WHITEPAPER

Electronic lookout function for increased ship safety

Lookout requirements can be met by technology, supporting crews on board and increasing vessel safety

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Introduction

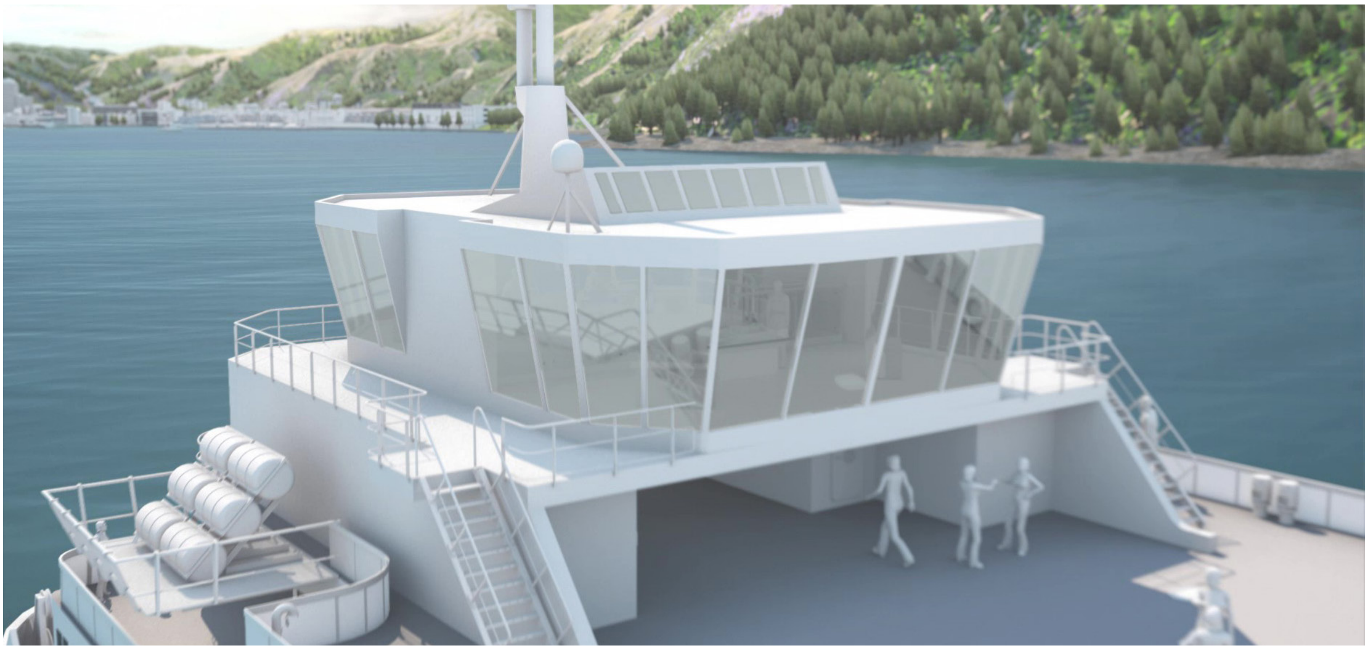
Traditionally, the navigational watch of ships consisted of the officer of the watch, the lookout and the helmsman. If the situation required enhanced safety, the watch could be extended with the master, a pilot and/or an additional lookout. In this paper, the task is to evaluate the possibilities and challenges of substituting the function of the lookout with a technology-based system.

When assessing the possibilities of defining a machine-based visual lookout for use in ships in international commercial traffic, it quickly becomes apparent that the current legal system needs some adjustment. The provisions in SOLAS, STCW 2010 and COLREG are very descriptive with the weight of requirements on matters such as the design and construction of the bridge and the vision and hearing of the able seaman or rating of the watch. In a goal-based system, it would be preferred to develop functional descriptions for the lookout, with the minimum levels of information input defined.

In general, the practice of automating functionalities in the marine industry has a requirement to achieve “equal or better” level of safety with use of an automated system, in comparison to a manual one. The main challenge is, therefore, to define the current level of safety. Human performance is defined rather vaguely in regulations, and depends significantly on the person, health, alertness, time of day, environmental conditions, etc. It is evident that the different combination of all affecting circumstances will add up to a very various quality of the human performed visual lookout. This makes defining the current performance level not at all straightforward. In the current regulatory system, there are no quantitative threshold values, which would define the minimum performance level. In order to define the requirements for the technology that would achieve “the same or equal” performance as the human lookout, such minimum quantitative threshold values and functional requirements are needed.

The main challenge from the regulatory perspective today is defining how to regulate the human eye-sight and decision-making abilities based on the sensory input. This paper mainly focuses on the open sea navigation tasks with no land in sight and where other vessels are generally far away.

This paper assesses the performance of an electronic lookout function from the available sensory input data and associated fundamental limitations of the visual lookout performed by a human. The conclusion demonstrates that an equal, or better, level can be achieved by means of technology. In addition, this paper does not study audible sensory input. Following the introduction of totally enclosed bridges, it is generally accepted that the audible signals can be provided by a sound reception system (SOLAS Ch. V/19.2.1.8).



[1] SOLAS Chapter V regulation 19.2.1.8, minimum standards of ISO 14859:2012(en)

Content

Current performance of human lookout **4**
Tasks and requirements of the lookout 4
Information sources for decision making **4**
The visual picture **6**
Fundamental boundary conditions 6
Limitation due to the visibility 6
Limitation due to the curvature of the Earth 7
Requirement of the human lookout expressed in numerical format 7
Combining the curvature of the Earth limitation with the required eyesight resolution of the human lookout 9
Human lookout is not a continuous wide-angle monitoring sensor 9
Low-light performance of a human lookout 10
Implications and minimum requirements for the technology **11**
Minimum sensory input for machine-based lookout 11
Detection – main task of the human lookout 11
Angular resolution, pixel resolution and field of view 12
Minimum detectable object size 12
Trials and lessons learned 13
From detection to decision 15
Beyond human performance 15

Current performance of human lookout

Tasks and requirements of the lookout

The task and purpose of the lookout is simple. So simple, in fact, that it is sometimes overlooked. The function of the lookout can be divided into two specific basic areas: the safety of the own vessel and the safety of everyone else in the vicinity. The task of the lookout can be described as assisting the officer of the watch to obtain the best possible situational awareness of the surroundings and the operating environment. As the purpose of the navigation rules is to prevent collisions, consequently the task of the lookout is to monitor and communicate the information required to avoid collisions. This fundamental purpose for maintaining a proper lookout needs to be kept in mind. Sight, hearing, and "all available means" are the tools of the lookout. The requirement regarding hearing is not considered in this paper.

Another duty of the lookout is contributing to the monitoring and controlling of a safe watch. This duty is invoked due to the requirements of human interaction for arranging and executing the relief, maintenance and handover of a watch in conformity with accepted practices and procedures. Human interaction requires the ability to understand orders, using shipboard terms and definitions, as well as to communicate in a clear and concise way with the officer of the watch, seeking advice/clarification on matters relevant to watchkeeping duties required to maintain a safe watch. With an electronic lookout function, the human interaction required for transferring information when handing over the watch, and consequently interruptions of the function, can be reduced.

The duties of the lookout and the helmsperson are separate, and the helmsperson shall not be tasked with additional duties, such as performing the function of a lookout. With the developments of navigational technology, the helmsperson may be waived from the muster list if the vessel is equipped with a functional and approved autopilot. It is already permitted for the officer in charge of the navigational duties to be the sole lookout during daylight and under certain conditions, performing all the duties described as the functions for safe navigation. This has been made possible through the development of supporting technologies. The requirement of maintaining a proper lookout by hearing can be performed through the means of technology by utilizing a sound reception system fulfilling the minimum standards of ISO 14859:2012(en).

The STCW 2010 convention[1] (see Table 1 for details) specifies the minimum standard of competence for ratings forming part of a navigational watch. It defines the duty of the watch to keep a proper lookout by sight and hearing. It is also required that the lookout shall have the professional competence to interpret the information available through the means at hand. Such information includes sound signals, lights and other objects, such as aids to navigation. The responsibility of the lookout is to report the approximate bearing of any observations in degrees or points to the officer of the watch. It is implicit that the function has no meaning unless the information can be communicated to the officer of the watch in a clear and concise way, using shipboard terms and definitions, with the best possible accuracy.

The STCW Code lays out the minimum requirements regarding watchkeeping arrangements and principles in its Part A, Section A-VIII/2, PART 1. More specifically, it is stated in PART 4-1 Paragraph 14 that the purpose of a navigational lookout is: "Maintaining a continuous state of vigilance by sight and hearing as well as by all other available means, with regard to any significant change in the operating environment" at all times in all weather conditions both day and night. "Significant" in this context refers to the relative quality of the information input to the officer of the watch and will be one of the key topics. This particular part of the STCW Code is hard to reflect in an algorithm, however, it is worth noting that it may be the most important one.

"Fully appraising the situation and the risk of collision, stranding and other dangers to navigation" is key to the safety of the own vessel and rather well understood and straightforward. "Detecting ships or aircraft in distress, shipwrecked persons, wrecks, debris and other hazards to safe navigation" describes both the safety of the own vessel and the safety of others. This has also been one of the most discussed parts in the discussion of Maritime Autonomous Surface Ships (MASS). The challenge is, how do we ensure that any party in distress in high seas receives the best possible chance of being detected and rescued? One specific task that could be included in the future definitions and regulatory development should be the detection and response to a "Man overboard" situation. The necessary future requirements for automated lookout functions would need to encompass a degree of image and pattern recognition in order to detect and notify of any abnormal conditions or occurrences.

STCW 2010 Medical requirements for duty on deck[2]:

- Vision (appendix A), hearing (appendix B) and physical capabilities (appendix C);
- Impairment from the use of medication (appendix D); and
- Presence or recent history of an illness or condition (appendix E).

The requirements of the lookout as stated in STCW 2010 are described are described in Table 1. The minimum aided distance vision requirement for deck officers and ratings is 0.5 in Snellen's chart, which corresponds to 6/12 (or 20/40) in visual acuity numbers.

1 https://www.imo.org/en/OurWork/HumanElement/Pages/STCW-Conv-LINK.aspx
https://www.edumaritime.net/stcw-code/stcw-ii-4-rfpnw
2 https://www.classnk.or.jp/hp/pdf/activities/statutory/mlc/flag/sgp/sc_no_13_of_2013annex_a.pdf

Table 1: Minimum in-service eyesight standards for seafarers

STCW Convention regulation	Category of seafarer	Distance vision Aided[1]		Near/immediate vision	Color vision[3]	Visual fields[4]	Night blindness[4]	Diplopia double vision)[4]
		One eye	Other eye	Both eyes together, aided or unaided				
I/11 II/1 II/2 II/3 II/4 II/5 VII/2	Masters, deck officers and ratings required to undertake look-out duties	0.5[2]	0.5	Vision required for ship's navigation (e.g., chart and nautical publication reference, use of bridge instrumentation and equipment, and identification of aids to navigation)	See Note 6	Normal Visual fields	Vision required to perform all necessary functions in darkness without compromise	No significant condition evident
I/11 III/1 III/2 III/3 III/4 III/5 III/6 III/7 VII/2	All engineer officers, electro-technical officers, electro-technical ratings and ratings or others forming part of an engine-room watch	0.4[5]	0.4(see Note 5)	Vision required to read instruments in close proximity, to operate equipment, and to identify systems/components as necessary	See Note 7	Sufficient visual fields	Vision required to perform all necessary functions in darkness without compromise	No significant condition evident
I/11 IV/2	GMDSS Radio operators	0.4	0.4	Vision required to read instruments in close proximity, to operate equipment, and to identify systems/components as necessary	See Note 7	Sufficient visual fields	Vision required to perform all necessary functions in darkness without compromise	No significant condition evident

Notes:

1. Values given in Snellen decimal notation.
2. A value of at least 0.7 in one eye is recommended to reduce the risk of undetected underlying eye disease.
3. As defined in the International Recommendations for Colour Vision Requirements for Transport by the Commission Internationale de l'Eclairage (CIE-143-2001 including any subsequent versions).
4. Subject to assessment by a clinical vision specialist where indicated by initial examination findings.
5. Engine department personnel shall have a combined eyesight vision of at least 0.4.
6. CIE colour vision standard 1 or 2. Other equivalent confirmatory test methods currently recognized by the Administration may continue to be used. (Added by Res.MSC.374(93))
7. CIE colour vision standard 1, 2 or 3. Other equivalent confirmatory test methods currently recognized by the Administration may continue to be used.

Information sources for decision making

Modern SOLAS ships have mandatory navigational equipment for assisting in determining the position, heading and detecting the relevant obstacles in the surroundings. In general, vessels typically have radar, gyrocompass, ECDIS, GNSS-based positioning system and an AIS. In addition to these devices, the lookout uses their eyes and ears to monitor the surroundings. If lookout performed by hearing is replaced by the already existing acceptance of using a sound reception system, the main sensory input for targets that are far away, in addition to the abovementioned navigational instruments, is the eyesight of the human lookout.

The visual picture

Fundamental boundary conditions

From the perspective of physics, there are two main aspects, which fundamentally limit the ability of a human lookout to detect targets from the bridge. Namely, the curvature of the Earth and the visibility. In perfect visibility conditions, the maximum range of the human vision performance to detect targets is limited by the curvature of the Earth. In order to determine quantitative values for the performance of the human lookout, very conservative limitations can be set by the physical limitations due to the visibility and the curvature of the Earth.

Limitation due to the visibility

The visibility in the lookout context defines the distance by which an object or light can be clearly discovered. The visibility can be impaired by fog, haze, rain, humidity, as well as any other disturbance that absorbs, scatters or blocks the visible light wavelengths and therefore decreases the visible range. The definition of visibility as a range is not unambiguous as it depends on the target properties, light conditions, etc.

This paper assumes that if the target is further away than the visibility range, a human lookout cannot detect it. On the other hand, if the target is closer than the visibility range, the human lookout can detect it. Therefore, this paper assumes that the visibility sets the maximum range where the human lookout can detect an object relevant for performing the lookout function

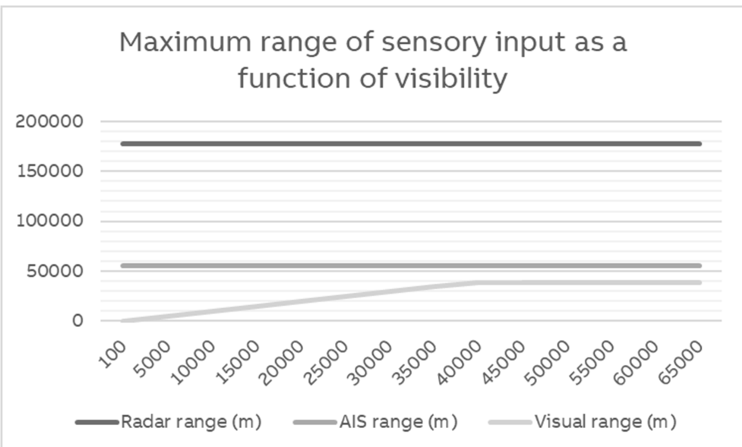


Figure 1: Illustrative detection performance range (in meters) of the sensory input of a human lookout as a function of visibility, assuming target and observer size allowing the target to be detectable for a human at 39,1 km.

Limitation due to the curvature of the Earth

The curvature of the Earth limits the visibility of targets on the horizon at open sea. The maximum distance that an observer with a height h_O can detect a target with a height h_T on a horizon can be calculated by

$$D_{max} \approx 3{,}57 \cdot \left(\sqrt{h_O} + \sqrt{h_T}\right) km.$$

As an example, consider an observer at height of $h_O = 30\ m$ and an object of height of $h_T = 30\ m$. In this setup, the distance at which the object disappears below the horizon is approximately D_{max} = 39.1 km.

On a clear day with perfect visibility, a human observer at the height of 30 m can see another object that has a 30 m height from the distance of approximately 39.1 km (neglecting the effect of refraction of the light, which may extend the range slightly). Target of the same height that is farther than 39.1 km will disappear below the horizon due to the curvature of the Earth.

Requirement of the human lookout expressed in numerical format

Human eyesight performance depends on the eye health, the visual acuity (clarity of the vision), light and impaired visibility (such as haze, rain and fog) in the line of sight, as well as the target that a human is looking at. In general, defining the current level of eyesight performance of the human lookout from the physiological perspective is not unambiguous and is therefore not considered here from all aspects. The paper rather defines a conservative criterion based on the resolution derived from the eyesight requirement. Generally, a common definition of the human eyesight angular resolution for perfect vision (1.0 in Snellen's chart)[3], is defined to be approximately 1 arcminute.

This means that a human with perfect eyesight can distinguish an object from a point or another object if the object extends 1 arcminute (0.0167°).

However, it is important to notice that STCW 2010 does not require perfect vision for human lookout. In fact, as described in Table 1 the requirement is 0.5 in Snellen's chart, which means 6/12 (or 20/40) in visual acuity numbers. In practice, this implies that the angular resolution requirement for human lookout is approximately 2 arcminutes (0.0334°).

In practical terms, this means that the farther the object is, the bigger it needs to be in order to be detectable by the human lookout. The practical aspect of the human lookout resolution requirement is illustrated in Figure 2, where the human lookout resolution is denoted by:

$$\alpha_{res,h} \approx 2\ arcminute\ \approx 0{,}0334°.$$

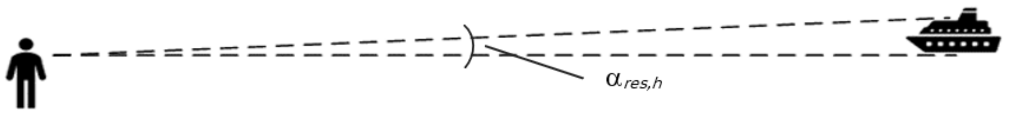


Figure 2: Illustration of the required resolution for the human lookout.

It is important to note that the current lookout requirement relates only to the maximum performance of the vision. In practice, this applies only in a very limited field of view around the point of fixation. As illustrated in Figure 3, when the object is outside the central field of view, the performance of the eyesight drops significantly. In this context, the term "foveal vision" is often used for defining the central 1.5–2° of the visual field. Vision within the fovea is generally called central vision, while vision outside of the fovea is called peripheral, or indirect vision[5]. The angle deviation from the point of fixation declines the performance of the vision. In terms of acuity numbers, 2° deviation from the center of the field of view decreases the acuity number to half of the foveal value[6]; deviation of 4° – to one-third, deviation of 6° – to one-fourth etc.

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3 https://www.classnk.or.jp/hp/pdf/activities/statutory/mlc/flag/sgp/sc_no_13_of_2013annex_a.pdf

4 http://www.icoph.org/downloads/visualstandardsreport.pdf

5 Strasburger, Hans; Rentschler, Ingo; Jüttner, Martin (2011). "Peripheral vision and pattern recognition: A review". Journal of Vision. 11 (5): 13. doi:10.1167/11.5.13. ISSN 1534-7362. PMID 22207654.

6 The decline is according to E2/(E2+E), where E is eccentricity in degrees visual angle, and E2 is a con-stant of approximately 2°. An E2 value of 2° results from Anstis' (1974) Figure 1, with the foveal value assumed to be standard 20/20 acuity.

The deviation of 30° decreases the acuity number to one-sixteenth of the foveal value.

The performance of the human lookout as a function of the angular deviation from the center of the field of view is illustrated in Table 2. In addition, the table describes the impact of the declined visual acuity and illustrates the impact on the angular resolution. Moreover, to illustrate the impact on the performance for the human lookout, an example results of the range to detect a 2-meter object is calculated and shown in the table. The table illustrates the limitation of the human lookout, where the performance decreases rapidly when the object is even 2° off from the center of the field of view.

Deviation from center of field of view (deg)	0	2	4	6	30
Acuity of human lookout	20/40	20/80	20/120	20/160	20/640
Angular resolution (arcminute)	2	4	6	8	32
Angular resolution (deg)	0.0334	0.0668	0.1002	0.1336	0.5344
Range (in m) to detect 2m object	3431	1715	1144	858	214

Table 2: Performance of the human lookout according to the STCW 2010 requirements as a function of deviation from the center of the field of view. The corresponding angular resolution as well as example calculation of the range to detect a 2-meter object.

Illustration of the detection capability for various target sizes as a function of off-center angle is illustrated in Figure 3. Note that the illustration is based on linear interpolation between the chosen off-center points, and not on the actual mathematical declination of the visual acuity. The illustration is made for emphasizing the fact that the human lookout visual acuity peaks at the center of the field of view, but declines rapidly as a function of the off-center angle.

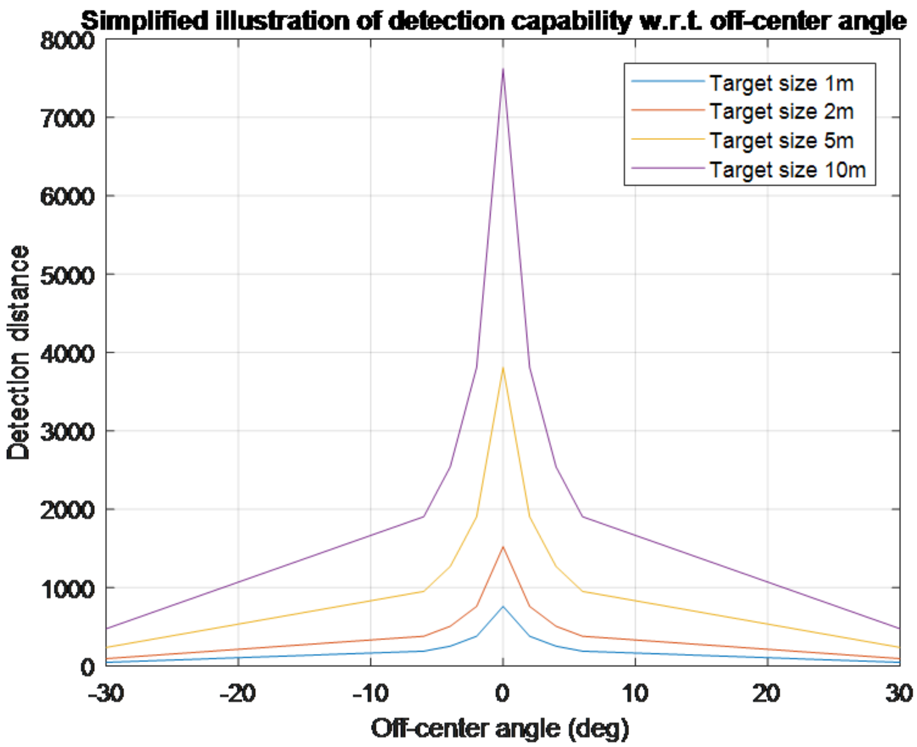

Figure 3: Simplified illustration of the detection capability of a human lookout for different target size according to the decrease in acuity numbers as a function of off-center angle.

Combining the curvature of the Earth limitation with the required eyesight resolution of the human lookout

When combining the curvature of the Earth limitation with the minimum angular resolution of the eyesight of the human lookout, one can calculate the practical maximum range of a target above the horizon that is detectable by a human. This can be achieved by matching the maximum distance and the resolution. The height of the object $h_{T,r}$ at distance $D_{max,h}$ matching the human lookout required eyesight resolution $\alpha_{res,h}$ can approximated by

$$h_{T,r} \approx \alpha_{res,h} \cdot D_{max,h}.$$

Combined with the distance approximation due to the curvature of the Earth so that the object is $h_{T,r}$ above the horizon, one obtains

$$\begin{cases} D_{max,h} \approx 3{,}57 \cdot \left(\sqrt{h_O} + \sqrt{h_T - h_{T,r}}\right) \\ h_{T,r} \approx \alpha_{res,h} \cdot D_{max,h} \\ 0 \leq h_{T,r} \leq h_T \\ D_{max,h} \geq 3{,}57 \cdot \sqrt{h_O} \end{cases},$$

Solving $D_{max,h}$ from the equation gives the approximation of the range a human lookout can detect.

As an example, considering an observer with h_O=30 m, combined with the human lookout required eyesight resolution, a h_T=30 m high object becomes distinguishable for a human lookout when the object is approximately at $D_{max,h}$=31.7 km distance. At this distance, the object is $h_{T,r}$=18.5 m above the horizon, which is approximately 2 arcminutes in angular resolution from the observer. The principle of the calculations is illustrated in figure 4.

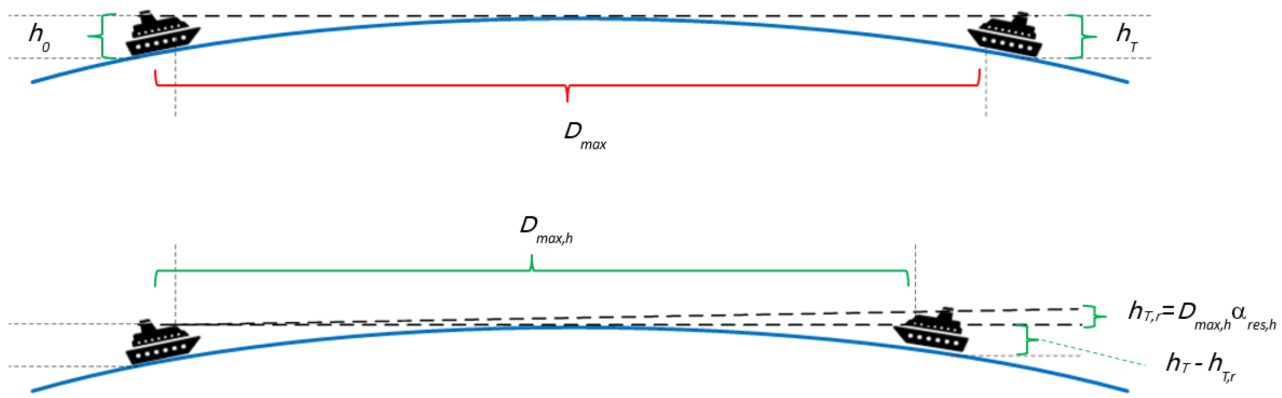

Figure 4: Illustration of the limitation due to the curvature of the Earth (top) and the decreased maxi-mum range due to the human eyesight resolution (bottom).

Human lookout is not a continuous wide-angle monitoring sensor

The eye is a contrast detector, and not an absolute detector like a sensor in a digital camera – thus the distinction[7]. The Human eye is able to function in bright sunlight and view faint starlight. The eye's resolution is the critical visual angle is a function of brightness and contrast. The eye is not a single-frame snapshot camera. It is more like a video stream. The eye moves rapidly in small angular amounts and continually updates the image in one's brain to create the detail. Our brains combine the signals from both eyes to increase the resolution further. We also typically move our eyes around the scene to gather more information.

What we “see” is, in fact, a constantly changing field of information, which we continuously update and reassemble into the “big picture”. Our eyes dart about gathering data, retaining static information, while continuously scanning the scene and updating details that change within our fields-of-view. The picture seen any given moment is a composition of numerous bits of data gathered over multiple moments in time. That said, the human eye really sees a larger field of view. Human vision, as interpreted by

7 See Figure 2.6 in Clark, 1990; Blackwell, 1946

the brain through two eyes, has a combined field of view of about 120-140°, sometimes a bit less, but seldom more. This means the human eyes see the world similar to the way a wide-angle, panorama camera captures it on film, minus the distortions. While the angle of view can be described as ultra-wide, the overall perspective and spatial relationships between objects within the image field are rendered as if taken with a regular lens. The amount of image area a human actually focus on at any given point in time is only about 0.5° of the total scene. Human lookout is not a continuous wide-angle monitoring sensor

Even though human is unconsciously updating the visual picture around the point of fixation by involuntary eye movements, the field of view is rather narrow when the eye is fixed to a certain object. This implies that a human cannot continuously focus on objects which are in totally different sectors at the same time. Having a full focus on one detail can lead to a situation where the human lookout may not be aware of changes to other surrounding objects. This, in turn, can lead to a situation where an object that the human lookout wasn't focusing on initially may appear in the field of view as a surprise, as focusing on one point can lead to the deterioration of the overall attention.

Human vision is not a continuous real-time wide-angle sensor designed for real-time monitoring of surroundings from a wide field of view. Rather the contrary. Human vision is very good at monitoring and interpreting a specific situation when required to focus on details, but due to the intermittent nature of wide-angle monitoring, it is very likely that in complex situations, a human very easily misses or forgets objects which may be relevant in the prevailing scenario. Therefore, one cannot assume that human would be able to continuously focus on 225° field of view monitoring as required in SOLAS ch5. req. 22. Instead, human lookout is performing the monitoring tasks in an intermittent manner, subject to the alertness, drowsiness and humane distractions.

Low-light performance of a human lookout

A human eye detects color in the central portion of the field of view, which is where most of the eye's color-sensitive cones are located. Cones are responsible for our daylight vision and are dedicated to capturing red, green or blue light. As daylight fades, the cones recede in activity and are supplanted by the rods, which are monochromatic. As a result, much of what is seen at night is rendered in black and white. Even in bright light, the edges of our field of view remain monochromatic. If someone stares straight ahead while another person enters the corner of the field of vision wearing a red shirt, the observer doesn't register the color of the shirt until his or her eye darts over to catch a fleeting glance of it.
Light sensitivity is extremely acute in rods, which can detect light levels as low as a single photon. As a point of reference, under average lighting conditions, a human eye recognizes about 3000 photons every second. And because the central area of the human field of view is overwhelmingly populated with daylight-oriented cones (especially in the centrally-located fovea), the eye actually sees more image detail off-center once the sun dips below the horizon.
The low light performance of the human lookout is limited to the perception of visible light. Even though human eye is very sensitive and has high performance in low light, there are two aspects which need to be emphasized when considering the performance of the human lookout in low light conditions. Firstly, the dark adaptation of the human eye takes a long time (20-30 minutes). In case the human lookout becomes subject to any bright light during operation, the low light performance of the lookout function before the eye has readapted to dark is poor. Secondly, human lookout only perceives visible light wavelengths. The modern cameras have automatic IR cut filter removal, which makes the camera more sensitive to IR wavelengths and therefore significantly improve the perception capability in low light conditions.

Implications and minimum requirements for the technology

Minimum sensory input for machine-based lookout

As discussed above, the sensory inputs for the human lookout are the SOLAS navigational aid equipment as well as the human eyes. As the navigational aid equipment required by the SOLAS convention is already digital, the main challenge is to define the technological requirements to achieve "as good or better" detection performance by visual means. The most advanced, yet commercially feasible technology to achieve the visual perception is camera technology, equipped with computer vision. In the following, the camera technology requirements are analyzed based on the fundamental boundary conditions set by the curvature of the Earth and visibility.

The human lookout performs the sensor fusion, combining, analyzing and evaluating the information received from each modality (visual, radar, charts, etc.) to determine the overall assessment of the situation manually, in order to achieve the same level of performance with a machine-based lookout. Therefore, it is only necessary to prove that the computer vision can achieve adequate level of performance in the boundary conditions. Consequently, the main tasks to demonstrate the equivalency by means of visual technology are:

- Detection of a target of which minimum projected dimension extends 2 arcminutes above the horizon in good visibility conditions.
- Detection of target of which minimum projected dimension extends more than 2 arcminutes in the field of view at the visibility range in decreased visibility/light conditions (various visibility conditions and object sizes should be tried).
- Detection of a target in front of the horizon that extends 2 arcminutes in the minimum projected dimension in good visibility conditions.

If the above can be demonstrated, the minimum level of a lookout, that is, detecting the targets is shown to be "as good or better" than human.

Detection – main task of the human lookout

In terms of surveillance terminology, where the tasks of a surveillance system are defined as monitoring, detection, recognition and identification, the tasks of the lookout are monitoring and detection. In practice, this means monitoring the surroundings and detecting anomalies, as well as communicating that to the officer of the watch.

There are global industrial standards for surveillance systems for designing a system corresponding to a certain requirement for a specific task. Therefore, the technical requirements for an electronic system matching the defined performance of the human lookout can be based on existing global standards, such as 'IEC 62676-4 Video surveillance systems for use in security applications – Part 4: Application guidelines'.

Consider a target that is just above the

Angular resolution, pixel resolution and field of view

horizon. In perfect visibility conditions, the target can barely be visible for a human lookout. Let us study the minimum angular resolution in order to define the requirements for detecting the targets optically. For targets this far away, the required minimum angular resolution to detect a target of 1 m width can be approximated by

$$\alpha_{res} \approx \frac{1}{D}\frac{180}{\pi}°/m,$$

where *D* is the target distance expressed in meters. Note that the approximation is not valid when *D* is small, and α_{res} describes the angular resolution (deg) required to detect a target of a size (width) of 1 m at distance *D*.

A commercial full HD camera has a pixel resolution of 1920 x 1080. In order to roughly determine the camera horizontal field of view (FOV) to match the pixel resolution with the angular resolution of a 1 m object at the distance *D* the following approximation can be used

$$F_{res} \approx P_{px} \cdot \alpha_{res} = P_{px} \cdot \frac{1}{D}\frac{180}{\pi}°/m,$$

where P_{px} is 1920 in case of a Full HD resolution camera. As an example, consider a 30 m high target at 39.1 km distance and an observer looking at the target at 30 m height. Such target can barely be visible in the horizon. The minimum horizontal FOV for a Full HD camera in order to achieve 1 m resolution per pixel at 39.1 km is approximately

$$F_{res} \approx 1920 \cdot \frac{1}{39100}\frac{180}{\pi}°/m \approx 2{,}81°/m.$$

Therefore, in order to achieve the resolution of 1 m / pixel at 39.1 km, the camera FOV should be 2.81°. Note that this approximation neglects the lens disturbance, and some other factors, which may affect the result.

Minimum detectable object size

To achieve the same level of performance with a machine-based lookout, the machine-based lookout needs to be able to detect objects with a resolution that is equal to the defined human lookout performance requirement derived from the STWC 2010 requirements. In that definition, a resolution with a focused eye (meaning very narrow field of view) is $\alpha_{res,h} \approx 2$ arcminute ≈0.0334° . With this criterion, one can estimate the size of a smallest object which can be detected from a fixed distance. Examples of the smallest dimensions of minimum detectable objects are described in Table 3.

Distance (km)	**Smallest dimension of a minimum detectable object (m)**
1	0.6
5	2.9
10	5.8
20	11.6
40	23.3

Table 3: Examples of smallest detectable objects from a fixed distance using the angular resolution criteria of 0,0334°.

In camera-based surveillance and monitoring, there are standard, accepted ways of estimating the distance from which one can monitor, detect, observe, recognize and identify an object. The IEC standard 'IEC 62676-4 Video surveillance systems for use in security applications – Part 4: Application guidelines' defines the requirements for each surveillance task.

Detection is defined as an ability to detect a presence of an object; the primary task of the lookout function is also detecting the presence of targets which are "something else than water".

Using digital camera technology, the different tasks of detection, recognition and identification are directly related to the number of pixels. The minimum projected dimension of an object needs to be represented in the picture for it to be detected, recognized or identified.

In the abovementioned IEC standard, the threshold for detecting a human presence (0,5 m x 1,7 m) is 25 px/m, where px refers to number of pixels. In practice, this means that the width of a human projection (0.5 m as a standard) needs to be represented by 12.5 pixels. Combining the standard detection criterion with the defined angular resolution criterion for the human lookout of $\alpha_{res,h} \approx 2$ *arcminute* $\approx 0.0334°$, the criteria for the performance requirement of camera system resolution to enable detection can be defined as an angular resolution of a single pixel α_{px}

$$\alpha_{px} = \frac{\alpha_{res,h}}{12,5} = \frac{0,0334°}{12,5} \approx 0,002672°.$$

This performance criterion can be achieved with several arrangements of digital cameras combined with suitable optics and mechanical systems. As an example, for a full HD camera, the optical arrangement needs to be chosen so that the horizontal field of view of the whole camera becomes

$$hFOV = 1920 \cdot 0,002672° \approx 5,12°.$$

Note that the human eye resolution decreases rapidly with regards to the angle away from the point of fixation. Deviating 2° off from the point of fixation already drops the resolution by 50 %. Therefore, the absolute boundary of the performance is defined as a very conservative criterion where the system needs to be capable at maximum when focused to a specific direction, not continuously monitoring 360° around the vessel.

Trials and lessons learned

In order to verify theoretical assertions, a camera-operated awareness system was tested in the Helsinki estuary, using a setup that utilized a full HD PTZ-camera with an 30x optical zoom. The horizontal field of view of the camera with maximum zoom settings was 2.3°. The camera was placed at a height of 10 meters above the sea level. The vessel on which the camera was mounted was stationary during the experiment.

Two pleasure crafts with dimensions equal to the “Small pleasure craft” and “Medium pleasure craft” described in Table 4 were used as targets. The crafts were operated at specific distances from the vessel where the camera was mounted. The air was clear, with 4 m/s wind from north east. The air pressure was 1019 hPA and visibility was good. The test was preformed between 04:00 am to 06:00 am.

According to the results, as illustrated in Figure 5, the system could detect the crafts even further than the standard detection criterion indicates. With the mentioned equipment, vessel size and the installation height of the camera, the “Small pleasure craft” should have been detectable at around 5.8 km, whereas the trial showed that the craft was still detectable at 6.8 km.

Figure 5: Picture on the left – two boats at 6.8 km (leftmost the “Small pleasure craft” and rightmost the “Medium pleasure craft”). Picture on the right – the same boats at approximately 9.6 km. Note that the zoom settings of the pictures are different.

The “Medium pleasure craft” could still be clearly detected at 9,6 km. Figure 5 presents the detection result of a deep neural network-based image processing algorithm trained to detect vessels from background.

It would be expected that the ‘Small pleasure craft’ would be detected at around 5.8 km by a human lookout. However, using the new setup, the boat was still detectable at 6.8 km.

The outcome of the test is shown in Table 4 the standard DRI detection criteria and the associated detection distance, considering the curvature of the Earth for various marine-relevant targets, with the detection distance estimated. It offers a detailed account of the way the camera setup can achieve the equal or better resolution than the human eye in good visibility conditions.

	Size of object				Detection distance - human lookout with STCW 2010 requirements	
	L (m)	**H (m)**	**B(m)**	**Detection distance - camera (km)**	**<2° off-center (km)**	**30° off-center (km)**
Small boat	4.7	1.0	1.5	3.8	1.7	0.1
Small pleasure craft	7.0	1.5	2.6	5.7	2.6	0.2
Small pleasure craft	10.2	3.0	3.5	11.4	5.2	0.3
Small passenger ferry	33.0	6.0	8.0	16.1	10.3	0.6
Bunkering vessel	87.8	26.6	13.4	27.1	24.0	2.9
RoPax vessel	136.1	30.0	24.2	28.3	25.3	3.2
Medium range tanker	205.7	30.5	34.3	28.4	25.4	3.3
Aframax	246.9	33.5	41.1	29.4	26.5	3.6
Suezmax	289.6	45.7	48.3	33.0	30.2	4.9
VLCC	378.0	61.0	63.0	36.9	34.2	6.5

Table 4: Comparison of range, human lookout versus HD Pan-Tilt-Zoom (PTZ) camera with resolution of 1920 x 1080 and zoom, installed at 10 m height

Figure 6: A ”Medium pleasure craft” at around 6.8 km range, and a RoRo ferry past the horizon at around 15 km.

Figure 7: Deep neural network-based detection of the “Medium pleasure craft” at around 9.6 km.

From detection to decision

A human lookout needs to process, remember and track the targets detected visually. The targets detected by AIS and/or ARPA radar are tracked by technology. When a human lookout analyzes visual information, it is quite likely that he or she can forget about the existence of some of the targets in a given situation. This may result in a seriously wrong assessment of the situation. In a machine-based lookout, the sensor fusion, target tracking and the analysis of the collected information is done by instruments, and therefore is not affected by factors such as human alertness or limitations for processing the information and detecting changes.

Beyond human performance

As discussed above, the minimum level for machine-based lookout performance is to demonstrate that the visual perception in different boundary conditions matches human performance. Modern monitoring technology allows achieving performance that surpasses the observation capabilities of a human. For example, thermal camera technology enables target detection in decreased visibility conditions that would not be possible for a human to detect even by using binoculars. Moreover, high frequency radars enable detection of small targets, which are not detected by navigational radars, even in presence of severe fog. However, it is important to note that the high-end additional technology for achieving the monitoring levels beyond human performance significantly increases the cost and complexity of the system. Therefore, an additional benefit of achieving the “better than human” level needs to be considered from the practical and financial standpoints.

Modern monitoring technologies also achieve performance beyond human observation capabilities for other reasons. For example, infrared (IR) camera technology can detect targets in decreased visibility conditions that a human with binoculars cannot. Short wave infrared (SWIR) cameras enable detecting other vessels even through fog, and long wave infrared (LWIR) cameras enable detecting other vessels, debris and floating obstacles even in pitch black conditions.

Automated advantages are cumulative: a human lookout needs to process, remember and track targets detected visually and reconcile this information with the information coming from the AIS and ARPA radar.

ANNEX 1

- lEC 60945:2002, Maritime navigation and radiocommunication equipment and systems — General requirements — Methods of testing and required test results
- IEC 61162-1, Maritime navigation and radiocommunication equipment and systems — Digital interfaces — Part 1: Single talker and multiple listeners
- IEC 61162-450, Maritime navigation and radiocommunication equipment and systems — Digital interfaces — Part 450: Multiple talkers and multiple listeners — Ethernet interconnection
- IEC 62288, Maritime navigation and radiocommunication equipment and systems — Presentation of navigation-related information on shipborne navigational displays — General re-quirements, methods of testing and required test results
- IMO Resolution A.468(Xll), Code on Noise Levels on Board Ships
- IMO Resolution A.694(17), General Requirements for Shipborne Radio Equipment Forming Part of the GMDSS and for Electronic Navigational Aids

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Notes on the Resolution and Other Details of the Human Eye

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