are 50% of all values. The whiskers show the latest values which are still within 1.5 * interquartile range (IQR).





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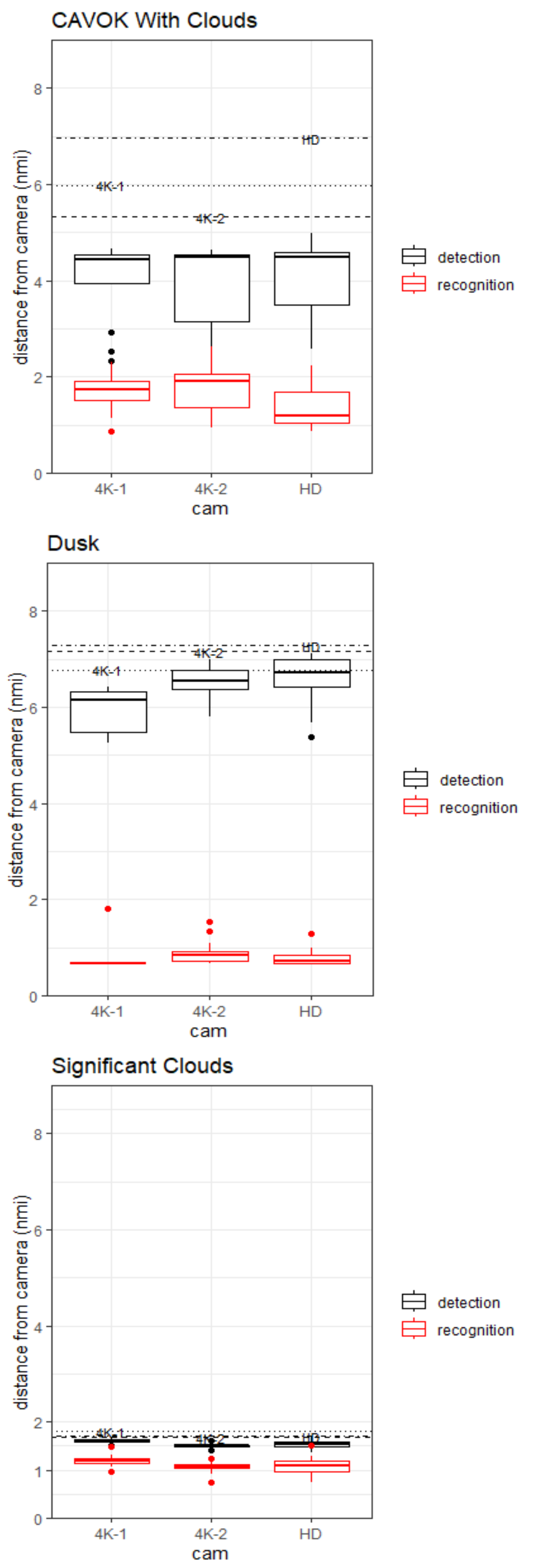

Figure 20. Seven Boxplot diagrams for each of seven different “Weather” conditions showing RWY26 approaches with distances for objective pixel appearance (dashed lines), Detection (black) and Recognition (red) Range Performances w.r.t. each of the three cameras (IV “Cam”).

C. Perceived Video Quality

1) Results for each Video Quality Category

In part two of the experiment, the test subjects were asked to judge the perceived video quality in between of the three simultaneously presented camera video streams via all 10 different weather/visibility conditions (see Figure 16). Their answers were summed up over the “Weather” conditions and the cameras “Cam” compared against each other via the five different video quality categories: “Motion”, “Noise”, “Color”, “Textures”, “Edges”.

The results are presented descriptively via median boxplots and by inferential static analysis pairwise t-tests. When significant differences were gained, it is marked by stars behind the p-value and in bold letters of the better performing camera (see Figure 21 to Figure 25 and TABLE VIII. to TABLE XIII.).

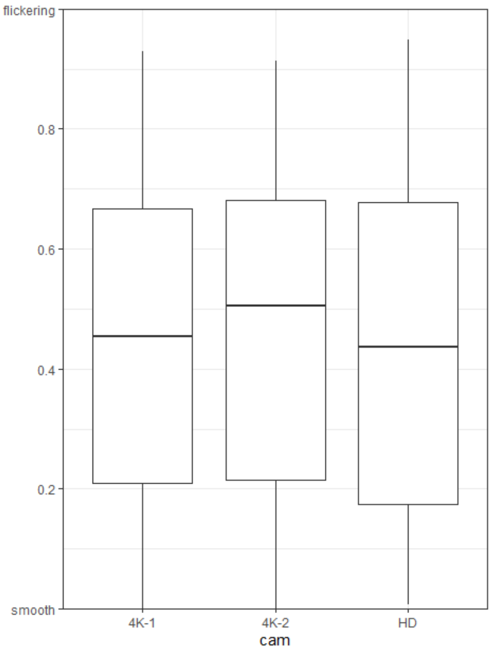

Figure 21. “Motion” - Boxplot diagrams with median and IQRs via three different cameras.

TABLE VIII. PAIRWISE T-TESTS FOR CATEGORY “MOTION”

Group 1	Group 2	n1	n2	t	df	p	p-adjusted	D	95% CI
4K-2	HD	200	200	1.85	199	0.066	0.199	0.025	[-0.002, 0.051]
4K-2	4K-1	200	200	1.44	199	0.152	0.456	0.017	[-0.006, 0.040]
HD	4K-1	200	200	-0.658	199	0.511	1.000	-0.008	[-0.032, 0.016]

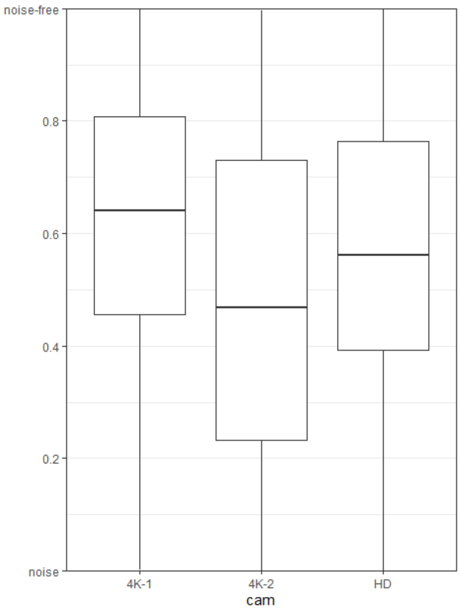

Figure 22. “Noise” - Boxplot diagrams with median and IQRs via three different cameras.

TABLE IX. PAIRWISE T-TESTS FOR CATEGORY “NOISE”

Group 1	Group 2	n1	n2	t	df	p	p-adjusted		D	95% CI
4K-2	**HD**	200	200	-3.03	199	0.003	0.008	**	-0.068	[-0.111, -0.024]
4K-2	**4K-1**	200	200	-5.80	199	0.000	0.000	***	-0.126	[-0.169, -0.083]
HD	**4K-1**	200	200	-2.62	199	0.010	0.028	*	-0.059	[-0.014, -0.103]

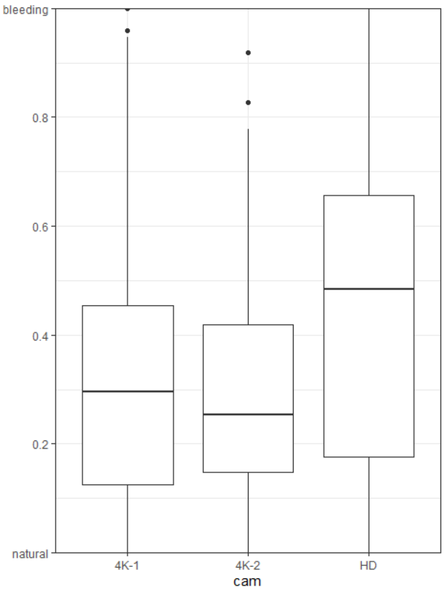

Figure 23. “Color” - Boxplot diagrams with median and IQRs via three different cameras.

TABLE X. PAIRWISE T-TESTS FOR CATEGORY “COLOR”

Group 1	Group 2	n1	n2	t	df	p	p-adjusted		D	95% CI
4K-2	HD	200	200	-6.77	199	0.000	0.000	***	-0.163	[-0.211, -0.116]
4K-2	4K-1	200	200	-1.19	199	0.237	0.711		-0.022	[-0.059, 0.015]
HD	**4K-1**	200	200	5.53	199	0.000	0.000	***	0.141	[0.192, 0.091]

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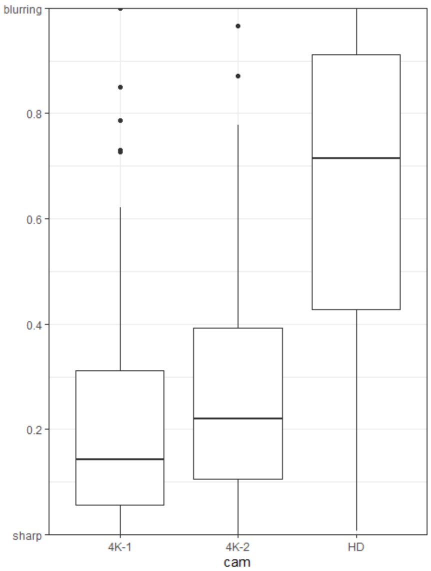

Figure 24. "Edges" - Boxplot diagrams with median and IQRs via three different cameras.

TABLE XI. PAIRWISE T-TESTS FOR CATEGORY "EDGES"

Group 1	Group 2	n1	n2	t	df	p	p-adjusted		D	95% CI
4K-2	HD	200	200	-15.00	199	0.000	0.000	***	-0.388	[-0.439, -0.337]
4K-2	**4K-1**	200	200	3.74	199	0.000	0.001	***	0.058	[0.028, 0.089]
HD	**4K-1**	200	200	16.40	199	0.000	0.000	***	0.446	[0.500, 0.393]

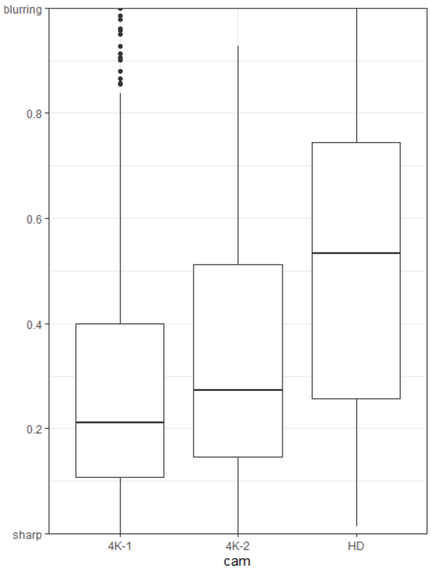

Figure 25. "Textures" - Boxplot diagrams with median and IQRs via three different cameras.

TABLE XII. PAIRWISE T-TESTS FOR CATEGORY "EDGES"

Group 1	Group 2	n1	n2	t	df	p	p-adjusted		D	95% CI
4K-2	HD	200	200	1.92	199	0.056	0.169		0.039	[-0.001, 0.080]
4K-2	**4K-1**	200	200	-6.83	199	0.000	0.000	***	-0.173	[-0.223, -0.123]
HD	**4K-1**	200	200	-7.81	199	0.000	0.000	***	-0.212	[-0.266, -0.159]

2) *General Perceived Quality of Video*

After watching the 21 videos for the RWY26 approaches, the test subjects were asked to rate their general perceived video quality on each single watched video, without the chance to compare it with simultaneously presented videos. TABLE XIII. shows the pairwise t-tests results and the respective descriptive boxplot diagram is seen in Figure 26 for the ratings on a Likert scale ranging from 1 to 5.

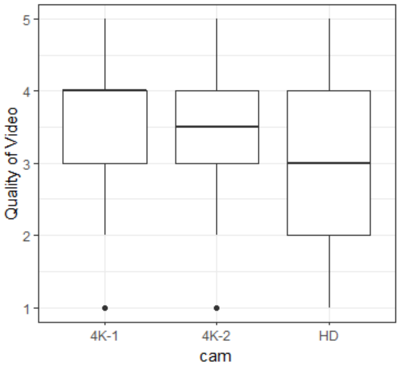

Figure 26. Video Quailty - Boxplot diagrams with median and IQRs showing the ratings for three different cameras via all 10 weather/visibility conditions and all video quality categories.

TABLE XIII. VIDEO QUALITY FOR THREE CAMERAS - PAIRWISE T-TESTS

Group 1	Group 2	n1	n2	t	df	p	p-adjusted		D	95% CI
4K-2	HD	126	126	3.33	125	0.001	0.003	**	0.294	[0.119, 0.468]
4K-2	4K-1	126	126	-2.15	125	0.033	0.100		-0.206	[-0.017, -0.396]
HD	**4K-1**	126	126	-5.10	125	0.000	0.000	***	-0.500	[-0.306, -0.694]

Two of the camera-pairwise comparison became significant, the 4K-1 and the 4K-2 are rated significantly higher than the HD camera.

3) *Readability of the Lettering sign*

With each of the 3 "Cam" x 7 "Weather" = 21 RWY26 approach videos, the test subjects were asked to judge the readability of sign lettering 240m away from the camera on a 5-point Likert scale. See TABLE XIV. and the respective descriptive boxplot diagram Figure 27.

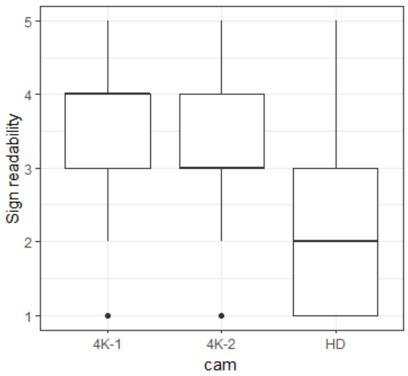

Figure 27. Lettering Sign Readability - Boxplot diagrams with median and IQRs via three different cameras for over all seven RWY26 weather/visibility conditions".

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TABLE XIV. PAIRWISE T-TESTS FOR “SIGN READABILITY

Group 1	Group 2	n1	n2	t	df	p	p-adjusted		D	95% CI
4K-2	HD	126	126	18.6	125	0.000	0.000	***	1.440	[1.290, 1.600]
4K-2	4K-1	126	126	-0.36	125	0.723	1.000		-0.040	[0.182, -0.261]
HD	**4K-1**	126	126	-12.0	125	0.000	0.000	***	-1.480	[-1.240, -1.730]

Both 4K cameras are significantly better in readability than the HD camera.

IV. DISCUSSION OF THE RESULTS

The overall goal of the study was to compare the performance of 4K vs. Full HD cameras in an RTOS environment, focusing on detection and recognition range performances, and the subjectively perceived video quality.

With respect to “detection”, results did not show a significant effect on the main factor “Cam”, but only on the “Weather” factor and on the “Cam x Weather” interaction. Therefore, hypothesis $H_{0,1}$ will not be rejected, saying: “There are no differences between HD and 4K cameras in terms of their detection range performance”. However, in dependence on the “Weather” conditions there are significant differences between the cameras, even when the effects are rather small.

For instance, in “Rain” and in “Low Visibility”, the 4K-1 is better than the HD camera, but, on the other side, much worse in the “Dusk” condition. The older generation 4K-2 camera often performs in between of the 4K-1 and HD performance. The same result pattern occurred with the detection of small aircraft from the North: There are no significant differences in between of the cameras over all “Weather” conditions.

With respect to “recognition”, there too is a significant main effect on “Weather” but also on “Cam” and its interaction, which makes the main effect “Cam” hard to interpret. Therefore, also $H_{0,2}$ cannot be rejected and will be retained, saying: “There are no differences between HD and 4K cameras in terms of their recognition range performance”. Again, there are significant differences in between of the cameras under the different “Weather” condition, saying, quite often the 4K-1 shows the better performance but also the HD has its advantages (see TABLE VII.).

Finally, $H_{0,3}$ states that there are no differences between HD and 4K cameras in terms of their perceived video quality. Except for the *Motion* category, where no significant differences could be found, which would not have been expected, since all cameras operated with the same video update rate of 30fps, the 4K cameras always performed significantly better than the HD. The 4K cameras are perceived to be sharper in terms of *textures* and *edges*, with more *color fidelity* and lower *noise*. $H_{0,3}$ is therefore rejected and the alternative hypothesis is to be assumed stating: “4K cameras in this setting deliver a better perceived video quality”. This decision is supported by the two further tests in which the test subjects were asked to generally assess the quality of the video, and also to assess the readability of a lettering sign 240m away. In both tests, the 4K cameras performed significantly better than the HD camera.

How can this result pattern be explained and what conclusions can be drawn for future implementations of an RTOS? As postulated in the three hypotheses, based on the technical performance and configurations of 4K and HD cameras used in this study, no tremendous performance differences were assessed, even if the 4K cameras were able to show significant advantages in some situations and with the perceived video quality. On the technical performance level, both (putting the old generation 4K-2 camera aside), the HD and 4K-1 camera, deliver at 50 Mbps max bitrate. By the chosen FoV, the 4K delivers 65 pix/°, the HD only 45 pix/°, saying, the 4K therefore has a higher angular resolution, but possibly loses this advantage again because the 4K has four times more pixels to deliver, which cannot be delivered with the same bit per pixel rate like the HD can do, because, in average, with a maximum bitrate of 50 Mbps, the 4K can process 1000 pixel with 200 bits, the HD instead up to 800 bits per 1000 pixel (see TABLE I.). These contrasting effects of a higher ‘angular resolution’ and lower ‘bits/pix*10^3’ rate probably compensate each other and detection and recognition rates are rather similar in between of 4K and HD, with slight advantages for the 4K in this experiment setting (TABLE I).

On the other hand, an RTOS typically delivers a 360° panoramic video stream with multiple cameras arranged in a circle and sums up the horizontal FoV of each camera into an overall 360° panorama. In our setting, with a 4K horizontal FoV of 60°, at least six (better seven cameras including some overlap needed when the streams get stitched to each other), and with the HD FoV of 43° at least nine cameras would be needed for a full 360° panorama video stream. With a maximum data stream of 50Mbps per camera, the nine HD cameras would consume 450Mbps, the 4K panorama just 7 x 50Mbps = 350Mbps. The bandwidth needs for HD panorama would be much higher, and thus the costs. However, both, 450, but also 350Mbps would be much too much and/or expensive for most prevailing infrastructures. The data streams have to be further compressed, down to a typically used maximum of 100Mbps (depending on the prevailing infrastructure and other constraints, often it is even less). To achieve this the HD panorama stream has to be compressed much more than the 4K panorama stream, factor 4.5 compared to 3.5. It cannot be stated directly what comes out of it because this panorama setting has not been tested but one would assume that the performance of the HD will continue to lose out compared to 4K panorama solutions. Furthermore, in this setting, the vertical FoV of the 4K is slightly higher, 33° for 4K and only 24° for the HD panorama, which would be another advantage for the 4K solution.

It is further to be noted that when transmitting more (up to four times more) pixels and if these pixels are to be presented pixel by pixel (pixel-true), more displays or higher resolution displays (typically 4K instead of HD) are needed. Since the pixels become smaller with more pixels presented on the same display size, the controller also has to move closer to the displays in order to resolve the presented pixels with the human eye resolution of approx. 60pix/°. With a 4K 27-inch display for instance, the eye distance from the display must not be greater than 53 cm, which becomes a challenging factor for the design of an RTOS working position.

The bottom line is that 4K is probably the better alternative. Even when the single sensor is slightly more expensive (by about 25%), energy-intensive with a smaller bit/pixel ration, the 4K offers on the positive side a better ratio of FoV and angular resolution, a slightly better detection and recognition performance, and a better perceived video quality. Further on, in a 360° panorama composition fewer cameras are needed, which compensates costs and energy consumption and improves the bit/pixel ratio compared to the HD solution.

V. CONCLUSION & OUTLOOK

In a nutshell, what is the better optical sensor for an RTOS, 4K or HD? Based on the current state of the art technology, there is no 100% clear answer. When comparing *individual* 4K and Full HD cameras, the measured performance differences in this setting were rather marginal. Although this study revealed slight advantages for the 4K camera, the advantages depend very much on the weather/visibility conditions and the camera settings chosen. The selected settings of the individual cameras in this comparison were chosen as they would be used in a 360° RTOS video panorama. In such a 360° composition of several individual cameras it is to be expected that the slight advantages of 4K technology would become even more apparent.

All cameras under investigation in this study facilitated the same codec H.264. More modern codecs like H.265 or AV1 allow higher max bitrates and thus could improve the overall quality of the video streams. On the other hand, the encoding principles of modern codecs tend to eliminate small details. This could even lead to a reduction of the detection performance compared to H.264. The influence of codec and bitrate needs to be investigated in a separate study.

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