DANIELA BORISSOVA

Night Vision Devices
Modeling and Optimal Design

Prof. Marin Drinov Publishing House
of Bulgarian Academy of Sciences

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B U L G A R I A N A C A D E M Y O F S C I E N C E S

INSTITUTE OF INFORMATION AND COMMUNICATION TECHNOLOGIES

Daniela Borissova

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The monograph concerns mathematical modeling of NVD taking into account the specifics of these devices. The proposed mathematical models of NVD are used to simulate different design scenario and allows estimating the theoretical evaluations of the designed device parameters before building a prototype. The developed generalized mathematical model of NVD is implemented in three different design methods – iterative, rational and optimal.

The other aspect of monograph is related with choice of a proper NVD according to different user's requirements and taking into account both the device parameters and the external surveillance conditions. For the goal, single or multicriteria optimization tasks are formulated.

Multicriteria optimization is used to determine different feasible combinations of external surveillance conditions which are compatible with given NVD technical specifications.

All of the proposed mathematical models and formulated optimization tasks are illustrated by proper numerical examples.

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Foreword

This monograph presents the author's research results about night vision devices (NVD), operating on the principle of light amplification.

The main goal of the monograph is to propose some approaches for mathematical modeling of NVD while taking into account the specifics of the devices. The monograph deals with various types of NVD, corresponding operating principles and properties of basic NVD components. An analysis of the used image intensifier tubes and optical systems has been made. A mathematical model of NVD is proposed, which describes the relationships between the elements of the device. Based on the deduced mathematical dependencies, an approach to theoretical determination of the NVD parameters is described. This approach is used for the formulation of deterministic and stochastic models, leading to the formulation of respective optimization tasks. The tasks are used to develop NVD design methods taking into account external surveillance conditions and considering given user requirements for the device parameters. Using mathematical modeling and optimization techniques allows some preliminary theoretical evaluations of the designed device parameters. Optimization models are also used for selection of a particular device from set of devices considering both the specific device parameters and external surveillance conditions. These models have been extended, to take into account the user preferences about the importance of the particular NVD parameters. An optimization model for determination of the feasible combinations of external surveillance conditions which are compatible with given NVD technical specifications is developed and implemented in relevant methodology. All of the developed mathematical models and formulated optimization tasks are illustrated by proper numerical examples.

The results presented in the monograph can be used both by professionals in the field of night vision devices and by a wide range of readers interested in contemporary NVDs.

Chapter 1

Night Vision Devices – Operating Principle, Types and Applications

Night vision technology that is providing the ability for observation at night is one of the most fascinating technologies in use today. The night vision devices (NVD) have their origin in the military research and development but it is the non-military applications that have led to the advancement of this technology. Night vision is becoming more and more popular nowadays. There exist two different night vision technologies each having its own advantages and disadvantages – low-light image intensifying and thermal imaging. The technology based on the use of electronic intensifying of the image is widely used in the most devices nowadays (**Антипова et al., 1998; Волков et al., 2000; Волков, 2001; Волков, 2003; Добровольский et al., 1998; Добровольский et al., 1999; Журавлев et al., 2000; Кощавцев et al., 2000; NVG in Civil Helicopter Operations, 2005; Car & Driver, 2012; Martinelli, Seoane, 1999; Winkel, Faber, 2001**). That is why the NVDs based on image intensifying technology are the object of investigations in the monograph.

Different applications require the development of different NVD types to satisfy specific requirements. In this regard, a recent scientific direction is the development of methods for preliminary theoretical evaluation of the devices more on the design stage. The aim is to reduce the cost for prototypes building and testing and thus to reduce the need of additional adjustments of the final project. In the process of developing a single NVD, various available components of NVD with different parameters and prices should be taken into account. This requires the usage of appropriate methods for selection of such elements. The main problem in the design process and selection of elements for NVD is defining of criteria for optimality to ensure satisfaction of the requirements for the device parameters. These criteria are often associated with parameters as: working distance, weight, focus range of the objective, field of view and eye relief, interpupillary distance and diopter adjustment, etc.

1.1. Night Vision Technologies

Night vision devices can be divided into two main classes accordingly to technology they are based on (**Morovision Night Vision, 2014**):

- *Night vision devices based on the light amplification.* They work in the visible and near infrared (IR) light range and require some ambient light in order to work properly. They use so called *image intensifier tube* (IIT) and the resulted image that is colored in shades of green (**Fig. 1.1b**):

Fig. 1.1. a) real image; b) NVD image

- The other night vision technology that does not require ambient light is *thermal imaging technology*. This technology detects the temperature difference between the background and the objects in foreground. It is known that all objects emit infrared energy as a function of their temperature and the hotter an object is the more infrared radiation it emits. One NVD based on this technology collects the infrared radiation (in the light wave range of 3-30 μm) from objects in the scene and creates an electronic image. Since these devices do not rely on reflected ambient light, they are entirely independent of ambient light-level conditions. They also are able to penetrate obscurants such as smoke, fog and haze (**Fig. 1.2**).

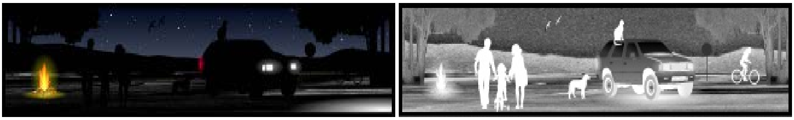


Fig. 1.2. a) real mage; b) image via thermovision

The advantages of the light amplification technology are: excellent low-light level sensitivity; enhanced visible imaging that yields to the best possible recognition and identification performance; high resolution; low power and cost (**Electrophysics, 2014**). One of the key advantages of this technology is the ability to perform target recognition rather than mere detection, as is the usual case of thermal imaging. The technology disadvantages are: some ambient light is required to use light amplification techniques. This technology is not useful when there is essentially no light; inferior daytime performance when compared to daylight-only methods; possibility of blooming and damage when observing bright light sources under night conditions.

The advantages of thermal vision devices are: they produce high contrast image in the darkest nights and can see through light fog, rain and smoke (**Electrophysics, 2014**). On the other hand, their disadvantages are: they are expensive to purchase and to operate, there exists necessity of temperature differences for proper operation and failure to identify the observed objects.

The most recent development in night vision is the so called fusion technology where thermal imaging and image intensification technology are being combined together as it is illustrated in **Fig. 1.3** (http://www.lahouxoptics.com/index2.html?show=clipir&sel=police&suffix=UK).

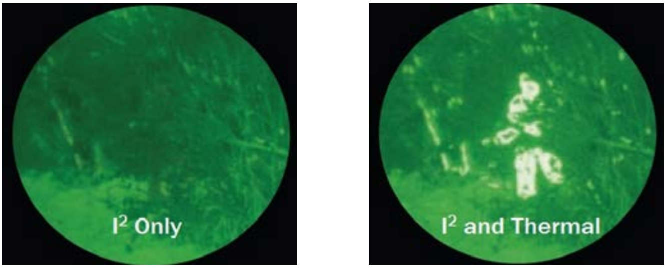


Fig. 1.3. a) image intensification technology; b) fusion technology

Fusion night vision is the new standard for low light operations. It gives significant tactical advantages by combining the unparalleled detection capabilities of thermal imaging with the superior identification capabilities of image intensification.

Today, the most popular and widely used method of performing night vision is based on the use of image intensifying technology. These class of night vision devices are subject of investigations in the monograph.

1.2. Basic Elements of NVD

Night vision devices are electro-optical devices that intensify (amplify) the available light. The main component of such a device is the *image intensifier tube* (IIT) (**Cobra Optics Ltd., 2001**). In general, the NVD is composed of: objective, IIT, eyepiece, power supply and mechanical construction. The objective lens collects the particles of light (photons) arriving from the observed object and focuses them on the IIT screen. Inside the image intensifier tube a photocathode absorbs these photons and converts them into electrons which are amplified from 900 to 50 000 times and are projected onto a green phosphor screen at the rear of IIT. When this highly intensified electron image strikes the phosphor screen, it causes the screen to emit light that can be seen by the observer. Since the phosphor screen emits this light in exactly the same pattern and degrees of intensity as the light that is collected by the objective lens, the bright night-time image seen in the ocular corresponds closely to the outside viewing scene (**Fig. 1.4**) (**ATN, 2014**).

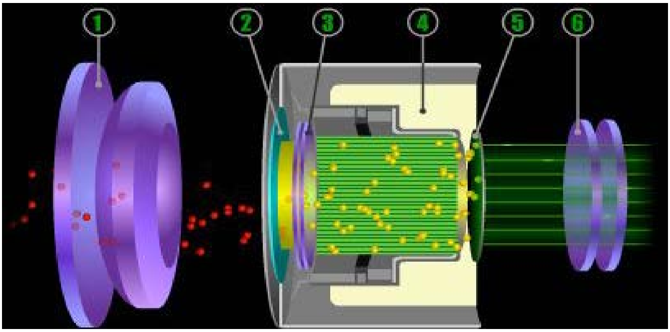


Fig. 1.4. Operating principle of NVD:
1 – objective; 2 – photocathode; 3 – microchannel plate; 4 – high voltage power supply; 5 – phosphor screen; (2-3-4-5 – IIT); 6 – ocular

The phosphor screen is colored green because the human eye can differentiate more shades of green than any other phosphor color. The principle of operation of the IIT and its development are essential for this study and will be examined in detail.

1.3. Image Intensifier Tube

Image Intensifier Tube is a device that amplifies low light level images to levels that can be seen with the human eye. IIT intensifies the reflected lowlight that may originate from natural sources, such as starlight or moonlight, or from artificial sources such as streetlights or infrared illuminators. The IIT photocathode is a very thin light sensitive layer that converts the photons into electrons (**Fig. 1.5**) (**Hamamatsu, 2009**).

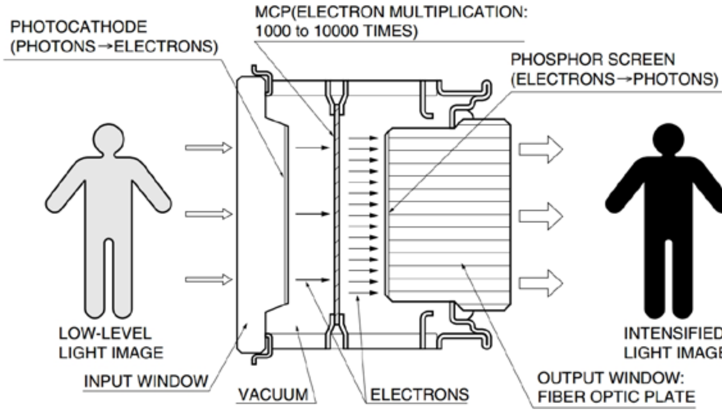


Fig. 1.5. IIT – operating principle

The low level of incoming light, which consists of photons, enters the IIT through its input window and strikes the photocathode powered by a high energy charge from the power supply. The energy charge accelerates across a vacuum inside the intensifier and strikes a phosphor screen where the image is focused. Thus obtained photoelectrons pass through microchannel plate (MCP). The MCP is a thin glass disc, less than a half a millimeter thick, which contains millions of small channels, whose diameters vary from 6 to 12 μm (**Fig. 1.6**) (**Hamamatsu, 2009**).

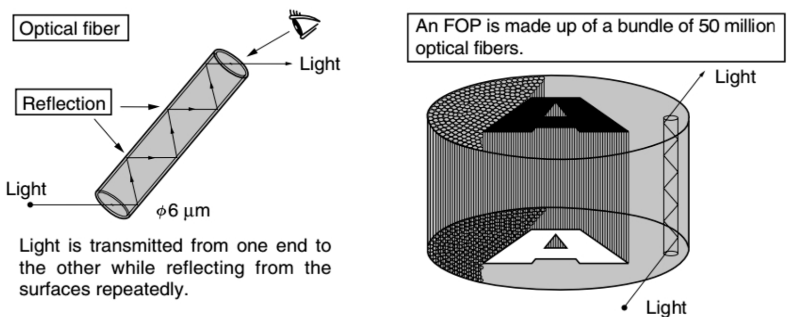


Fig. 1.6. Microchannel plate (MCP)

When an electron coming from the photocathode strikes the inner wall of one channel, several secondary electrons are generated by the impact. Each of these secondary electrons will in turn be accelerated within the MCP by another high electric field, once again striking the inner wall of the channel, and generating even more secondary electrons. This process is repeated along the depth of the MCP channels. For each electron that enters the MCP, approximately one thousand electrons are generated and subsequently accelerated from the output of the MCP by a third electrical field towards the phosphor screen. The phosphor screen is a thin phosphorous light emitting layer deposited on the inside of the output window of the intensifier tube which converts the electrons back into photons. When the multiplied flow of electrons out of the MCP strikes that layer, tens of thousands of photons will be generated for every single photon that was initially converted by the photocathode. This entire multistage process creates an “intensified” image, much brighter than the original image, which can subsequently be seen by the human eye.

The last element of the IIT structure is its output, which can be flat glass or fiber optic plate (**Fig. 1.7**). Fiber optic plate (FOP) consists of several million optical fibers arranged in parallel to each other (**Hamamatsu, 2009**).

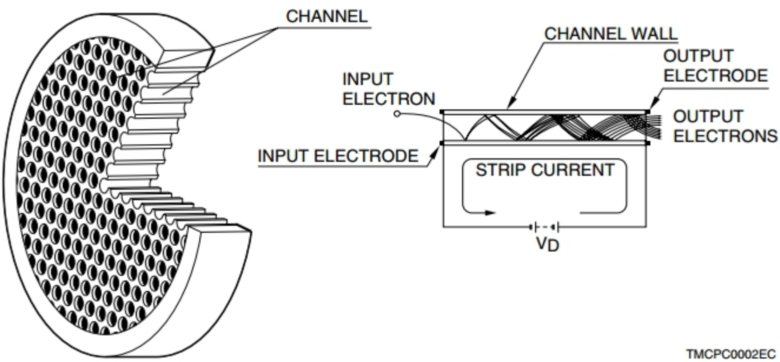


Fig. 1.7. Fiber-optic plate structure

Each individual optic fiber transmits light and this light can be received as an image. An important advantage of FOP is its ability to transmit the image without loss and distortion (**Fig. 1.8**).

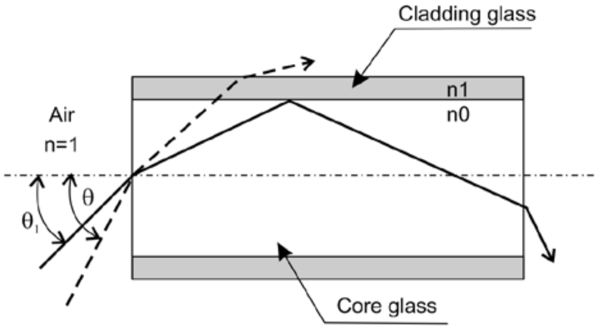


Fig. 1.8. Single fiber structure

1.3.1. Image Intensifier Tube Generations

Technological differences over the past 40 years resulted in substantial improvement to the performance of NVD. The different paradigms of technology have been commonly identified by distinct generations of image intensifiers. The classification of NVD in *generations* (shortened Gen) explains the respective development step of the used image intensifier tubes in general. According to the accepted terminology, IIT are classified according to their chronological and technological development in generations as 0, 1, 2 (with intermediate levels 1+, 2+), 3 and 4. There is no uniform standardisation or protection of the term *generation*. The development step from Gen 0 to Gen 1 consists less in the design than in the use of a more photo-sensitive multi-alkali coating of the photocathode.

A very large step in the night vision technology meant the introduction of the microchannel plate (MCP) starting from Gen 2. In general, generation numbering is related to significant changes in design of IITs that improve (with some exceptions) performance of these tubes. For example, Gen 3 is a term used mainly by US manufacturers (and almost considered as a brand name), in order to mark tubes with a particularly sensitive Gallium Arsenide coating (GaAs) of the photocathode (**Intas, 2014**).

<u>Generation 0 (1950)</u>

Devices of this generation have so little low light amplification that as a rule, additional IR-illuminators must be used for observation. Therefore they are also called “active night vision devices”. The structure of the IIT of Gen 0 is shown in **Fig. 1.9** (**Intas, 2014**).

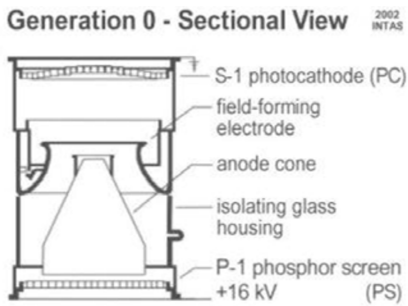


Fig. 1.9. Structure of IIT Gen 0

Gen 0 typically uses an S-1 photocathode with peak response in the blue-green region (with a photosensitivity of 60 μA/lm) using electrostatic inversion and electron acceleration to achieve gain (**Intas, 2014**). Gen 0 tubes are characterised by the presence of geometric distortion and the necessity for active infrared illumination. The Gen 0 has wide sensitivity in the deep infrared range between 750 and 950 nm. The Gen 0 IITs are single-chamber and multi-chamber glass devices with an uneven distribution of the resolution in the visual field (**Кощавцев et al., 1999**).

<u>Generation 1 (1960)</u>

With the introduction of the so-called multi-alkali photocathode a higher luminous gain of the IIT was achieved. Under some specific conditions additional IR-illumination is unnecessary for this generation. The Gen 1 image intensifer tube works in the lower IR spectrum (750 to 800 nm). The structure of a Gen1 tube corresponds in principle to that of Gen 0 (**Intas, 2014**). It uses S-20 photocathode with a photosensitivity of 180-300 μA/lm (**Intas, 2014**). Light amplification is about 120-900 times and resolution in the centre varies between 25-35 lp/mm. The Gen 1 tubes are characterised also by the presence of geometric distortion in image (**Fig. 1.10**) and at lower illumination also need additional IR-illumination (**Intas, 2014**).

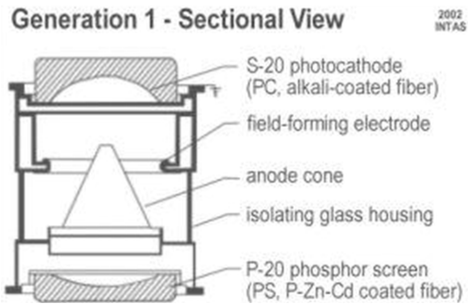


Fig. 1.10. a) structure of IIT Gen 1; b) Image with IIT Gen 1

The weight of Gen 1 tubes vary in the range 75 to 455 g. The service life of the Gen 1 image intensifier tube is increased compared to Gen 0 up to approximately 1000 to 2000 hours.

Multistage or Cascade IIT Gen 1

To achieve a larger luminance gain consistently two, three or more IIT can be used. In such cases, cascade IIT are built by combining two or three single tubes (**Fig. 1.11**).

The gain of three-stage IIT is 20 000 to 50 000 times. IIT coupling like this leads to increasing of distortion and to reducing the resolution at the edges of the field of view. The NVD using multistage IIT are quite large and heavy and gradually are replaced by small-sized IIT from Gen 1+ and Gen 2, having better performance and lower cost.

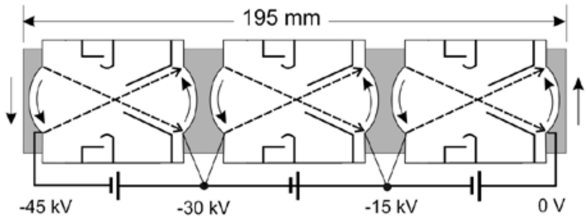


Fig. 1.11. 3-stage IIT

<u>Generation 1+ (Super+)</u>

This is the next development of the first generation IIT. The designation “Generation 1+” refers to the use of glass fiber bundles (instead of glass windows) at the input/output side of the tube but still technology is the same as in Gen 1. The working range here is between 750 and 800 nm wavelength. They feature the addition of a fiber optic plate (not an MCP) on the front of the tube. There is less geometric distortion which gives much better edge-to-edge definition than standard Gen 1 tubes. Resolution in the center can be as good as 42 lp/mm (a 30% increase over the best Gen 1) and there is much reduced geometric distortion around the periphery with a resolution here of about 32 lp/mm. The gain of this generation is about 1000 times, the photocathode sensitivity is smaller than or equal to 280 μA/lm. The NVD with IIT of Gen 1+ are effective under night illumination corresponding to 1/4 moon. At low night illumination levels additional IR illumination is required. Gen 1 and Gen 1+ are considered as technically outdated.

<u>Generation 2 (1970)</u>

The main difference between Gen 1 and Gen 2 tubes is the presence of a microchannel plate (MCP). Gen 2 uses an S-25 photocathode with photosensitivity of 240-400 μA/lm and with a microchannel plate (MCP) achieves the gain of 25 000 to 50 000 times. Normally - fiber-optic inversion is used – **Fig. 1.12** (**Intas, 2014**).

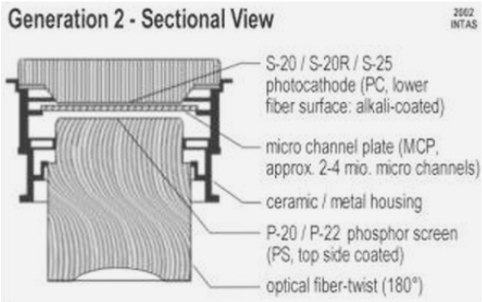


Fig. 1.12. a) structure of Gen 2 IIT; b) Image with Gen 2 IIT

The MCP has a natural upper limit of emitable electrons, so that a strong beam of light does not immediately damage the image intensifier. Starting from Gen 2, control electronics is used to regulate the current depending on the actual low light situation – this adjustment is called ABC (Automatic Brightness Control). With the introduction of the MCP night vision devices became smaller in dimensions and less heavy (particularly important for night vision googles). Gen 2 tubes provide good performance in low light levels and exhibit very low distortion making them reasonable for use with video or still cameras. They are equipped with automatic gain control, flash protection and feature edge-to-edge definition. They are more tolerant of urban lighting than Gen 3 systems. Resolution in the center varies between 28-32 lp/mm. The life span is increased to approximately 2500 to 5000 h. Apart from the elimination of the problematic afterglow also the image distortions disappeared with the utilization of an MCP. The Gen 2 works mainly within the range between 780 and 850 nm wavelength.

Generation 2+ and SuperGen (1970)

Generation 2+ is based on Gen 2 technology, but has enhanced photocathode sensitivity. The improved variants of the Gen 2 incorporate changes in the MCP, in the photocathode and in the phosphor screen. The resolution was refined by at least 4 million micro channels, while an optimized inclination of the micro channels made it possible to display some background-image areas against a partly blinding direct light-source (bright source protection). The background noise is also reduced. The new S-25 photocathode is more sensitive to infrared light. A changed phosphor mixture of the screen reacted faster (less traces of glowing objects on the screen) and provided brighter images (more contrast). With using of image intensifiers of SuperGen the sensitivity was continued to shift into the IR spectrum by the new S-20R (redshift) photocathode. The light amplification is about 25 000 to 35 000 times. The photocathode sensitivity for Gen 2 is 500-600 μA/lm and for SuperGen it is 600-700 μA/lm. The resolution in the center varies between 32-45 lp/mm for Gen 2+ and is 45-60 lp/mm for SuperGen (**Intas, 2014**). The life span of this generations is about 10 000 h.

Generation 3 (1990)

The improvements of this generation are based, apart from refined control electronics, MCP and the P-20 phosphor screen, on a new photocathode coating. A mixture from the elements gallium and arsenic (GaAs) showed an enormous level of luminous sensitivity, significantly higher than all known coating-mixtures before. Typical characteristic of the GaAs-coating are so-called "Halos" (large, bright shining disc-shaped areas around any spotlight displayed in the image). Gen 3 can produce more than 800 μA/lm in the 450 to 950 nanometer region of the spectrum. Gen 3 provides very good to excellent low-light-level performance and long tube life. Gen 3 tubes show virtually no distortion (**Fig. 1.13**) (**Intas, 2014**).

Resolution in the center varies between 45-64 lp/mm. The life span of this generation is up to 10 000 h. The light amplification is about 50 000 times. The devices of this generation work well in low light, the image is saturated, sharp and with good contrast. All countries producing Gen 3 image intensifier tubes strictly control the availability and export of these systems – mostly, they are limited to strictly military/government agency use.

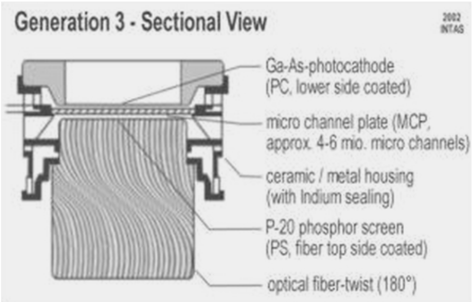


Fig. 1.13. a) Structure of Gen 3 IIT; b) Image with Gen 3 IIT

Generation 4 (2000)

At present, in the context of the OMNI V & VI contract, US armed forces are issued so-called “filmless” and “thin filmed” tubes, which are very sensitive in the deep IR range. The mentioned protective film within these tubes is strongly reduced or even missing while the power supply is shuttered very fast (“gated”, “autogated”). According to the industry this feature guarantees a tube life of 15 000 hours and protects the tube of being damaged from bright light exposure. Although manufacturers are in prospect of new contracts and still another clear improvement in performance is achieved, it is not completely clear whether these image intensifiers represent officially the 4th Generation (**Intas, 2014**).

Technologically seen the term Gen 4 would be apparently justified. Export of this technology even to friendly states is very unlikely at present. The newest European “autogated” tubes (e.g. DEP XR5, Photonis XH 72) seem to have a practical advantage in that they can be operated even by day without problems (e.g. night vision riflescope: day/night transitions). Because of their different photocathode coating bright spotlights do not draw so large halos on the intensified image (**Fig. 1.14**) (**Chrzanowski, 2013**).

The Gen 4 uses MCP with reduced diameter up to 6 μm instead of the traditionally used 12 μm which leads to increasing of their limiting resolution up 64-84 lp/mm.

Fig. 1.14. a) Gen 3 IIT; b) Gen 4 IIT

1.3.2. Comparative Analysis between Generations

The choice of the particular IIT is affected by the following parameters: radiant sensitivity, luminous sensitivity, luminance gain, resolution and signal to noise ratio. Radiant sensitivity is the ratio of current induced into a photocathode (in mA units) of tested tubes by incoming light (in Watt units) for a specified wavelength. Luminous sensitivity is the ratio of current induced into a photocathode (in μA units) of the tested tube by flux (in *lumen* units) of incoming polychromatic light of color temperature equal to 2856 K. Luminance gain is a ratio of luminance of output image (tube's screen) to luminance of input image (tube's photocathode). Measurement is done using light source of color temperature equal to 2856 K. Image generated by a tube of low luminance gain looks darker than image generated by a tube of high luminance gain at the same input luminance conditions. Resolution of IIT is defined as a spatial frequency of a minimal 3-bar pattern of USAF 1951 target that can be resolved by an observer. Resolution is presented in lp/mm (line pairs per millimeter) units. Nowadays, the resolution of typical IIT available on market vary in the range of 50-57 lp/mm and resolution of the best one can reach level of 81 lp/mm. Signal to noise ratio (SNR) is a ratio of two components of a light signal emitted by a small part of a tube screen: average signal to root mean square signal (noise). The output signal is generated by illuminating a small part of photocathode (diameter 0.2 mm) at typical level of 108 μlx. Nowadays, SNR of the available on market IIT is about 18-22 and the best IIT can reach level of SNR up to 30.

Different generations of IITs use different photocathodes. There is a big positive difference between S-1 photocathode used by Gen 0 tubes and S-10 photocathode used by Gen 1 tubes. The positive difference between S-25 photocathode used by Gen 2 tubes and S-10 photocathode used by Gen 1 tubes is not so obvious. However, it must be taken into account that critical parameter of photocathodes of IITs – luminous sensitivity – is measured using light sources of 2856 K color temperature. This measurement method (simulating to some degree real applications) strongly favors photocathodes with more sensitive in near infrared range – in this case S-25 photocathode. Finally, GaAs photocathodes used in Gen 3 tubes are again clearly more sensitive than S-25 photocathodes used in tubes of previous generation **- Fig. 1.15** (**Chrzanowski, 2013**).

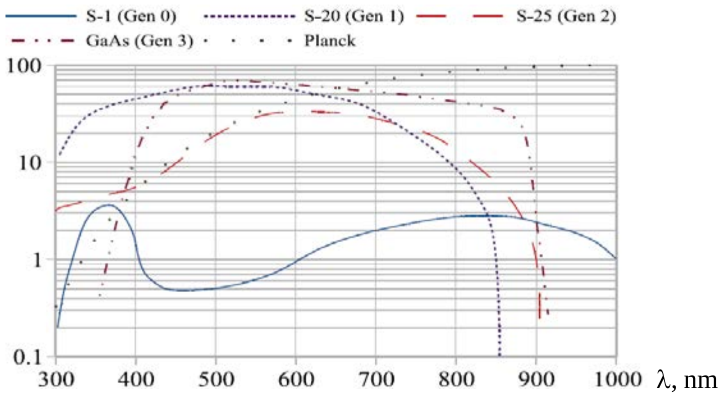


Fig. 1.15. Spectral sensitivity of typical photocathodes:
S1(Gen 0), S-20 (Gen 1), S-25 (Gen 2)

The luminous sensitivity is a decisive parameter of IIT. Each generation offers more sensitivity and can operate effectively on less light. Only NVD with well selected IIT and combined with proper optics can provide acceptable parameters, under surveillance conditions with presence of 1/4 moon. Each subsequent generation of IIT differs from previous with improved parameters – resolution, signal-to-noise ratio and luminous sensitivity of the photocathode shifted to near IR range. The displacement of the spectral sensitivity of the photocathode of each generation to the near IR range is due to the bigger transparency of the atmosphere in this range.

In each subsequent IIT generation distortion become smaller, the contrast is better and it is possible to work at lower illumination, the lifetime duration is longer and the overall dimensions and weight are decreased (**Fig. 1.16**).

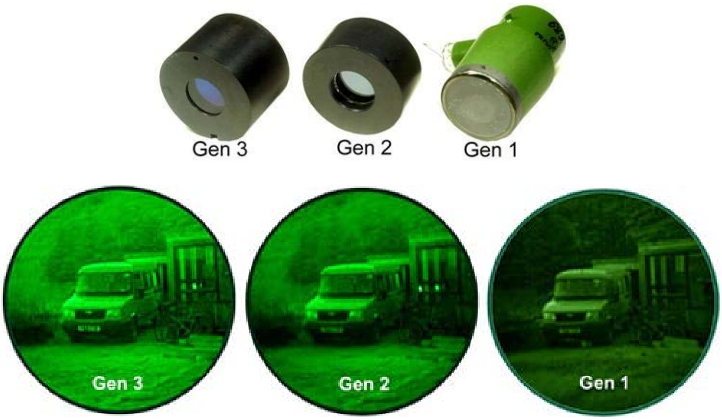


Fig. 1.16. Images by different IIT generations

The main parameters of the IIT from different generations and different manufacturers are shown in the **Tables 1.1, 1.2** and **1.3**.

Table 1.1. Parameters of the IIT of company DEP

Parameter	**IIT**					**Units**
	Gen II	**Super Gen**	**SHD-3™**	**XD-4™**	**XR5™**	
Limiting resolution	45-50	45-50	45-54	58-64	64-70	lp/mm
Signal-to-noise Ratio (@108µlx)	14-16	17-19	18-20	20-24	25-28	
Luminous sensitivity (2850K)	350-450	500-550	500-600	600-700	800-850	µA/lm
Mean time to failure	2000	10 000	10 000	15 000	15 000	hrs
Weight (18 mm)	85-98	85-98	80-95	80-95	80-95	g

Table 1.2. Parameters of the IIT of company PHOTONIS

Parameter	IIT					Units
	Gen II+ XX1410	**SuperGen XX1610**	**HP SuperGen XX1660**	**HyperGen XX1860**	**XH72 XX3060**	
Limiting resolution	32	40	45	57/50	72	lp/mm
Signal-to-noise Ratio (@108µlx)	12	15.5	18	20	22/24	
Luminous sensitivity (2850K)	350	500	600	700	700/750	µA/lm
Mean time to failure	2000	10 000	10 000	10 000	10 000	hrs
Weight (18 mm)	100	100	100	100	100	g

Table 1.3. Parameters of the IIT of company ITT

Parameter	IIT			Units
	Gen II M884	**Gen III FS9901**	**Gen IV MX10160B**	
Limiting resolution	32	45-64	57-72	lp/mm
Signal-to-noise Ratio (@108µlx)	--	19-21	20.6-36.0	
Luminous sensitivity (2850K)	240	1350-1800	1500-2100	µA/lm
Mean time to failure	17.5	17.5	17.5	mm
Weight (18 mm)	2000	10 000	10 000	hrs
Limiting resolution	126		85	g

Though image intensification technology employed by different manufacturers varies, from the tactical point of view a night vision system is an optical device that enables vision at low light. It is recognized that the technology itself makes little difference as long as an operator can see clearly at night. The US bases export regulations not on the generations, but on a calculated factor called figure of merit (FOM). That is the way night vision devices can be compared. FOM is an abstract measure of image tube performance and is calculated as system resolution (SR) multiplied by signal-to-noise ratio (SNR):

(1.1) $$FOM = SR \,.\, SNR$$

The best Gen 3 devices available on the market have FOM of 1400 to 1600. The comparisons between different IIT generations and its FOM are shown in **Table 1.4**.

Table 1.4. Comparison of the IIT

Specifications	Gen I	Gen II	Gen II+	Gen III
Image Intensifier Light Amplification	100-500	20,000-30,000	20,000-30,000	20,000-30,000
Signal-to-Noise Ratio	--	12-15	15-25	15-30
Resolution, lp/mm	25-30	30-68	45-68	45-68
FOM	--	<750	750-1200	800-1600

Source: http://www.newcon-optik.com/faq.html

Each generation offers more sensitivity and can operate effectively on less light. With each generation the spectral sensitivity of the IIT photocathode is shifted to the IR spectrum, wherein the spectral density of the natural night illumination is greater than in the visible range. The parameters of IIT manufactured by different companies even of the same generation differ in their parameters. Therefore, the IIT performance can be compared by using the abstract measure FOM (figure of merit).

1.4. Types of NVD Depending on the Purpose, Structure and Additional IR Illumination

There are several basic types of night vision devices, depending on their purpose – goggles, binoculars and sights, as shown in **Fig. 1.17**.

Depending on the constructive design the NVD can be divided into a monocular type (with single optoelectronic channel), binocular type (with two independent optoelectronic channels), and biocular or cyclop type (with one objective, one IIT and two oculars).

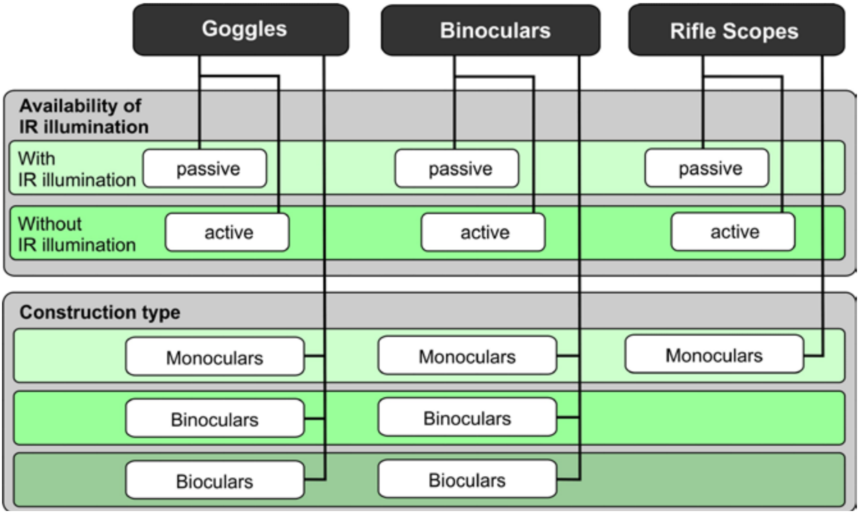


Fig. 1.17. Classification of NVD

According to the presence or not of an additional IR illumination the NVD are divided into active and passive devices (**Fig. 1.17**). Passive devices did not require an external source of infrared illumination but could, instead, amplify any reflected light (both infrared and visible light) from sources like the moon and the stars.

1.4.1. Active and Passive NVD

Depending on the use or non use of additional IR illumination, NVD are divided into two main classes: active and passive NVD.

<u>**Active NVD**</u>

The active NVDs need additional IR illumination to operate properly (**Fig. 1.18**).

The optical axes of the additional IR illumination and the device are to be parallel. IR illuminators used with night vision devices operate in the near infrared range of the light spectrum from the high side of 700 to 940 nm.

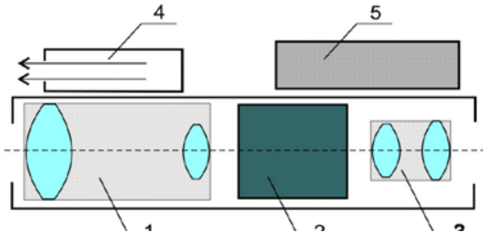


Fig. 1.18. Structural scheme of active NVD:
1 – objective, 2 – IIT, 3 – ocular, 4 – additional IR illumination, 5 – power supply

This area of the light spectrum is invisible to the human eye and to most animals. Other than the dull red glow of the illuminator element, the IR light will only be visible to another.

Passive NVD

In contrast to active NVD, passive NVD rely on ambient light instead of an additional infrared light source (**Fig. 1.19**). The passive NVD type is similar to those of the active type, but it lacks the additional IR illumination.

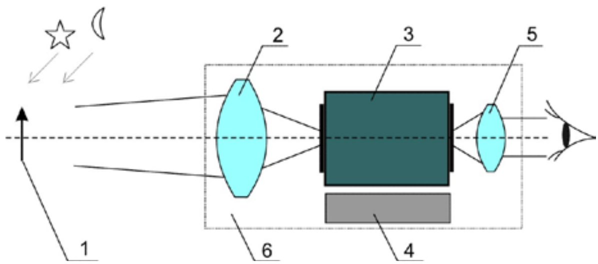


Fig. 1.19. Structural scheme of passive NVD:
1 – surveillance target, 2 – objective, 3 – IIT, 4 – power supply, 5 – ocular, 6 – optoelectronic channel of NVD

1.4.2. Monocular, Binocular and Biocular NVD

NVD have consistently been modified and specialized for use ranging from covert ground operations to aviation, successfully creating stronger, smaller, lighter, and more versatile devices. Depending on the design type of NVD, they can be divided into monocular type, binocular type, and biocular or cyclop type.

Monocular Type NVD

Monocular NVD construction has the simplest design consisting of a single objective, one IIT and one eyepiece, i.e monocular type of NVD has an optoelectronic channel (**Fig. 1.18a**) (http://www.atncorp.com/). This design type is used for both of devices without magnification (1x) and devices with magnification of 2×, 3×, 4×, 6× and others. The NVD with magnification have reduced field of view (2 to 15 degrees) and as field of view is less so much the magnification is bigger.

Fig. 1.20. Monocular type of NVD

By changing the objective, this design scheme can be easily modified to the desired magnification of monocular NVD type – **Fig. 1.20b** (Patent 7826, 2013). The monocular NVD design can be held by hand, sticks to photo or video camera, or to be mounted on a weapon or on operator's helmet.

The monocular design construction uses only one IIT and due this fact it is widespread and more often come with high quality IIT.

Biocular Type NVD (Cyclop type NVD)

To reduce the weight and cost of NVD, a design composed of an objective lens, an eyepiece and two IIT has been developed. This NVD design type is known as biocular, cyclop or pseudo-binocular design type (**Fig. 1.21**) (http://www.atncorp.com/).

Fig. 1.21. Biocular type of NVD

Due to presence of single objective and single IIT, the weight and cost of the device is significantly reduced compared to the binocular type of NVD. This design scheme requires an additional optical system to divide the obtained image from the IIT to both oculars. Two costly image intensifier tubes are replaced by one tube. Comfortable observation by two-oculars is possible. Some depth perception is still achieved even during a single channel observation.

A disadvantage of this biocular construction is the lack of stereoscopic vision. An advantage of biocular construction is the possibility to use one but high quality IIT. The presence of a single objective and IIT reduces the weight and cost of NVD.

Binocular Type NVD

Binocular type of NVD consist of two identical and independent optoelectronic channels as shown in **Fig. 1.22** (http://www.atncorp.com).

Fig. 1.22. Binocular type of NVD

1.4.3. Night Vision Goggles (NVG)

A specific type of NVD are the night vision goggles (NVG). This type of devices can utilize either one intensifier tube with the same image sent to both eyes, or a separate image intensifier tube for each eye. The night vision goggles have magnification equal to 1 (i.e. real image without magnification) and a field of view in the range of 33-43 degrees. The NVG with two separate optoelectronic channels provide stereoscopic effect that makes this type of devices useful when driving of vehicles. The night vision goggles, which can be mounted on the helmets of aircraft pilots, can be adjusted for each individual. Distance from the eye, alignment and tilt can be regulated (**Fig. 1.23**) (http://www.photonics.com/Article.aspx?AID=36720)

Fig. 1.23. Night vision goggles for aircraft pilots

For a substantial increase of the FOV, another NVD design is developed and known as *panoramic night vision goggles* (PNVG) as shown in **Fig. 1.24** (http://www.gpssignal.com/gpnvg.html).

The most striking feature of the PNVG is the presence of four separate image intensifier tubes with four separate objective lenses arrayed in a panoramic orientation. Like traditional dual tube goggles the center of two lenses points forward giving the operator more depth perception, while two more tubes point slightly outward from the center to increase peripheral view.

Fig. 1.24. Panoramic NVG

The two tubes on the right and the two on the left are spliced at the eyepieces. The PNVG is a helmet-mounted night vision device with a wide 97 degree horizontal field of view that allows for observation and/or target identification under adverse conditions and is ruggedized for ground applications.

Another type of NVG is so called "*Helmet-mounted display*" shown in **Fig. 1.25** (http://theaviationist.com/2012/07/17/a400-hmsd/).

Fig. 1.25. Helmet-mounted display

The helmet-mounted display (HMD) is a device that is used for activities in modern aircrafts to provide horizontal field of view of *80 degree* and *40 degree* vertically. The system is designed for day, night and brownout flight environments.

The advantage of binocular constructive scheme with two independent optoelectronics channels is the ability to provide stereoscopic effect and to give the perception of depth. The depth perception allows estimating absolute distances between an object and the observer or the relative distances between two objects, i.e. how far to the left or right the object is and whether the different objects are in front or behind each other. As disadvantage of this design scheme, the device's weight and cost can be considerably high due to the availability of two optoelectronic channels.

1.4.4. Night Vision Weapon Sights

Night vision rifle scope often known as night vision scopes are night vision devices of monocular type with magnification. Within optical system of these devices red or green reticle system is integrated (**Fig. 1.26**) (http://www.atncorp.com/).

a) external view b) image through weapon sight

Fig. 1.26. Night vision weapon sight

The devices of this class have a smaller field of view (2-12 degrees), and higher magnification (1.5-16.5 times). They usually have possibility for diopter adjustment in the range of –4 to +6 diopter (sometimes +5 to –5) and adjustable focus range depending on magnification. Compared to NVG, the eye relief is bigger.

The parallax in optical sights is of great importance. A rifle scope parallax is a known optical illusion where the target looks out of focus and the focal plance of the target is offset from rifle scope reticle. The parallax in optical sights refers to the apparent movement of the target relative to the reticle (or red dot) if head is moved when looking through the scope. The line of sight is different than the axis of the bore, because the sight is mounted above the bore. This distance between the line of sight and the center of the bore (about 1.5 inches for a low mounted scope) creates parallax. To minimize the effect of parallax, the optical sight should be mounted as close to the bore as possible.

The longer eye relief is necessary to keep the scope from hitting the shooter's eyebrow when the rifle recoils. High magnification scopes tend to have less eye relief, as do variable power scopes. The optical sight should be mounted as close to the bore as possible to minimize the effect of parallax.

1.4.5. Night Vision Binoculars

The night vision binoculars can be found in the three design variants – monocular type, biocular type and binocular type (with 2 independent channels). Distinguishing characteristics of binoculars are the magnification (2-6 times), field of view (13 to 5 degrees), bigger dimensions and weight. In most cases these devices are equipped with different objective sets for different magnification (**Fig. 1.27**).

Fig. 1.27. Night Vision Binocular:
a) devices, b) image with corresponding magnification

These devices usually have possibility for diopter adjustment, adjustment of focus range depending on magnification and interpupillary distance can be adjusted too (54-70 mm).

To reduce the price of NVD, this type of device use more often biocular design scheme (one objective, one IIT and two oculars). The lack of stereoscopic effect is not essential due their main purpose for surveillance. There are night binoculars of classic type with two independent optoelectronic channels and binoculars with one optoelectronic channel.

1.5. NVD Optical Systems

The optical system used in NVD is composed of objective and ocular. Through objective the image of the object is projected onto the photocathode of the IIT and through the eyepiece, the resulting image is observed on the IIT screen. The main parameters of the optical system (objective-eyepiece) defining its quality and efficiency are: *diameter of the inlet pupil and exit pupil, focal length, transmittance coefficient, field of view, limiting resolution, stability of the optical properties under different climatic conditions, vibration, shock, etc.* By using these parameters it is possible be determine the overall dimensions, energetic, aberration, operational and technical and economic characteristics of the optical systems. There are a variety of design solutions, both with regard to objective, and with respect to the eyepiece. One possible solution of the optical system used for a binocular structure NVG is shown in **Fig. 1.28**.

Due to the requirements for reduction of device weight and cost, a widely accepted constructive design is so called biocular type or cyclop type of NVD (**Саликов 2000; Волков, 2002**) (**Fig. 1.29**).

This constructive design includes a objective, a IIT and optical system that splits the image into two eyepiece. Common drawback of the most widespread traditional NVD is their longitudinal length. This dimension determines the torque load on the neck and facial muscles and operator fatigue.

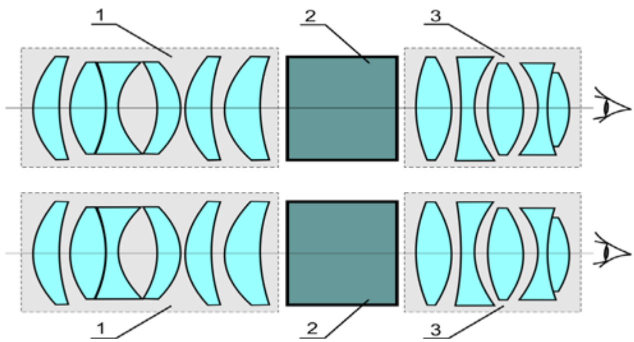


Fig. 1.28. Optical systems of binocular type of NVD:
1 – objective, 2 – IIT, 3 – ocular

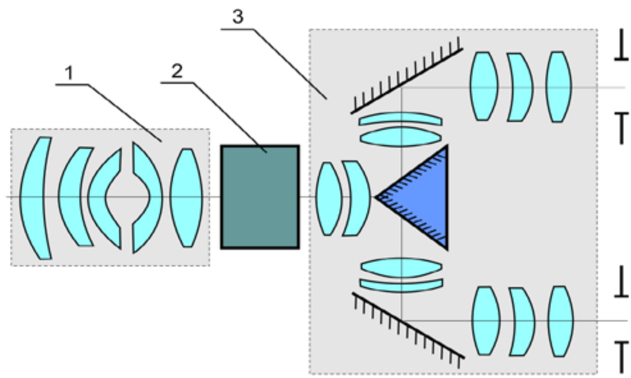


Fig. 1.29. Optical systems of biocular type of NVD:
1 – objective, 2 – IIT, 3 – ocular system

Therefore, developers of NVD are oriented to create a low-profile UNV with small longitudinal dimensions. Typical representatives of this type NVD are: “GN-2” of the company Simrad (Norway) (**Volkov, 2002**) and “Lucie” of the company ANGENIEUX (France) (**ANGENIEUX, 1999**). Optical system with ocular prism structure used in biocular type of NVD allows navigation of airplanes and helicopters and also simultaneous observation of the night scene outside the pilot’s cockpit and monitoring gauges in the cabin. These type of NVD have small longitudinal dimensions.

One approach to reducing the weight of both the objective and the eyepiece is the use of plastic lenses. Another contemporary decision option for lighter optical systems is the use of aspheric optics (*OpTaliX*, **Rouke et al., 1998**, *ZEMAX*). In order to eliminate spherical aberration and coma, the lens of some modern objectives have a parabolic, hyperbolic or other axial-symmetric shape.

To ensure continuous observation as night and during the day, NVD incorporate both night and day channel. When monitoring at night, the operator sees the image in the night channel containing IIT. Simultaneously, by means of a prism ocular system, the operator can observe the object outside the night channel. In case of increased level of illumination (fires, lights of headlights, etc.), the night channel is switched off, and the operator can monitor through the daytime channel. This tendency of using the day-night device is valid for all three NVD types – goggles, binoculars and sights (**Волков et al., 2000**).

There are a variety of high-quality optical systems for objectives and eyepieces, which can be used in the design of optoelectronic channel of NVD.

1.6. Scientific Research and Development in the Area of NVD

Scientific research in the area of NVD can be classified broadly into three main groups. The first group includes methods for testing the parameters of developed NVD. Before the production of devices it is important to ensure consistency between the requested design parameters and the really obtained parameters. In most cases, compliance is established after testing of real prototypes. When there is a gap between design requirements and actual parameters, a new design, new prototyping and testing is needed and all of this is accomplished with additional costs. The proposed test methods are appropriate as a tool for selecting the appropriate devices for specific application. The second group of scientific research focuses on development of methods for optimization of the developed NVD. Achievement of optimal parameters of NVD in the sense of some predetermined criteria is the main goal of the design process. It requires achieving the best desired parameters, avoiding or limiting to some extent the process of repeatedly processing and testing. Some of the recent results described in this monograph deal with the problems of optimization in the development of NVD. The third group envelops the research related to the development of methods and tools for training users to use the NVD. The skills of NVD users are perishable and require frequent practice. In this regard, some methods and appropriate tools have been developed, based on the use of modern computer technology.

1.6.1. Methods for Testing the NVD Parameters

The *NVD resolution* is one of the key parameters for comparing the quality of the various devices. The most common method for determining the resolution of NVD is described by means of Air Force resolving rower test target USAF 1951 (**Fig. 1.30**).

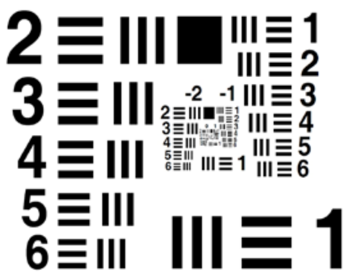


Fig. 1.30. USAF 1951

The pattern used in the USAF 1951 target consists of 3 dark lines against a light background. These patterns occur in pairs which have vertical and horizontal orientation of the three lines. The limiting resolution is the highest spatial frequency (density of lines) which can be seen using the system under a specific set of operating conditions. The resolution of NVD is performed by a trained observer, which observes the tri-bar resolution chart at specific illumination. Using the tri-bar pattern shows observer resolution discrepancies of as much as 60%. (**Pinkus & Task, 1998**).

Another method for determining the NVD resolution is based on diagram containing 3×3 square fields as shown in **Fig. 1.31** (**Pinkus & Task, 1998**).

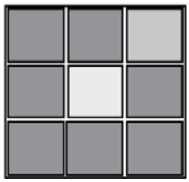


Fig. 1.31. 3×3 NVG Chart

The target array was developed as a means for pilots to do a quick verification that their NVGs were operating correctly and were capable of resolving detail to a specified level. This chart has several features that set it apart from the 1951 AF target. The chart has nine square-wave patterns, arranged in a 3×3 array. For its standardized viewing distance of 20 ft., each pattern is sized to equal specific Snellen values of 20/20 through 20/60 in increments of five. Their locations and orientations within the array are randomized. The chart is placed at a 20 ft viewing distance and illuminated with a 2856K color temperature illumination source that could be adjusted to various desired illumination levels. However, the step sizes between patterns are relatively large making this pattern unsuitable for comparing the capability of different NVGs that are somewhat close in their resolving power (**Pinkus & Task, 1998**). In an effort to refine the square-wave grating pattern to obtain smaller step sizes between resolutions, a variation is developed and constructed containing six pairs of vertically and horizontally oriented squarewave gratings as shown in **Fig. 1.32** (**Pinkus & Task, 1998; Task 2001**).

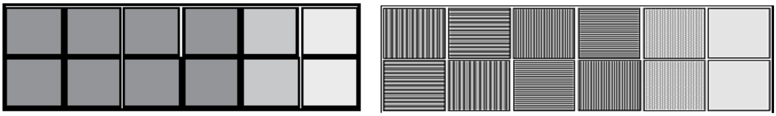


Fig. 1.32. Example of the square-wave chart used in the step-back method

While looking through the NVG at the pattern from a distance of 30 ft, the observer selects the smallest resolvable target pair. Then the observer slowly steps backwards until the selected target pair was no longer resolvable. The spatial frequencies of the square-wave patterns were sufficiently close together in spatial frequency that the observer would not have to step back more than 3 ft (10% of the baseline viewing distance), thereby minimizing the effect of possible objective lens misfocus. When conducting an NVG resolution evaluation, measurements were typically repeated several times (e.g. 5 times) for 3 trained observers and then averaged to determine the final value.

Another assessment method uses Landolt C stimuli (**National Academy of Sciences, 1980**). The Landolt C (**Fig. 1.33**) is a perfectly circular C (no serifs) that has a specified contrast and gap size.

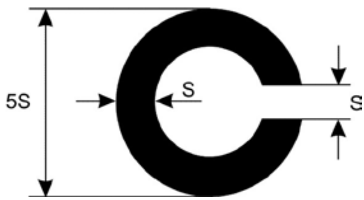


Fig. 1.33. Landolt C stimuli

The gap size is varied as is the orientation (**Pinkus & Task, 1998**). The observer's task is to detect the orientation of the gap. This method allowed relatively efficient convergence to a threshold acuity usually within 10 to 35 trials. The step method yielded reasonable results, but informal repeatability tests found that the observer's scores varied from day to day. A method for assessing the quality of night vision devices in terms of *resolution* is proposed in (**Рамм, Родионов, 1977**). It is based on criterion for optimum device which is capable to distinguish two random signals on the background of correlated interference, taking into account the device field of view and the presence of noise in the image receiver.

A procedure for measuring the NVD parameters *field of view* and *diopter adjustment* of panoramic night vision goggles is described in (**Marasco, Task, 1999**). Two methods are used to determine the field of view (**Fig. 1.34**) – simultaneous testing of both optoelectronic channels or sequentially testing each of them.

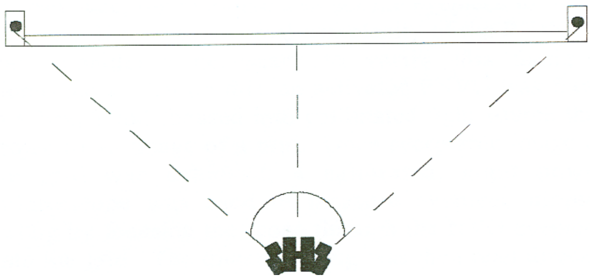


Fig. 1.34. Measurement of field of view

The method is sufficiently accurate and objective as it requires the observer to determine whether visible or not are the relevant boundary markers. The determination of some NVD parameters as *magnification, field of view, eye relief and exit pupil diameter, diopter adjustment and interpupillary distance* of NVG “Prilep” is described in (**Borissova, Dekov, 2002**). NVD field of view is determined as described in (**Marasco, Task, 1999**). The range of interpupillary distance can be adjusted in the range of P_2 to P_1 taking into account the distances L_1 and L_2 (**Fig. 1.35**).

One of the most important parameters of NVD is its *working range.* Determination of the NVD working range in real conditions is accompanied by expenditure of time and labor. Furthermore, any testing is carried out under specific night conditions, state of the atmosphere and the background environment and the results are valid only for these conditions.

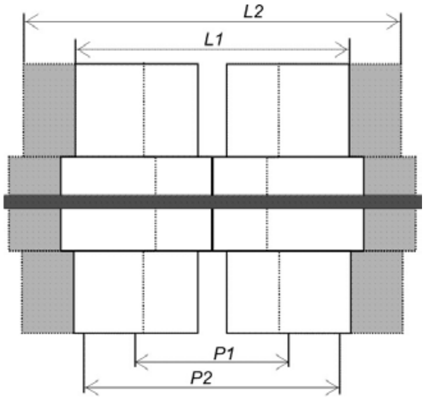


Fig. 1.35. Measurement of interpupillary distance

This requires the development of methods for theoretical or laboratory determination of the NVD working range. A method based on the finding of the regression correlation for obtaining the working range of the device, depending on the measured outside conditions is proposed in (**Кривошапкин, Эдельштейн, 1998**). It is assumed that within certain limits this dependency can have linear dependence. After finding the coefficients of the regression and setting the normalized parameters of the external conditions, it is possible to determine the device working range for these conditions.

Another method and a computerized system for determining the NVD working range under laboratory conditions is described in (**Григорьев et al., 2000**). If the resolution and noise of NVD are measured, it is possible to determine the working range at given conditions by proposed statistical model of the observer.

NVD can be considered as deterministic-stochastic system consisting of deterministic unit – optoelectronic channel and stochastic unit – visual analyzer (**Эдельштейн, 1998**). Using this assumption allows to be determined the working range without the field tests by checking the objective parameters of optoelectronic channel that fully describes the functionality of the device. Significant conclusion of this approach is the possibility of using relatively simple physical and mathematical models to determine the distance of the performance of the device as a function of the parameters of NVD and the external surveillance conditions. By analyzing the parameters of the elements of NVD optoelectronic channel it is shown that at low levels of light the working range can be increased by improvement of the energy parameters of the system’s components while at high light levels this can be achieved by the enhancement of resolution (**Кощавцев et al., 1999**).

A formula for determination of the NVD working range as a function of the objective parameters (optics transmittance, diameter of the entrance pupil), integral sensitivity of the photocathode of IIT, resolution of device, and external surveillance conditions (atmosphere transmittance, ambient night illumination and contrast between observed object and the background) is represented in (**Гоев, 2002**):

(1.2) $$R = 3.10^5 \sqrt{\frac{\tau_o \tau_a D_{in} S_\Sigma E K}{M.\gamma}} \text{ [m]},$$

where: D_{in} – diameter of the objective entrance pupil in m, τ_o and τ_a – atmosphere and objective transmittance, S_Σ – IIT luminous sensitivity in A/lm, E –ambient night illumination in lx, K – contrast, M – signal-to-noise ratio, γ– device resolution in rad.

The relation (1.2) takes into account the overall device resolution and the luminous sensitivity of the used IIT. Disadvantage of (1.2) is that NVD working range does not take into account the size of the observed object.

A known and widely used method for the NVD optoelectronic channel design is based on light energy equations (**Елизаренко et al., 1981**). Using this approach, a formula for theoretical estimation of the NVD working range is proposed in (**Borissova et al., 2001**):

(1.3) $$R = \sqrt{\frac{A_{in} A_{ob} \tau_o \tau_a E K}{\pi.M.\varPhi_{th.ph}}} \text{ [m]},$$

where: A_{in} – objective inlet pupil area in m^2, A_{ob} – target area in m^2, τ_o – objective transmittance, τ_a – atmosphere transmittance, E – ambient light illumination in lx, K – utilization flow coefficient, M – signal-to-noise ratio, $\Phi_{th.ph}$ – IIT threshold sensitivity in lm.

The relation (1.3) takes into account the target area without considering the resolution of device. The NVD working range depends on many variables, including the lens focal length and the diameter of the inlet pupil (**Малинин, 2003**). In the process of NVD design it is necessary to select such ratio of parameters for which the NVD working range is optimal relative to given requirements.

Each of the described methods for testing the resolution has certain advantages and disadvantages. The choice of a particular method depends on the purpose for which it will be used. The analysis of the methods for determination of the NVD working range shows that the device parameters and external surveillance conditions should be taken into account. The described methods show a tendency to replace the traditional field testing with proper laboratory tests and theoretical calculations, that reduce the subjectivity and associated cost of field tests, and allow comparing the parameters of different NVD types under identical conditions.

1.6.2. Optimization and NVD

A relatively new trend in the design of NVD is the use of *optimization* methods (**Гоев, 2002a**). The process of modernization which includes: enhanced functionality, improved basic parameters, extending the applicability, providing better ergonomic characteristics of NVD, requires solving problems related to the technical-economic optimization. For this purpose, proper tasks are formulated to select a combination of parameters that will provide maximum possible quality at predetermined conditions. From consumer's perspective, one of the most important parameters is the NVD working range and this parameter is selected as a criterion of quality for optimization defined as a function of device parameters and external surveillance conditions (**Гоев, 2002a**).

Another direction of optimization of NVD is the use of unified modules (**Гоев, 2002b**). This is convenient from a production point of view as it allows relatively simple modernization of NVD without major structural adaptations. This direction also contains the concept of optimization, since it requires selection of modules from the given set, wherein the selection has to satisfy certain criteria. Extending of the functionality of NVD is described in the prospectus of the Litton company. The developed unified modules of eyepieces, adapters and other accessories enable relatively simple way to adapt to new functional applications of NVD. Using the base unit M944 (monocular) with IIT of III generation and different lenses, the device is modified as monocular with magnifications $1^{\times}$, $3^{\times}$, $4^{\times}$ or $6^{\times}$ and can be mounted to 35-mm camera and camcorder. The allowance for a drop in relative illumination across the field of view is vitally important to the image intensifier objective lens designer. One approach to problems elimination in the lens edge design is described in (**Hall, 2002**). It is shown that adjusting the vignetting alone reduced the weight by 35% and eliminates mechanical interference problems near the lens edges. An optoelectronic implementation of a genetic algorithm using binary logic operations, crossover and mutation of a population of chromosomes that can be carried out in parallel is very suitable for optical optimization (**Feng et al., 2000**).

All of these described optimization approaches demonstrate an increasing interest in the use of optimization methods in the area of optoelectronic applications.

The developed lens-design software is used to optimize image-forming optical systems. This software falls into two broad categories: classical lens-design software (for example, three of the major packages are ZEMAX, OSLO and CODE V) and illumination packages. Once the optical system has been designed and optimized it is needed to take a closer look at it. This is where illumination packages come in. The software systems ASAP, LightTools, TracePro and ZEMAX incorporate all the necessary modules for the design of high-quality optical systems, including modules for optimization of these systems in terms of aberrations, size, weight, etc. (**Mirzu, 2000**). Recently, the similar software systems implement sophisticated mathematical methods to design the aspherical lens as OpTaliX, ZEMAX, etc. This is a new and promising direction for achieving the desired optical requirements while reducing the number of lenses and the weight of the optical system (**Rouke et al., 1998**).

Despite the optimization approaches used during the optical systems development, the optimization of optoelectronic devices as a whole is a relatively new field. There are publications that mark a new direction in theoretical research of NVD – optimization of device as a whole in terms of predefined quality criteria for the unit. The NVD working range is one of the most important parameters, and is one of the major components of a criterion for optimization of NVD.

1.6.3. Methods and Tools for User Training

Use of night vision equipment requires specific skills and also intensive training. Night vision goggles (NVG) allow the user to see and detect more things at night than using unaided vision and to do it in a more natural way. When used in air operations NVG provide enhanced situational awareness and therefore increase tactical capability and flight safety. Limitations in the use of NVG result from design characteristics (for example, limited resolution and field of view, etc.), perceptual limitations (degraded depth perception, inaccurate distance estimation to light sources, etc.) and environmental conditions (illumination levels, weather, etc.). These limitations may result in mishaps that are due to over dependence on the NVG visual imagery, overconfidence, a lack of appreciation of the visual limitations inherent in the NVG image. The NVG users need early and continued exposure to the night environment across a broad range of visual conditions to develop and maintain the necessary perceptual skills. In this regard, different technologies for education and training in the use of NVD are developed. The results of efforts to demonstrate a low-cost night driving simulator concept for training night driving skills with NVG and to identify and evaluate the required techniques are described in (**Ruffner et al., 1997; Ruffner et al., 1999**). The night driving simulator concept for training night driving skills include traditional classroom training, practical training, simulation and training in real conditions. These traditional techniques are complemented with new computer technologies that include computer simulations and training through the Internet, regardless of time and place (**Ruffner et al., 2001**). The use of NVG has the potential for enhancing driving operations at night by allowing increased mobility and safer operations. However, with this increased capability has come the requirement to manage risks and provide suitable training. A relatively new technology for NVG training is computer-based training also known as computer-based instruction and interactive multimedia instruction. The primary advantages of computer-based training are that it provides interactive self-paced instruction, exploits the advantages of multimedia, can utilize a variety of learning strategies, can automate the measurement of user performance, and can provide feedback and remedial instruction within the program. Computer-based training can be used to reinforce topical instructional points made during classroom training, hands-on training, and simulator training. In addition, advanced computer-based training techniques are used to provide intelligent or adaptive training that adjust the difficulty and content according to user performance (**Ruffner et al., 2004**). At the present time there is little formal training available to help military drivers to obtain the required knowledge and skills and little opportunity to obtain and practice the necessary perceptual skills with representative imagery and scenarios prior to driving in the operational environment. The night driving training aid can serve as a valuable training asset for both military and civilian drivers who have a requirement to drive with image intensifier devices. The software architecture proposed in (**Ruffner & Woodward, 2000**) is easily adaptable to training knowledge and skills required for using NVG in a variety of other applications.

Using NVG requires prior training and exercise. Skills to work with NVG are perishable and require constant practice and maintenance. Capabilities of modern computer technology can be used to create computer simulators to support training for the NVG usage.

Chapter 2

Basic Parameters of NVD

The technological development and constant reducing of the cost of NVD led to their mass application in many different areas. In this regard, there is a strong interest in investigation of these devices and using of the results for different goals. There exists a special interest in using of mathematical modeling in design of NVD to produce devices with certain quality parameters (**Борисова et al., 2001**). The quality of NVD is determined by various parameters and most important characteristics from a practical point of view are: *the working range, field of view, limiting resolution, aberrations, dimensions, weight and price*.

This chapter presents the main parameters of the NVD and their relationship with the external surveillance conditions in order to define criteria for quality, suitable for modeling of optoelectronic channel of NVD. A formula for theoretical estimation of the NVD working range as a function of the parameters of the objective (diameter of the inlet pupil, focal length, optical transmittance), IIT parameters (limiting resolution, sensitivity, signal to noise ratio) and external surveillance conditions (ambient night illumination, contrast between background and target, atmosphere transmittance, target area) is proposed. Using the Johnson criteria, a new parameter "reduced target area" of the observed object is introduced and used to determine the different types of NVD working range – namely, distance of *detection*, distance of *orientation*, distance of *recognition* and distance of *identification*.

2.1. NVD Parameters

The main parameters of NVD that are subject of discussion in this section are: *magnification, field of view, limiting resolution, relative aperture and f-number, eye relief and exit pupil, aberrations of the optical system and IIT, objective focus range adjustment, ocular diopter adjustment and adjustment of interpupillary distance, stereoscopy, ergonomics and working range*.

2.1.1. Magnification

The magnification in optics can be represented mathematically by the relation between the size of an image and the size of the object creating it. Linear magnification refers to the ratio of image length to object length measured in planes that are perpendicular to the optical axis. A negative value of linear magnification denotes an inverted image. Longitudinal magnification denotes the factor by which an image increases in size, as measured along the optical axis. Angular magnification is equal to the ratio of the tangents of the angles subtended by an object and its image when measured from a given point in the instrument, as with magnifiers and binoculars (**Fig. 2.1**) (**Вълева, 1993**):

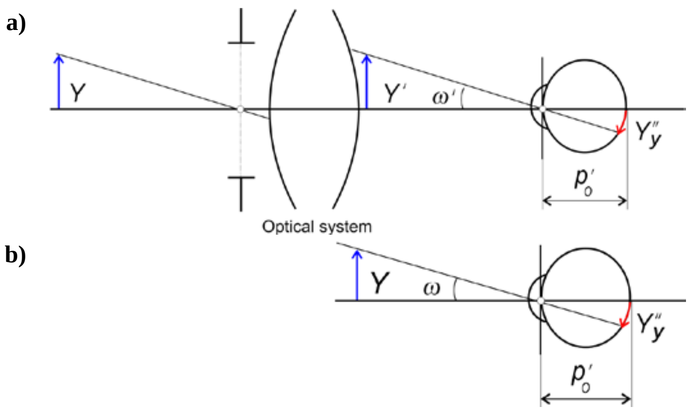


Fig. 2.1. *a) monitoring through optical device; b) monitoring without optical device*

(2.1) $$\Gamma = \frac{Y''_y}{Y''} = \frac{p'_o \, tg\omega'}{p'_o \, tg\omega} = \frac{tg\omega'}{tg\omega},$$

where: ω – the angle at which the object is observed with the naked eye, ω' is the angle at which the observed image object after optical device.

For complex optical systems such as NVD, the magnification Γ is defined as (**Вълева, 1993**):

(2.2) $$\Gamma = -\frac{f'_{ob}}{f'_{oc}} \prod_{i=1}^{m} \beta_i ,$$

where: f'_{ob} – objective focal length in mm, f'_{oc} – ocular focal length in mm, β_i – linear magnification of the optical system component located between the objective and ocular, m – number of components.

The typical magnification of the NVG is equal to 1 ± 2% (**Turpin, 2001**).

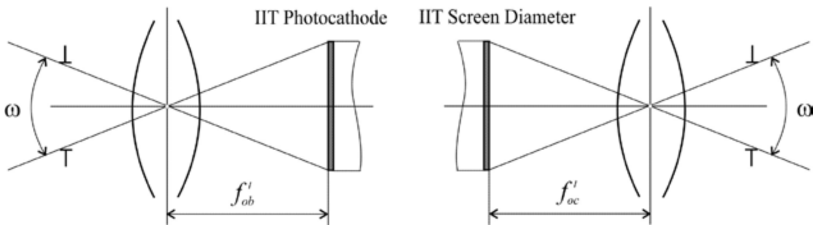
The required magnification for the NVG can be achieved by using of objective and ocular with equal focal lengths. The used IIT should provide a magnification (–1) that means using of an inverting IIT. The other NVD type could have a smaller field of view (2-12 degrees) and higher magnification (1.5 to 16.5 times) that can be achieved by using of objective and ocular with different focal lengths and/or by using of IIT with magnification.

2.1.2. Field of View

The field of view is measured by the angle or size that can be seen through the NVD, measured horizontally and vertically. It can be expressed in angular units (degrees, minutes, seconds) or in linear units (visible size in meters for a certain distance). The greater is the field of view, the greater is the visual information for the observer. The objective field of view can be defined by the ratio of the IIT photocathode diameter to the focal length of the objective (**Fig. 2.2a**):

(2.3a) $$f'_{ob} = \frac{D_{phIIT}}{2tg(\frac{\omega}{2})},$$

where: f'_{ob} – objective focal length in millimeters, ω – field of view in degrees, D_{phIIT} – diameter of the IIT photocathode in millimeters.



a) **b)**

Fig. 2.2. Field of view:

a) objective field of view; *b) ocular field of view*

The ocular field of view can be represented by the ocular focal length and by the diameter of the IIT screen as follows (**Fig. 2.2b**):

(2.3b) $$f_{oc} = \frac{D_{screenIIT}}{2tg(\frac{\omega}{2})} \text{ [mm]},$$

where: f_{oc} – ocular focal length in millimeters, ω – field of view in degrees, $D_{screenIIT}$ – diameter of the IIT screen in millimeters.

The NVG devices have typical field of view of 40 degrees, with the tendency to increase it as in the case of panoramic night vision goggles.

2.1.3. Resolution

Resolution is the ability of an image intensifier or night vision system to distinguish between objects that are close to each other. Image intensifier resolution is measured in line pairs per millimetre (lp/mm) while system resolution is measured in cycles per miliradian. For any particular night vision system, the image intensifier resolution will remain constant while the system resolution can be affected by altering the objective or eyepiece optics, by adding magnification or relay lenses. Often the resolution in the same night vision device is very different when measured at the centre of the image and at the periphery of the image. IIT resolution usually is determined from a 1951 Air Force resolving power test target – USAF 1951 (MIL-STD-150A). This target consists of a series of different sized patterns composed of three horizontal and three vertical lines. The lines and spacing between lines in each of the different patterns differ in width; the narrower the width, the greater the resolution is needed to distinguish the lines in a given pattern (**Bijl, Valeton, 1994**). Human test subjects must be able to clearly distinguish all the horizontal and vertical lines of a particular pattern in order for an image intensifier to achieve the resolution represented by that pattern.

It should be noted that the image of each point source is not a point and can be presented by diffraction pattern. Because of diffraction from the system stop, an aberration-free optical system does not image a point to a point. An Airy disk is produced having a bright central core surrounded by diffraction rings (**Fig. 2.3**).

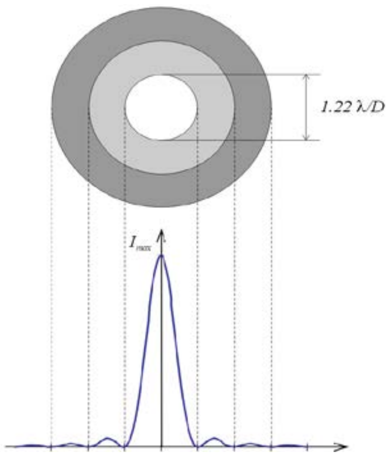


Fig. 2.3. Airy disk diffraction pattern

In optics, the Airy disk describes the best focused spot of light that a perfect lens with a circular aperture can make, limited by the diffraction of light. Central maximum contains 83.8 % of the energy, first diffraction maximum contains 7.2 %, second diffraction maximum contains 2.8 %, etc. The Airy disk diameter (*d*) depends on the optical system aperture and wavelength. Mathematically, the diffraction pattern is characterized by the wavelength of light illuminating the circular aperture, and the aperture's size. The diameter of the Airy disk is:

$$d_{Airy} = \frac{1.22\lambda}{D}, \tag{2.4}$$

where: D – circular aperture diameters.

Angular resolution, or spatial resolution, describes the ability of any image-forming device optical or eye, to distinguish small details of an object, thereby making it a major determinant of image resolution. The Rayleigh criterion is the generally accepted criterion for the minimum resolvable detail – the imaging process is said to be diffraction-limited when the first diffraction minimum of the image of one source point coincides with the maximum of another (**Fig. 2.4**).

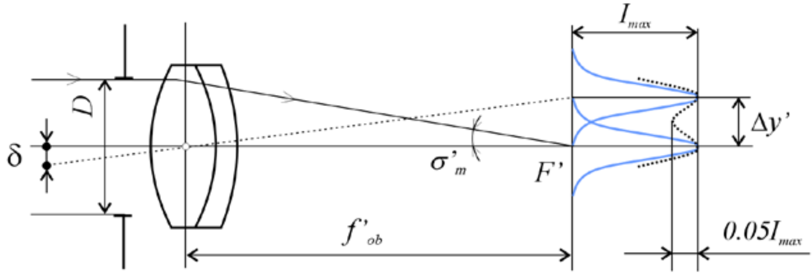


Fig. 2.4. Rayleigh criterion for the minimum resolvable detail

If aberrations are missing in the optical system, then the resolution is limited by the diffraction of light and depends on the aperture diameter D and the aperture angle σ_m.

(2.5) $$\sigma_m' = \frac{D}{2f'}$$

where D and λ have equal units.

The minimum distance between two points separated in the image is defined as (**Николов, 1993**):

(2.6) $$\Delta y' = \frac{0.51\lambda}{\sigma_m'}$$

For infinitely located object the angular value of diffractive resolution can be determined as (**Николов, 1993**):

(2.7) $$\delta = \frac{\Delta y'}{f'} = \frac{120''}{D}$$

for wavelength λ = 546 nm.

The resolution for real objectives is less than δ =140''/*D* (**Николов, 1993; Вълева, 1993**).

If all parts of an imaging system are considered to be perfect, then the resolution of any imaging process will be limited by diffraction. Therefore, the limit resolution for the optical systems is related with the *inlet aperture diameter, the wavelength of light and aberrations*. The resolution is measured in number of lines per unit of angle (*lines/rad*) for remote objects while for the closely spaced objects is measured in number of line pairs per unit length (lp/mm).

The resolution of NVD depends on the resolution of the optoelectronic channel, or more precisely, on the parameters of the used objective, IIT and ocular.

2.1.4. Relative Aperture and f-number

The relative aperture of an optical system is determined by the absolute value of the ratio of the aperture diaphragm diameter *D* to the focal length *f:*

(2.8) $$\left|\frac{D}{f}\right|.$$

The so called *f*-number accurately describes the light-gathering ability of lens only for objects placed in an infinite distance. In optics, the *f*-number (sometimes called *f*-stop, *focal ratio*, *f*-ratio or *relative aperture*) of an optical system is the ratio of the lens's focal length *f* to the diameter *D* of the entrance pupil. To calculate the *f*-number, the focal length is divided to the diameter of the entrance pupil (effective aperture) and is dimensionless:

$$f\# = \left| \frac{f}{D} \right| . \tag{2.9}$$

It should be noted, that an increase in the relative aperture of the lens reduces the image quality, since the large entrance pupil increase the system aberrations.

The values of objectives *f*-number for NVD vary in the range of 1.05 to 1.4.

2.1.5. Eye Relief and Exit Pupil

Eye relief is the distance between the ocular lens or the last surface of an eyepiece at which the eye can obtain the full viewing angle, or to put it another way, it is the distance that an optical instrument can be held from the eye and the full field of view can still be comfortably observed. The shorter this distance, the more difficult it can be to observe.

The exit pupil is a virtual aperture in an optical system. Only rays which pass through this virtual aperture can exit the system. The exit pupil is the image of the aperture stop in the optics that follows it (**Fig. 2.5**).

The primary function of the eyepiece is to focus the image of the object, so as to ensure the required field of view of sufficient size and eye relief and exit pupil diameter. To achieve this it is required to perform a series of calculations to determine the ocular's parameters as a function of the objective lens and field of view.

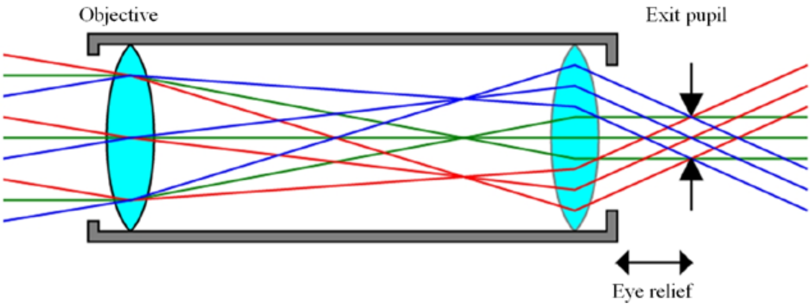


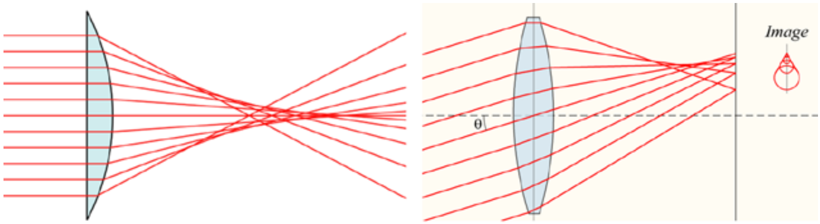
Fig. 2.5. Eye relief and exit pupil

2.1.6. Aberrations of the Optical System and IIT

The modern optical devices have high requirements toward image quality, but it should be noted that fully correction of aberrations leads to an increase in the lens number and increasing of the total weight of the lens, respectively objective and eyepiece. The aberrations (geometric distortion) of the optical system significantly reduces its theoretical resolution. The value of the wave aberration determines the quality of the optical system (**Родионов, 2000**). When light of only a single wavelength is present, there are five aberrations to be considered, called *spherical aberration, coma, astigmatism, curvature of field,* and *distortion.* In the case of NVD using the output image is colored in green and therefore only *monochromatic* aberrations are to be considered.

<u>Spherical Aberration and Coma</u>

A bundle of light rays coming from one point on the optical axis is focused at a different place than the focused point depending on the distance from the optical axis when the light incidents. This deviation is caused by variations in angles of each incident light ray, and is called *spherical aberration*. For lenses made with spherical surfaces, rays which are parallel to the optic axis but at different distances from the optic axis fail to converge to the same point. Rays passing through the lens close to its centre are focused farther away than rays passing through a circular zone near its rim (**Fig. 2.6**).



a **b**

Fig. 2.6. Spherical **aberration** and coma:
a) spherical aberration; b) coma

Lens with spherical surfaces produce spherical aberration due the fact that different rays do not meet after the lens in one focal point. The further the rays are from the optical axis, the closer to the lens they intersect the optical axis. A simpler optical design to reduce spherical aberrations can be obtained using aspheric lenses. Instead of spherical surfaces, an aspheric lens has surface curvatures that deviate from a spherical surface such as being parabolic in shape.

Field Curvature

Field curvature is a failure to focus the entire image on a single plane perpendicular to the optical axis. Instead of the focal plane there is a paraboloid surface resembling a bowl or meniscus. This produces a characteristic inability to focus the center and edges of the field at the same time. Field curvature, also known as *curvature of field* or *Petzval field curvature*, is a common optical problem that causes a flat object to appear sharp only in a certain part(s) of the frame, instead of being uniformly sharp across the frame. This happens due to the curved nature of optical elements, which project the image in a curved manner, rather than flat (**Fig. 2.7**; see also https://photographylife.com/what-is-field-curvature).

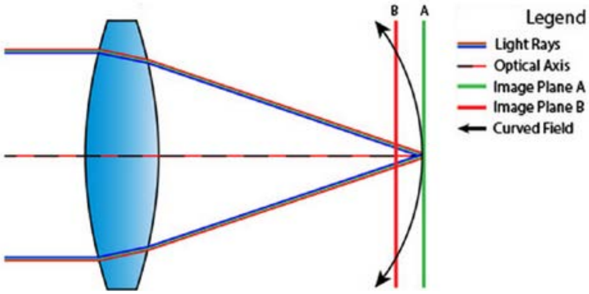
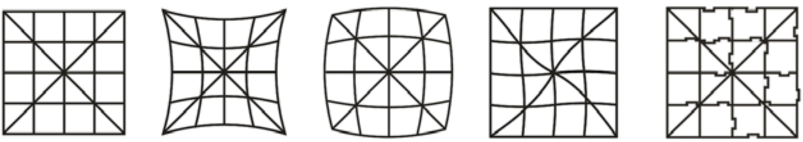


Fig. 2.7. Curvature of field

In curvature of field, the image of a plane object perpendicular to the optical axis will lie on a paraboloidal surface called the *Petzval surface*. Due the nature of curvature of field this aberration cannot be corrected (**Вълева, 1993**).

Distortion

The *geometric optics distortion* is a deviation from rectilinear projection, a projection in which straight lines in a scene remain straight in an image. It is a form of *optical aberration*. In the presence of distortion, the image is clear, but deformed. The distortion is due to the fact that cross-increase is not the same for different points of the plane perpendicular to the optical axis. Three types of distortion are most significant to night vision devices: *geometric*, “*S*” and *sheer*, shown in **Fig. 2.8**.



a) object *b) geometric distortions* *c) S-distortion* *d) sheer*

Fig. 2.8. Types of distortions

Geometric distortion is inherent in all Gen 0 and Gen I image intensifiers and in some Gen II image intensifiers that use electrostatic rather than fibre-optic inversion of the image. Geometric distortion is eliminated in image tubes that use a microchannel plate and fibre-optics for image inversion, however, some S-distortion can occur in these tubes.

S-distortion is result from the twisting operation in manufacturing fibre-optic inserters. Usually S-distortion is very small and is difficult to detect with the unaided eye.

Sheer distortion – can occur in any image tube that uses fibre-optic bundles for the phosphor screen. It appears as a cleavage or dislocation in a straight line viewed in the image area as through the line were sheered.

Non-inverter IIT using microchannel plate and flat glass as an output and have no distortion. Permissible relative distortion, at which no sensation is distorted in the image perception by the human eye, varies within the range of 5–10 % (**Родионов, 2000**).

In the case of NVD the permitted distortion is less than 4% for the whole field of view (Turpin, 2001).

Astigmatism

Astigmatism combines features of focus and magnification errors and is intimately associated with both the field curvature and the distortion. Astigmatism occurs when light rays from perpendicular cross-sections of the image cone do not have the same focal distance along the optical axis. It is therefore an error both of focus and of magnification. Astigmatism is pervasive in optical systems, and occurs in all abaxial light passed through any refracting lens. It is the most difficult aberration to correct. Rays emitted from a point object form a right circular cone and are oriented towards a lens. When the point object is located off-axis, the cone of rays forms an ellipse on the surface of the lens. The tangential plane intersects the major axis of the ellipse, and it contains both the optical axis and the object point. The sagittal plane is oriented perpendicular to the tangential plane (**Fig. 2.9**) (**Вълева, 1993**).

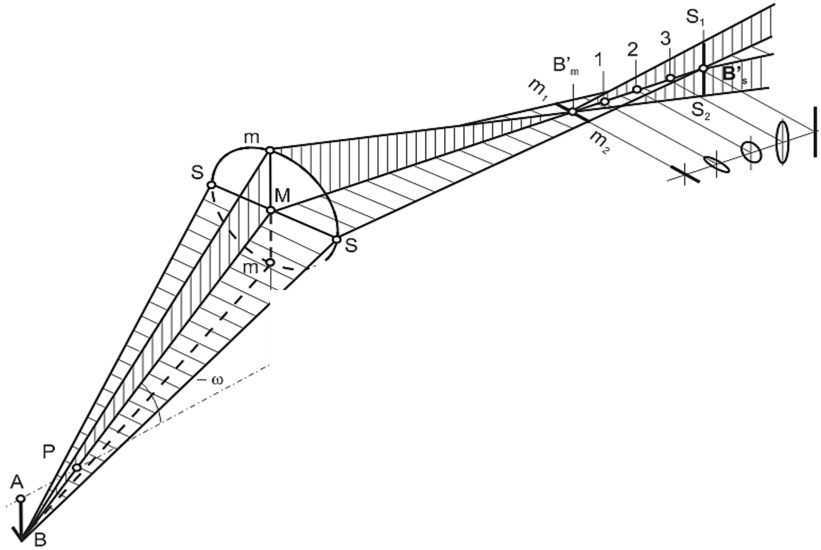


Fig. 2.9. Astigmatism

An optical system with astigmatism is one where rays that propagate in two perpendicular planes have different focus. If an optical system with astigmatism is used to form an image of a cross, the vertical and horizontal lines will be in sharp focus at two different distances.

Increasing of the objective diameter, respectively the eyepiece results in an increase in all types of aberration. **Fig. 2.10** (http://toothwalker.org/optics.html) below and **Table 2.1** illustrate the dependence of third-order lens aberrations on the aperture diameter *d* and distance *y* from the image center.

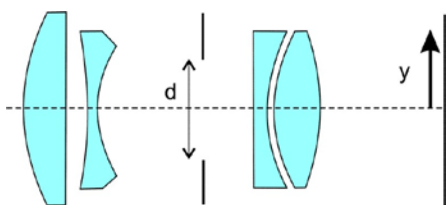


Fig. 2.10. d – aperture diameter, y – distance from the image center

Table 2.1. Relation between aberrations and aperture diameter

Aberration	Diameter	y
Spherical aberration	d^3	–
Coma	d^2	y
Astigmatism	d	y^2
Field curvature	d	y^2
Distortion (%)	--	y^2
Axial color	d	--
Lateral color	--	y

It is an approximation that does not include higher-order terms, but it provides useful insight.

2.1.7. Adjustment of Objective Focus Range, Ocular Diopter and Interpupillary Distance

The ability to adjust the objective focus range is essential when using NVD. This adjustment allows surveillance of both distant and closely spaced objects (for example, using a map for orientation or in case of repairs, etc.). The focus can vary in the ranges 0.2-0.41 m to infinity. The diopter adjustment of ocular allows to correct different user requirements in the ranges of: (– 6, +2), (–2, +6), (–3, +3), (–4, +4), (–4.5, +4.5), (–5,+5) diopter. The NVD with two separate optoelectronic channels (binocular NVD) should provide also an appropriate adjustment of interpupillary distance for different users. The limits of adjustment of interpupillary distance are different – the bottom is about 51 to 58 mm, and the upper is 72 to 80 mm.

The values of minimum focus range of objective vary within 0.2-0.41 m to infinity, ocular diopter adjustment varies within –6 to +6 diopter and the limits of adjustment of interpupillary distance cover the range between 51 to 80 mm.

2.1.8. Stereoscopy

Stereoscopy, called also *stereoscopics*, is a technique for creating or enhancing the illusion of depth in an image by means of stereopsis for binocular vision. Most stereoscopic methods present two offset images separately to the left and right eye of the viewer. These two-dimensional images are then combined in the brain to give the perception of depth. Stereoscopy creates the illusion of three-dimensional depth from given two-dimensional images. Human vision, including the perception of depth, is a complex process which only begins with the acquisition of visual information taken in through the eyes; much processing ensues within the brain, as it strives to make intelligent and meaningful sense of the raw information provided. *Depth perception* is the ability to estimate absolute distances between an object and the observer or the relative distances between two objects, i.e. how far to the left or right the object is and whether the different objects are in front or behind each other. Because the eyes of humans are located at different lateral positions on the head, binocular vision results in two slightly different images projected to the retinas of the eyes. The differences are mainly in the relative horizontal position of objects in the two images. These positional differences are referred to as *horizontal disparities* or, more generally, *binocular disparities*. Disparities are processed in the visual cortex of the brain to yield depth perception. Maintaining this effect in binoculars is a matter of very precise adjustment of the optical axes of both visual channels. Stereoscopy is retained when using binocular devices (devices with two separate channels for the left and right eye), but is missing for the other NVD types.

When NVD for driving of different types of vehicles (aircraft, jeep, car, etc.) are used, it is obligatory to use NVD with two independent optoelectronic channels that will provide the effect of stereoscopy.

2.1.9. Ergonomics

Ergonomics, also known as *comfort design*, is functional and user-friendly design, which purpose is creation of products intended to maximize productivity by reducing operator fatigue and discomfort. The convenience of using NVD is essentially important. Ergonomics depends on mechanical design and weight and determine the comfort or discomfort when using the device. The length of the objective together with that of the IIT and the eyepiece, determine the length of the optoelectronic channel. The NVD overall dimensions depend on the NVD type (monocular, binocular or biocular) and on the dimensions of the used optoelectronic channel modules (objective, IIT and ocular). The NVD length, the NVD center of gravity and the NVD weight define a rotating moment provoking weariness and discomfort during the long time usage. In most cases this rotating moment cannot be avoided but decreasing of the discomfort by decreasing of the NVD dimensions helps to avoid degrading of the NVD performance.

The importance of ergonomics of NVD is confirmed in (**Добровольский et al., 1998**) where a criterion for quality of NVD based on the ratio of the field of view and the torque value is proposed:

$$K = \frac{2\omega R}{aM}, \tag{2.10}$$

where: 2ω – NVD field of view, R – identification distance, a – distance from the fulcrum point of the face to the center of gravity of NVD, M – weight of NVD.

NVD with light weight create a lower torque that reduces the user fatigue during continuous operation. Except light weight, the longitudinal size of NVD is also an important parameter that should be taken into account in the design process.

2.1.10. Working Range

One of the most important parameters of the NVD is its *working range*. In the literature a number of variations of the working range is described depending on the desired specificity of surveillance – *detection* distance, *orientation* distance, *recognition* distance and *identification* distance (**Bijl, Valeton, 1998**):

- *Detection range* (R^D) – the distance to the object at which the object is detected, i.e. the object can be distinguished as an unknown object from the background.
- *Orientation range* (R^O) – the distance, where it is possible to determine the spatial orientation of the object (determining the direction of a larger size in a minimal bounding box).
- *Recognition range* (R^R) – the distance at which the details of the observed object of a certain size can be seen. At this range the target can be classified e.g. human, car, etc.
- *Identification range* (R^I) – the distance at which the object can be described in detail, e.g. woman versus a man, the specific model of car and so on.

The following relations between the different types of working ranges can be stated:

$$R^D < R^O < R^R < R^I \tag{2.11}$$

The NVD working range depends on both the device parameters and the external surveillance conditions. Analytical determination of the NVD working range considering the device parameters and external surveillance conditions is described in detail in the next section 2.2.

The NVD working range is a generalized parameter. In particular calculations, one of its varieties (detection, orientation, recognition, identification) can be considered. Regardless of the specified variation of the working range, this parameter is a mandatory component in defining the criterion of quality of NVD.

2.2. Determination of the Working Range of NVD

As the working range is one of the most important parameters of NVD, it is necessary to be examined in detail, and to find its functional dependence on the parameters of the device's optoelectronic channel. This relationship will enable the determination of theoretical values for the different variations of the working range depending on the used NVD modules. In most cases, the results obtained by analytical calculation differ from the actual measurement results, but give a fairly good basis for the parameters of the designed device. To obtain a theoretical estimation for the NVD working range it is necessary to formulate analytical dependence that adequately reflect both the parameters of the individual modules of the device and the parameters of the external surveillance conditions. This will allow obtaining a theoretical estimation for this important device parameter on the design stage before field testing.

Different physical parameters affect the working range of NVD. It is clear that larger objects can be seen more easily, i.e., working range depends on the size of the observed object. The surveillance conditions including weather conditions (as fog, rain, snow, etc.) are also essential for determination of the working range. The presence of light and atmosphere transmittance will provide greater working range of device. On the other hand, the parameters of the modules of optoelectronic channel (IIT, objective and ocular) directly influence the device working range.

One of the most common methods used in the design of NVD is the method based on energetic calculations (**Елизаренко, 1981**). This approach allows to estimate the working range when the device parameters are known and external surveillance conditions (brightness, contrast, etc.) are given. This method can also be used to determine the device parameters by a predefined working range value.

2.2.1. Energetic Calculations for Working Range Determination

The analytical determination of the NVD working range requires taking into account the parameters of the elements used in the NVD optoelectronic channel and the external surveillance conditions. The goal of energy calculations method is to determine the minimum energy threshold of NVD optoelectronic channel considering the used parameters of optical elements (**Elizarenko et al., 1981**). This means to get some estimates for the useful input signal and values for the minimum input signal under which the device will operate normally. This method can be used to estimate the theoretical value of NVD working distance considering NVD parameters and external surveillance conditions.

The basic stages of the method are: 1) determination of minimum luminous flux at which the device will be able to operate; 2) estimation of the threshold of device sensitivity, and 3) determination of the relation between emitted flux and received flux on the optical system inlet pupil (**Елизаренко, 1981; Borissova, 2005**). At first, the minimum luminous flux at which the device will be able to operate has to be calculated. At the second stage, the estimation for threshold device sensitivity is needed and estimation about its dependence on external and internal factors is to be done. At the third stage, the the emitted flux that is received in the optical system inlet pupil have to be expressed. The useful part of the light flux is expressed as a function of external conditions and the parameters of the optical system. Finding the appropriate optimal ratio between the luminous flux from the object and the minimum luminous flux (flux threshold) for optical system operation is essential. Selection of an optimal relation between these two flows – thresholds and minimum, represents *signal-to-noise* parameter. This optimal relation for signal-to-noise parameter is the minimum signal-to-noise ratio at which the device still operates. If the relation between the signal and the noise becomes less than the necessary minimum, the device will stop working. Following these considerations, the basic energy dependence can be presented as:

(2.12) $$M=\Phi/\Phi_{th} \text{ or } (M = E/E_{th}) \text{ and } M \geq 1,$$

where: μ represents the required minimum ratio of signal to noise, Φ – the required minimum input flow, Φ_{th} – threshold of sensitivity.

The equation (2.12) can be solved toward one of its participating parameters. The equation of the effective background flow $\Phi_{b.eff}$ falling on the IIT photocathode can be represented by the following relationship:

(2.13) $$\Phi_{b.eff} = L_b(\lambda)A_{in}\omega K_b \text{ [W]},$$

where the background brightness $L_b(\lambda)$ is determined by:

(2.14) $$L_b(\lambda) = \frac{E}{\pi}\int_{\Delta\lambda} \rho_b(\lambda)d\lambda \text{ [W/sr m}^2\text{]},$$

where: E – illumination in lx, $\rho_b(\lambda)$ – spectral reflectance of the background, A_{in} – area of an entrance pupil [m^2], ω – angular field of view of the device in steradians [sr], K_{ph} – utilization coefficient of flow from the photocathode:

(2.15) $$K_{ph} = \int_{\Delta\lambda} \tau_a(\lambda)\tau_o(\lambda)\varphi(\lambda)d\lambda .$$

The parameters in (2.15) τ_a and τ_o are integrated coefficients of atmosphere transmittance and the input optics transmittance, within the operating range of the photocathode of the IIT, and the spectral sensitivity of IIT is denoted by $\varphi(\lambda)$. Replacing the $L_b(\lambda)$ in (2.13) and taking into account the fact that for certain wavelength with valid relation $\tau_a(\lambda) = \tau_a$, $\tau_o(\lambda) = \tau_o$, $\varphi(\lambda)=S$, the following relation is obtained:

(2.16) $$\Phi_{b.eff} = \frac{EA_{in}\omega\tau_o\tau_a S}{\pi}\int_{\Delta\lambda} \rho_b(\lambda)d\lambda .$$

If $K'_b = \int_{\Delta\lambda} \rho_b(\lambda)d\lambda$ then:

(2.17) $$\Phi_{b.eff} = \frac{EA_{in}\omega\tau_o\tau_a SK'_b}{\pi} .$$

Similarly, for an object with angular size ω_{ob} is valid:

(2.18) $$\Phi_{ob.eff} = \frac{EA_{in}\omega_{ob}\tau_o\tau_a SK'_o}{\pi} ,$$

where: $K'_o = \int_{\Delta\lambda} \rho_o(\lambda)d\lambda$ and $\rho_o(\lambda)$ is the spectral reflectance of the object.

In the presence of an object in the field of view, the effective flow of background is reduced to:

(2.19) $$\Phi'_{b.eff} = \frac{EA_{in}(\omega - \omega_{ob})\tau_o\tau_a SK'_b}{\pi} .$$

The total flow from object and background can be obtained as:

(2.20) $$\Phi_{\Sigma eff} = \Phi_{ob.eff} + \Phi'_{b.eff}\,.$$

The difference in flows received by the object and the background, falling on the photocathode is:

(2.21) $$\Delta\Phi_{eff} = \Phi_{\Sigma eff} - \Phi_{b.eff} = \Phi_{ob.eff} + \Phi'_{b.eff} - \Phi_{b.eff}\,.$$

Spatial observation angles of the background and the object (ω and ω_{ob}) can be determined using the definition of solid angle, where R is the distance to the observed object/background in meters and A_b and A_{ob} are the areas of the background and the object in m^2:

(2.22) $$\omega = A_b/R^2\ [\text{sr}],\ \omega_{ob} = A_{ob}/R^2\ [\text{sr}].$$

The difference between the flow of the background and the flow of the object is:

(2.23) $$\Delta\Phi_{eff} = \frac{A_{ob}A_{in}\tau_o\tau_a ES}{R^2\pi}\left|K'_{ob} - K'_b\right|.$$

The contrast between the observed object and the background can be denoted by $K = \left|K'_{ob} - K'_b\right|$ and (2.23) is modified as:

(2.24) $$\Delta\Phi_{eff} = \frac{A_{ob}A_{in}\tau_o\tau_a ES}{R^2\pi}K\,.$$

To operate the device the effective flow must exceed M times the threshold flow, where M characterizes the signal-to-noise ratio:

(2.25) $$\Delta\Phi_{eff} \geq M\Phi_{th.ph}\,.$$

Replacing the relation (2.24) in (2.25) leads to:

(2.26) $$\frac{A_{ob}A_{in}\tau_o\tau_a ESK}{R^2\pi} \geq M\Phi_{th.ph}\,.$$

The obtained equation (2.26) can be solved toward one of its participating parameters. The main difficulty here lies in the fact that at this stage of the NVD design more than one parameter is unknown. Therefore, some values of the unknown parameters are set to determine one of them. For the purpose of this study it is necessary to determine the NVD working range.

Using the relation (2.26), the NVD working range can be determined as follows (**Borissova et al., 2001**):

(2.27) $$R = \sqrt{\frac{A_{in} A_{ob} \tau_o \tau_a ESK}{\pi M \Phi_{th.ph}}}.$$

The disadvantage of the resulting formula is that it does not account for the impact of the device resolution. This disadvantage is overcome in (**Гоев, 2002**). The resolution of real optical systems is defined as (**Вълева, 1993; Николов, 1993**):

(2.28) $$\gamma = \frac{140}{D_{in}}.$$

where: γ – optical system resolution in seconds, D_{in} – diameter of inlet pupil in millimeters.

The inlet pupil area can be determined using its diameter by the relation:

(2.29) $$A_{in} = \frac{\pi D_{in}^2}{4} \text{ [m}^2\text{]}.$$

Substituting (2.29) in (2.27) leads to the representation for working range as:

(2.30) $$R = \sqrt{\frac{\pi D_{in}^2}{4} \frac{A_{ob} \tau_o \tau_a ESK}{\pi M \Phi_{th.ph}}}.$$

Using (2.28) to express D_{in} via γ, and taking into account that A_{in} in (2.29) is in meters (therefore the D_{in} must be expressed in meters too), the following modification of (2.30) can be obtained as

(2.31) $$R = \sqrt{\frac{0.035 D_{in} A_{ob} \tau_o \tau_a ESK}{\gamma M \Phi_{th.ph}}}.$$

Disadvantage of (2.31) is the fact that it takes into account the resolution of the device as a whole. This implies the development of a prototype and measure the value of device resolution to be used for determining the working range. To avoid the development of prototypes and the associated loss of time and resources it is interesting to find a formula for theoretically estimation of the NVD working range using the parameters of particular elements of the optoelectronic channel. It is obviously that the device resolution depends on the resolution of the optoelectronic channel, i.e. depends on the used objective, IIT and eyepiece. The resolution of modern eyepieces is high enough and does not affect the device resolution, therefore to determine the optoelectronic channel resolution it is sufficient to consider the resolution of the used objective and IIT.

For infinitely located object, the angular value of the diffractive resolution of the objective is determined as (**Николов, 1993**):

(2.32) $$\delta = \frac{\Delta y}{f'_{ob}},$$

where: f'_{ob} – objective focal length in millimeters (**Fig. 2.11**).

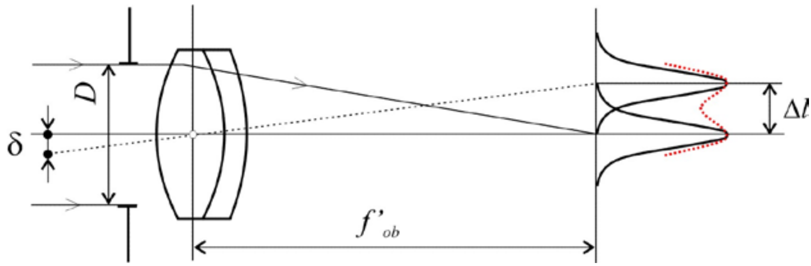


Fig. 2.11. Diffraction-limited resolution

The minimum size that can be distinguished from the IIT is determined by its resolution δ_{IIT} [*lp/mm*] as (**Borissova, Mustakerov, 2006**):

(2.33) $$\Delta l = \frac{1}{2\delta_{IIT}}.$$

In practice, the resolution of the available IIT is smaller than that of the objectives resolution. Therefore, instead Δy in (2.32) can be used Δl from (2.33) and the following expression can be used for the optoelectronic channel resolution (**Borissova, Mustakerov, 2006**):

(2.34) $$\delta_{ob-IIT} = \frac{\Delta l}{f'_{ob}} = \frac{1}{2\delta_{IIT} f'_{ob}}.$$

Using this theoretical resolution for optoelectronic channel in (2.31) the formula for calculation of the NVD working range is (**Borissova, Mustakerov, 2006**):

(2.35) $$R = \sqrt{\frac{0.07 D_{in} f'_{ob} \tau_o \tau_a S \delta_{IIT} E A_{ob} K}{M \Phi_{th.ph}}},$$

where: D_{in} – diameter of the objective inlet pupil in m, f'_{ob} – objective focal length in mm, τ_o – objective transmittance, τ_a – atmosphere transmittance, $\Phi_{th.ph}$ – IIT photocathode limiting light flow in lm, δ_{IIT} – limiting resolution of IIT in lp/mm, S – IIT luminous sensitivity in A/lm, M – signal to noise ratio, E – ambient night illumination in lx, K – contrast between target and background, A_{ob} – target area in m^2.

The formula (2.35) allows to determine the NVD working range as a function of the parameters of the optoelectronic channel elements – objective (diameter, focal length and transmittance), IIT (photocathode sensitivity, signal/noise ratio and resolution), external surveillance conditions (ambient night illumination, contrast between the target and the background, atmosphere transmittance and target area). It should be noted that (2.35) can be used both for devices without magnification (night vision goggles) and for night vision with magnification (binoculars and sights), as it takes into account the objective focal length, and the objective and eyepiece ratio determine the NVD magnification.

Using the proposed formula (2.35), it is possible to determine a theoretical estimation the NVD working range taking into account the parameters of the optoelectronic channel elements and external surveillance conditions. This formula can be used in optimization models as a criterion for quality of NVD working range.

2.2.2. Types of Working Range According to Johnson Criteria

Johnson's criteria describe both image-domain and frequency-domain approaches to analyze the ability of observers to perform visual tasks using image intensifier technology. Target acquisition is generally concerned with the detection of points of interest and their subsequent recognition and identification. These criteria were originally quantified by John Johnson in the 1950s. He investigated the relationship between the ability of the observer(s) to resolve bar targets (one black bar and one white bar equate to one cycle) through an imaging device and their ability to perform the tasks of detection, recognition, and identification of military vehicles through the same optical sensor. The empirical relationship that Johnson developed serves as the foundation for the *de facto* standard based on critical dimension of the target.

The minimum required resolution according to Johnson's criteria are expressed in terms of line pairs of image resolution across a target, in terms of several tasks as: *detection* – an object is present; *orientation* – symmetrical, asymmetric, horizontal, or vertical; *recognition* – the type object can be discerned, a person versus a car; *identification* – a specific object can be discerned (**Kopeika, 1998**).

The number of just resolvable cycles required across a target's critical dimension for various discrimination tasks. The resolution values for different targets accordingly the Johnson's criteria are shown in **Table 2.2** (**Lombardo, 1998**).

These values of resolution give a 50 percent probability of an observer discriminating an object to the specified level. The critical target dimension is illustrated in **Fig. 2.12** according to Johnson's criteria (**Lombardo, 1998**):

As it was mentioned, there are four different types of the working range: *detection*, *orientation*, *recognition* and *identification*. Using the Johnson's criteria and determined values for the minimum number of lines pairs for different targets the corresponding variations of the working range can be defined. For this purpose, a new parameter called *reduced target area* (A'_{ob}) is introduced.

Table 2.2. Johnson's criteria

Target	Resolution per minimum dimension (line pairs)			
	Detection	Orientation	Recognition	Identification
Tank M-48	0.7	1.2	3.5	7.0
Tank T-34	0.75	1.2	3.3	6.0
Tank "Centurion"	0.75	1.2	3.5	6.0
Truck	0.9	1.25	4.5	8.0
Half truck	1.0	1.5	4.0	5.0
Jeep	1.2	1.5	4.5	5.5
Command car	1.2	1.5	4.3	5.5
Standing man	1.5	1.8	3.8	8.0
Howiter 105	1.0	1.5	4.8	6.0
Average	**1.0 ±0.25**	**1.4 ±0.35**	**4.0±0.8**	**6.4±1.5**

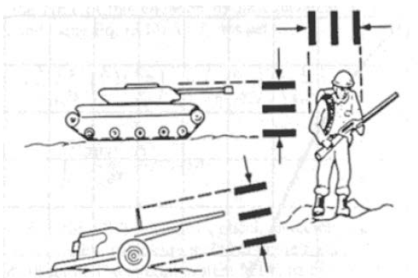


Fig. 2.12. Critical target dimension accordingly Johnson's criteria

The reduced target area A'_{ob} is calculated as the ratio of the area of the observed object A_{ob} to the minimum number of lines pairs (according to the Johnson's criteria), required for detection, orientation, recognition and identification. In the formula (2.35) instead of the observed object area A_{ob} the reduced target area A'_{ob} can be used to determine different types of working range (**Borissova, Mustakerov, 2006**):

(2.36a) $$R^D = \sqrt{\frac{0.07 D_{in} f_{ob} \tau_o \tau_a S \delta_{IIT} E K A_{ob}^{'d}}{M \Phi_{th.ph}}};$$

(2.36b)
$$R^O = \sqrt{\frac{0.07 D_{in} f_{ob} \tau_o \tau_a S \delta_{IIT} E K A_{ob}^{'or}}{M \Phi_{th.ph}}} \;;$$

(2.36c)
$$R^R = \sqrt{\frac{0.07 D_{in} f_{ob} \tau_o \tau_a S \delta_{IIT} E K A_{ob}^{'r}}{M \Phi_{th.ph}}} \;;$$

(2.36d)
$$R^I = \sqrt{\frac{0.07 D_{in} f_{ob} \tau_o \tau_a S \delta_{IIT} E K A_{ob}^{'i}}{M \Phi_{th.ph}}} \;.$$

The particular values of the reduced target areas are determined by the specific target type (person, jeep, tank, etc.) according to the Johnson's criteria.

Using the Johnson's criteria, a new parameter "reduced target area" is introduced for determination of different type of the NVD working range – *detection, orientation, recognition and identification.* Using the "reduced target area" parameter four modifications (2.36a, b, c, d) of the formula (2.35) are proposed to determine the different types of NVD working range.

2.3. Internal NVD Parameters and External Surveillance Conditions

For mathematical modeling of NVD, it is necessary to take into account both internal parameters (device parameters) and external parameters (surveillance conditions).

2.3.1 Internal Parameters NVD Parameters

The following parameters can be associated as essential NVD internal parameters:

- magnification;
- field of view and its dependence of the objective focal length and IIT photocathode diameter;
- objective f-number;

- optical transmittance;
- exit pupil and eye relief;
- limiting resolution;
- IIT photocathode's sensitivity;
- and signal to noise ratio.

In case of NVG the magnification must be equal to 1, which can be achieved by using of objective and eyepiece with equal focal length

(2.37) $$f_{ob} = f_{oc}.$$

The magnification for other type of NVD is always greater than 1 and can be expressed by the focal length of the objective and eyepiece as:

(2.38) $$\Gamma = \frac{f_{ob}}{f_{oc}}.$$

The field of view is internal parameter of NVD that can be determined by the following inequality:

(2.39) $$f_{ob} \le \frac{D_{ph.IIT}}{2tg\left(\frac{\omega}{2}\right)}.$$

As seen from (2.39), the device field of view is related with the objective focal length and diameter of the IIT photocathode.

Ignoring differences in light transmission efficiency, a lens with a greater *f*-number projects darker images. In the case of NVD, the smaller *f*-number is the better:

(2.40) $$f\# = \frac{f_{ob}}{D_{in}} \le 1.4.$$

The used IIT have the same diameters for the IIT photocathode and for the IIT screen. To fully utilize IIT screen the diameter of an appropriate ocular with field of view satisfying the relation should be used:

(2.41) $$\omega_{ob} \le \omega_{oc}.$$

2.3.2 External Surveillance Conditions

There are many different variables that can affect the performance of NVD. First, what is the viewer trying to see – boat on the water or rabbit in the woods. The larger the object is, the easier it is to see. What is needed to be seen – details or just to see if something is there? A second variable is the lighting conditions. The more ambient is the light (starlight, moonlight, and infrared light), the better and further one is able to see. A third important variable is contrast between background and surveillance target – a deer on background of forest in autumn or a deer on background of forest in winter.

The external surveillance conditions that should be taken into account in the process of mathematical modeling of NVD can be summarized as: ambient night illumination; target area; contrast between background and target; atmosphere transmittance.

The atmosphere transmittance depends on the weather surveillance, the range of spectral sensitivity of the IIT photocathode and the distance. Accordingly the Beer-Lambert law, the atmosphere transmittance can be represented as (**Petty, 2002, Ryer, 1997**):

(2.45) $$\tau_a = e^{-\alpha L},$$

where: α – coefficient of radiation attenuation per unit length equal to the sum of absorption and attenuation of radiation and with dimension (m^{-1}), L – the distance light travels through the substance.

The NVD detection range dependence on the used IIT generation and ambient night illumination is shown in **Table 2.3** (http://www.atncorp.com/).

Table 2.3. Dependence on working range, ambient illumination and IIT generation

IIT generation	Target type	Full moon 0.1 lux	Quarter moon 0.01 lux	Starlight 0.001 lux	Overcast 0.0001 lux	R
I	standing man	228.60	182.88	137.16	91.44	m
II	standing man	457.20	411.48	274.32	137.16	m
III	standing man	594.36	457.20	342.90	182.88	m
IV	standing man	685.80	548.64	365.76	228.60	m

The NVD effectiveness depends on various device parameters. An essential specific of the NVD design is the necessity of considering the external surveillance conditions. The ambient night illumination, the contrast between background and surveillance target, the atmospheric transmittance and the surveillance target type directly influence on the one of the most important NVD operational characteristics – working range. Using of the introduced new parameter “reduced target area” that takes into account the criteria of Jonson, different types of the NVD working range can be defined (detection, orientation, recognition and identification). In the most general case, the external surveillance conditions are random variables, and for the purposes of theoretical estimations their mathematical expectations can be used.

Chapter 3

Optimal Design of NVD

Engineering design process can be considered as decision making process in which the engineering sciences are applied to convert resources optimally to meet a preliminary goal. The engineering design process focuses on the following general aspects: research, conceptualization, feasibility assessment, establishing design requirements, preliminary design, detailed design, production planning and tool design, and production (**Ertas, Jones, 1996**). This design process involves a series of steps that lead to the development of a new product or system. Design of NVDs is apparently easy because crucial modules like image intensifier tubes, objectives and oculars are available on the market from dozen or more sources. Despite this apparent design simplicity, however, the process of creating output image by these imaging systems is quite sophisticated (**Chrzanowski**, **2013**).

The design process is the process of originating and developing a plan for a new object. It requires research, thought, modeling, interactive adjustment, and re-design. The engineering design process can be represented by the following steps (**Gomez, 2004; Garrett, 1991**):

1) Identify the problem – understand the scope and the nature of the problem.
2) Define working criteria and goals – establish preliminary goals, develop working criteria to compare possible solutions.
3) Research and gather data – stay consistent with working criteria while researching, keep info found through all steps of the design process and add to it.

4) Brainstorm and generate creative ideas – develop as many creative ideas as possible.
5) Analyze potential solutions – eliminate duplicate ideas, clarify ideas, select ideas to analyze in more detail.
6) Develop and test models – develop models for the selected solutions, test each model against working criteria and goals.
7) Make the decision – evaluate the results of testing to determine the solution to use; if none of the solutions is ideal, return to stage 4 or 5; once a solution is selected, continue to stage 8.
8) Communicate and specify – document the design's specifications and measurements and communicate to all groups.
9) Implement and commercialize – final design revisions.
10) Post-implementation review and assessment – review the product's performance; assess the product's strength and weaknesses and document; suggestions for future improvements.

The conceptual design is the very first phase of design, in which drawings or solid models are the dominant tools and products. The conceptual design gives a description of the proposed system in terms of a set of integrated ideas and concepts about what it should do and look like and should be understandable by the users. The problems with the conceptual design are related with the uncertain nature of the initial design concepts and the availability of different options that engineers need to test.

Establishing design requirements is one of the most important elements in the design process. The design requirements control the design of the project throughout the engineering design process.

The preliminary design bridges the gap between the design concept and the detailed design phase. In this task, the overall system configuration is defined, and schematics, diagrams, and layouts of the project will provide early project configuration. During detailed design and optimization, the parameters of the part being created will change, but the preliminary design focuses on creating the general framework to build the project on.

Optimal design is the design process that can be largely improved using modern modeling, simulation and optimization techniques. The key question in optimal design is the measure of what is good or desirable about a design. Among the fundamental elements of the design process are the establishment of objectives and criteria, synthesis, analysis, construction, testing and evaluation. Before looking for optimal designs it is important to identify characteristics which contribute the most to the overall value of the design. A good design typically involves multiple criteria (objectives) such as cost/investment, profit, quality and/or recovery of the product, efficiency, process safety, operation time etc. Therefore, in practical applications, the performance of process and product design is often measured with respect to multiple criteria. These objectives typically are conflicting, i.e. achieving the optimal value for one objective requires some compromise on one or more of other objectives. That is true for all real engineering design problems characterized by the presence of many, often conflicting and incommensurable, objectives. This raises the issue about how different objectives should be combined to yield a final solution. There is also the question on how to search for an optimal solution to the design problem. For any given design, the designer has to give the different characteristics such as low initial cost, long life and small value for the parameter weight. This is usually not done explicitly, but intuitively the designer does that. During the design process, the designer must tradeoff characteristics against each other. Design variables are parameters that the designer might "adjust" in order to modify the design. There are many types of design variables (**Anderson, 2000**).

- Independent design variables are the actual quantities the designer directly deals with, such as geometry, material properties, production volume, surface finish, configuration of components, lubrication properties and many more. Independent design variables are usually called just design variables or design parameters. Here the term 'design parameters' will be used.
- Dependent variables are variables the designer cannot directly assign values to, however, he works with them through the design parameters.

The dependent variables are usually named *characteristics* or *attributes* of the design. The value of a design is largely a function of the characteristics of the design. In optimization, the term objective function value corresponds to the value of a particular characteristic. An objective function is then the relation between the design parameters and the value of a particular characteristic. For a general design problem, it might be very difficult or even impossible to represent this relation analytically, as the characteristic might be the outcome of a complex simulation.

- State variables are an intermediate type of design variables between dependent and independent design variables.
- Operating variables are variables that can be changed after the design has been actually built.
- The environmental variables or the external variables are the environmental factors that affect the design when used. The designer has to determine the working conditions of the design in order to assess both the environmental and the operational variables.

In the process of defining mathematical models of real systems, it is important to reduce the dimensions of the formulated models in such a way to make opportunities the corresponding optimization tasks to be solved (**Taha, 2010**). Simplification of the real systems requires to identify the dominant parameters and constraints that define the main characteristics of the real systems. Formulated in such a way optimization model will present the most significant relations in the form of objective function and a set of constraints. As the real world problems of engineering design are multi-objective by nature, the corresponding engineering design problem is multi-objective optimization problem.

The generalized multi-objective design problem can be represented as follows:

(3.1) $$max\,\mathbf{F}(\mathrm{x}) = [f_1(\mathrm{x}), f_2(\mathrm{x}),.., f_k(\mathrm{x})]^{\mathrm{T}}$$

subject to:

(3.2) $$\mathbf{X} = [x_1, x_2, ..., x_n]^{\mathrm{T}}\ ,\ \mathbf{X} \in S\ ,$$

(3.3) $$g_i(\mathbf{X}) \leq b_i$$

where **F**(x) is the vector of the *k* objectives functions $f_1(x)$, $f_2(x)$,...,$f_k(x)$, **X** = (x_1, x_2 ,..., x_n) is the vector of the *n* optimization parameters, $S \in R^n$ is the solution or parameter space. Inequalities of the type (3.3) describe specific physical, technical or user restrictions.

There is no single answer which optimization method is best suited for any given problem. It is all a matter of opinion; very much depending on the nature of the problem and the availability of different optimization software that fits the problem statement. As most optimization problems are multi-objective by their nature, there are many methods available to tackle these kind of problems. Generally, the multiobjective optimization problem can be handled in four different ways depending on when the decision-maker articulates the preferences on the different objectives: never, before, during or after the actual optimization procedure as shown in **Fig. 3.1** (**Andersson, 2000**):

- No articulation of preference information,
- Priori aggregation of preference information,
- Progressive articulation of preference information,
- Posteriori articulation of preference information.

The DM sets the information that expresses preferences toward the demand solution (importance of individual criteria). A *priori methods* require that sufficient preference information is expressed before the solution process. Well-known examples of a priori methods include the utility function method, lexicographic method, and goal programming. A *posteriori methods* aim at producing all the Pareto optimal solutions or a representative subset of the Pareto optimal solutions. Most a posteriori methods fall into either one of the following two classes: mathematical programming – based a posteriori methods, where an algorithm is repeated and each run of the algorithm produces one Pareto optimal solution, and evolutionary algorithms where one run of the algorithm produces a set of Pareto optimal solutions.

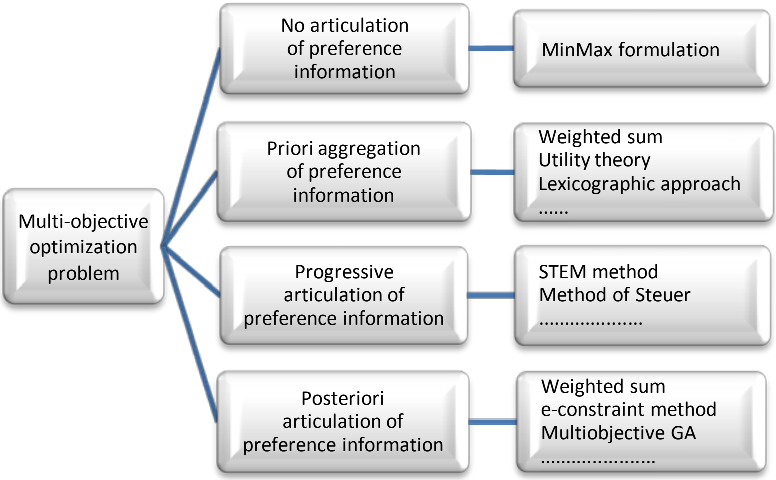


Fig. 3.1. A classification of some multiobjective optimization methods

In *interactive methods*, the solution process is iterative and the decision maker continuously interacts with the method when searching for the most preferred solution. The DM has to express his preferences at each iteration in order to get Pareto optimal solutions that are of interest to him/her and learn what kind of solutions is attainable. A common approach for the solution of multiobjective problems is to transform the original multicriteria problem into a series of scalarized, single criterion subproblems which are then solved using classical methods from constrained or unconstrained programming. Multi-objective optimization problem *scalarization* means to formulate a single objective optimization problem such that optimal solutions to the single objective optimization problem are Pareto optimal solutions to the multi-objective optimization problem. In addition, it is often required that every Pareto optimal solution can be reached with some parameters of the scalarization. With different parameters for the scalarization, different Pareto optimal solutions are produced (**Miettinen, Makela, 2002**). Therefore, the choice of the particular scalarization approach has to be done very carefully, since different scalarizations typically produce different Pareto optimal solutions.

In practical applications, the performance of process and product design is often measured with respect to multiple objectives. These objectives typically are conflicting, i.e. achieving the optimal value for one objective requires some compromise on one or more of other objectives. The solution of multi-objective optimization problem is called *nondominated*, *Pareto optimal*, *Pareto efficient* or *noninferior*, if none of the objective functions can be improved in value without degrading some of the other objective values. Without additional subjective preference information, all Pareto optimal solutions are considered equally good (as vectors cannot be ordered completely).

3.1. Basic Relationships between NVD Modules and NVD Parameters

Modular design is a design approach that subdivides a system into smaller parts like modules that can be independently created and then used in different systems. A modular system can be characterized by functional partitioning into discrete scalable, reusable modules, use of well-designed modules and making use of industry standards for them. The basic modules of passive night vision devices (NVDs) can be reduced to objective, image intensifier tube (IIT), ocular and power supply as shown in **Fig. 3.2**.

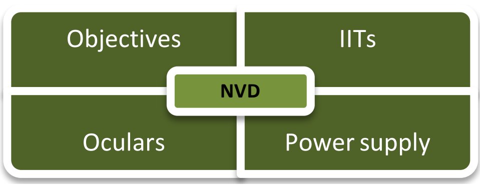


Fig. 3.2. Basic NVD modules

The variety of night vision applications require a variety of the NVD designs. The best design for a particular user is a design that is created taking into account the requirements of this user. As the NVDs are not under mass production it is important to offer for user estimation different virtual designs before actual producing of the device. This can be done by a software system for virtual design of NVDs that will help a preliminary assessment and estimation of the design.

A well managed product development process is an important factor in order to stay competitive. When the repetitive nature of the development processes is recognized, the process can be modeled in order to predict the system performance. Design process modeling can be one course of action to discover key activities that have great impact on process lead-time and cost. The existence of variety of basic elements for NVD requires a proper choice of modules to ensure the required device parameters. The optoelectronic channel is included into any NVD type (NVG, NVB, NVS) and parameters of the NVD optoelectronic channel are representative indicators for NVD functionality.

The choice of NVD optoelectronic channel components (objective, image intensifier tube and ocular) could be recognized as a combinatorial problem. When set of discrete design alternatives exists a combinatorial approach can be used to reduce the possible solutions by modelling of problem based on the characteristics of a specific situation. Considering NVD design as a decision making problem means that there exist a decision-maker (DM) and the final solution depends on DM preferences.

Practical experience shows the most essential parameters for the NVD functionality are *working range, field of view, magnification, electrical battery power supply lifetime, weight* and *price*. The mathematical model of NVD design should provide the optimal choices for IIT, objective, eyepiece and electric battery power supply, taking into account all dependencies and constraints between modules (**Fig. 3.3**).

The design of engineering systems have to comply many preliminary specified requirements with regard to the system performance.

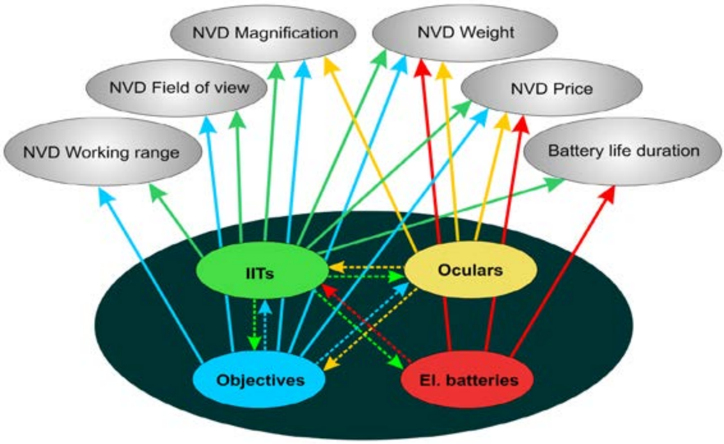


Fig. 3.3. Relations between NVD modules and NVD parameters

Based on above assumptions this process can be formalized as an optimal combinatorial problem that can be solved by using of appropriate mathematical optimization methods. This would allow to get a preliminary theoretical evaluation of the designed device parameters and would reduce the time and cost of building and testing prototypes. Depending on the model of the formulated optimization problem, various optimization techniques may be used – linear programming, non-linear programming, integer or mixed integer programming, discrete optimization, etc. An essential part of optimization problem formulation is the choice of the number and type of criteria for optimum design. Multicriteria formulation can be seen as a natural choice as often the modeled problem has more than one and incompatible characteristics that have to be optimized.

3.2. Determination of NVD Parameters

The described NVD parameters in chapter 2 can be used to formulate a generalized criterion for NVD quality. The most frequently asked quality requirements to the NVD can be summarized by the following components of NVD quality criterion:

- working range;
- field of view;
- f-number;
- objective focus range;
- eye relief;
- objective and ocular aberrations;
- weight;
- price.

Thus, the defined quality criterion for NVD comprising these components can be used to formulate the optimization models of the NVD optoelectronic channel.

3.2.1. NVD Working Range

One of the most important components in the proposed NVD quality criterion is the working range. The proposed in Chapter 2 formula (2.35) can be used to estimate the NVD working range as a function of device parameters and external surveillance conditions. Different types of the NVD working range (detection, recognition and identification) can be estimated by the introduced parameter reduced target area. This is summarized in the following relation (**Borissova, Mustakerov, 2006**):

$$R = \sqrt{\frac{0.07 D_{in} f_{ob} \tau_o \tau_a S \delta_{IIT} E K A'_{ob}}{M \Phi_{th.ph}}}, \qquad (3.4)$$

where: D_{in} – diameter of the objective inlet pupil (in m), f_{ob} – objective focal length (in mm), τ_o, τ_a – objective and atmosphere transmittance, $\Phi_{th.ph}$ – IIT photocathode limiting light flow (in lm), δ_{IIT} – limiting resolution of IIT (in lp/mm), S – IIT luminous sensitivity (in A/lm), M – signal to noise ratio, E – ambient night illumination (in lx), K – contrast between target and background, A'_{ob} – reduced target area (in m^2).

In terms of choice of the IIT, the above formula can be simplified by introducing a new generalized parameter *quality IIT* (K_{IIT}):

(3.5) $$K_{IIT} = \frac{S\delta_{IIT}}{M\Phi_{th.ph}}.$$

Introducing of generalized parameter *quality lens* (K_{ob}) as:

(3.6) $$K_{ob}=D_{in}f_{ob}\tau_o.$$

Therefore, the formula for the NVD working range can be represented as:

(3.7) $$R=\sqrt{0.07\tau_a EKA'_{ob}\, K_{IIT}K_{ob}}\ .$$

In case of determining the maximum NVD working range (in any of its variants) the selection of single IIT from a given set should be performed. This selection is realized by introducing of binary integer variables x_i as:

(3.8) $$K_{IIT} = \sum_{i=1}^{m} x_i K_i^{IIT}\ , x_i \in \{0, 1\},$$

where: m – number of IIT, x_i – binary integer variables used to determine the single choice of IIT, i.e. satisfying the relation:

(3.9) $$\sum_{i=1}^{m} x_i = 1\,.$$

Similarly, the choice of the objective from a given set is realized by using binary integer variables y_j :

(3.10) $$K_{ob} = \sum_{j=1}^{n} y_j K_j^{ob}\ , y_j \in \{0, 1\},$$

where: n – number of objectives, y_j – binary integer variables used to determine the single choice of objective and satisfying the relation:

(3.11) $$\sum_{j=1}^{n} y_j = 1\,.$$

Using these variables for selection of a single IIT and single objective, the different types of NVD working range can be expressed as:

(3.12) $$R = \sqrt{0.07\tau_a EKA'_{ob}\sum_{i=1}^{m} x_i K_i^{IIT} \sum_{j=1}^{n} y_j K_j^{ob}}\ ,$$

(3.12a) $$R^d = \sqrt{0.07\tau_a EKA'_{ob}\sum_{i=1}^{m} x_i K_i^{IIT} \sum_{j=1}^{n} y_j K_j^{ob}}\ ,$$

(3.12b) $$R^r = \sqrt{0.07\tau_a EKA'_{ob}\sum_{i=1}^{m} x_i K_i^{IIT} \sum_{j=1}^{n} y_j K_j^{ob}}\ ,$$

(3.12c) $$R^i = \sqrt{0.07\tau_a EKA'_{ob}\sum_{i=1}^{m} x_i K_i^{IIT} \sum_{j=1}^{n} y_j K_j^{ob}}\ ,$$

where τ_a – atmosphere transmittance, E – ambient night illumination, K – contrast between target and background, A'^d_{ob}, A'^r_{ob}, A'^i_{ob} – reduced target areas that are considered as known numerical values.

One of the above formulas can be used as a component of the quality criteria for the designed optoelectronic channel, respectively NVD depending on the required type of NVD working range.

3.2.2. Field of View

Another parameter used as a component in the quality criteria of NVD optoelectronic channel is the field of view of the objective and ocular field of view. The objective field of view W_{ob} and ocular field of view W_{oc} participate in the quality criteria by the following equations:

(3.13) $$W_{ob} = \sum_{j=1}^{n} y_j W_j^{ob}\ ,$$

(3.14) $$W_{oc} = \sum_{k=1}^{l} z_k W_k^{oc}\ ,$$

where: l – number of oculars, z_k – binary integer variables used to determine the single choice of ocular and satisfying the relation:

(3.15) $$\sum_{k=1}^{l} z_k = 1,\ z_k \in \{0, 1\}.$$

The next relation (3.16) is used to select the proper objective and ocular for devices with or without magnification.

(3.16) $$W_{ob} = \theta W^{oc},$$

where: $\theta = 1$ in case of NVG, $\theta > 1$ for NVD with magnification.

3.2.3. Objective f-number

Each objective is characterized with known parameters as: *focal length, diameter of the entrance pupil, optical transmittance, f-number, range focus, weight* and *aberrations* (*spherical, astigmatism, curvature of field, distortion*). In this regard, another important from a practical point of view, a component of the NVD quality criterion is the parameter *f*-number. The choice of objective is realized through the following dependence:

(3.17) $$f\# = \sum_{j=1}^{n} y_j f_j^{\#},$$

where: *f#* – objective *f*-number, *n* – objectives number.

3.2.4. Objective Focus Range

An essential component of the NVD quality criteria is the objective focus range. The smaller focus range allows focusing a closer and this is important for some specific night vision device using, for example map reading in night conditions. The choice of a particular objective with known focus range is realized through dependence:

(3.18) $$F = \sum_{j=1}^{n} y_j F_j,$$

where: F – objective focus range, n – number of objectives.

3.2.5. Aberrations

Unavoidable residual aberrations in optical systems and errors in manufacturing, assembling and setting the apparatus, influence the image quality formed by the optical system. The NVD quality criterion should take into account the aberrations of the selected objective and eyepiece. The optimal choice of objective taking into consideration the aberrations is done by the following relations:

(3.19) $$AS_{ob} = \sum_{j=1}^{n} y_j AS_j^{ob} ,$$

(3.20) $$AA_{ob} = \sum_{j=1}^{n} y_j AA_j^{ob} ,$$

(3.21) $$AD_{ob} = \sum_{j=1}^{n} y_j AD_j^{ob} ,$$

(3.22) $$AC_{ob} = \sum_{j=1}^{n} y_j AC_j^{ob} ,$$

where AC_j^{ob}, AA_j^{ob}, AD_j^{ob}, AC_j^{ob} are spherical aberration, astigmatism, distortion and curvature of field for objective with index j.

Similarly, the choice of the eyepiece with optimal parameters requires to take into account its aberrations:

(3.23) $$AS_{oc} = \sum_{k=1}^{l} z_k AS_k^{oc} ,$$

(3.24) $$AA_{oc} = \sum_{k=1}^{l} z_k AA_k^{oc} ,$$

(3.25) $$AD_{oc} = \sum_{k=1}^{l} z_k AD_k^{oc} ,$$

(3.26) $$AC_{oc} = \sum_{k=1}^{l} z_k AC_k^{oc} ,$$

where AS_k^{oc}, AA_k^{oc}, AD_k^{oc}, AC_k^{ok} are spherical aberration, astigmatism, distortion and curvature of field for ocular with index *k*.

3.2.6. Eye Relief

The bigger eye relief provides greater comfort when observing with NVD and can also be included as a component of quality criteria. The choice of the eyepiece with optimal eye relief can be realized by the following relation:

(3.27) $$ER = \sum_{k=1}^{l} z_k ER_k ,$$

where: *ER* – ocular eye relief, *l* – number of oculars.

3.2.7. Battery Supply Lifetime Duration

From a practical point of view, the type of battery (capacity, weight and price) also affects the quality of the device as a whole. The electrical battery power supply lifetime depends both on the capacity of the particular battery, and the current demand of the used IIT:

(3.28) $$L_B = \frac{C_B}{I_{IIT}} \text{ [hours]},$$

where: L_B – electrical battery power supply lifetime duration, C_B – electrical battery capacity, I_{IIT} – current demand of IIT.

There exists variety of electrical batteries with different parameters that can be divided into two basic categories depending on their type and supply voltage: AA type batteries with supply voltage 1.5 V and button (coin) cell type with 3.0 V supply voltage. The typical supply voltage needed for the IIT of the NVD is 3.0 V. To increase the device electrical battery power supply capacity and respectively its lifetime it is possible to use a number of parallel connected batteries, i.e. to design a custom electrical battery power supply. The custom electrical battery power supply mechanics influences on the device weight and price, so it is necessary to include it in the optimization model also. The requirement for the bigger electrical battery power supply lifetime reflects on its supporting mechanics – the bigger capacity requires the bigger mechanics to pack chosen electrical batteries.

3.2.8. Weight

Parameters such as weight, size and ergonomics are essential in the use of NVD. The more compact and lightweight are NVD, the more comfortable they are. A good approximation of the NVD weight could be estimated as a sum of IIT, objective, ocular and electrical battery power supply as:

$$T = T_{IIT} + T_{ob} + T_{oc} + T_{bat}, \tag{3.29}$$

where

$$T_{IIT} = \sum_{i=1}^{m} x_i T_i^{IIT}, \tag{3.30}$$

$$T_{ob} = \sum_{j=1}^{n} y_j T_j^{ob}, \tag{3.31}$$

$$T_{oc} = \sum_{k=1}^{l} z_k T_k^{oc}, \tag{3.32}$$

$$T_{bat} = N\left(\sum_{p=1}^{t} a_p\left(s_p \sum_{q=1}^{k_p} b_q^p H_B^q + \sum_{p=1}^{t} t_p\right)\right), \tag{3.33}$$

where: N – number of the parallel connected batteries, a_p – binary variable for battery *p*-type, b_q^p – binary variable for battery *q*-subtype of *p*-type battery, $s_p = 1$ – for the 3 V batteries and $s_p = 2$ – for the 1.5 V batteries, H_B^q – weight of the *p*-type and *q*-subtype electrical battery, t_p – single *p*-type electrical battery power supply mechanics weight and different battery types and

subtypes
$p \in \{1, 2, \ldots, t\}$.

The single choice of the electrical battery type without combining of the different battery types and subtypes for each $p \in \{1, 2, \ldots, t\}$ is (**Borissova, 2007**):

(3.34) $$\sum_{p=1}^{t} a_p = 1,$$

(3.35) $$\sum_{p=1}^{t} \left(a_p - \sum_{q=1}^{k_p} b_q^p \right) = 0 \cdot$$

3.2.9. Price

The NVD price is an essential parameter that should be included as a component of NVD quality criteria using the relation:

(3.36) $$C = C_{IIT} + C_{ob} + C_{oc} + C_{bat},$$

(3.37) $$C_{IIT} = \sum_{i=1}^{m} x_i C_i^{IIT},$$

(3.38) $$C_{ob} = \sum_{j=1}^{n} y_j C_j^{ob},$$

(3.39) $$C_{oc} = \sum_{k=1}^{l} z_k C_k^{oc},$$

(3.40) $$C_{bat} = N \left(\sum_{p=1}^{t} a_p \left(s_p \sum_{q=1}^{k_p} b_q^p C_B^q + \sum_{p=1}^{t} k_p \right) \right),$$

where: C_B^p – price of the p-type and q-subtype electrical battery, k_p – single p-type electrical battery power supply mechanics price.

All described parameters of the NVD elements can be used as components of the quality criterion of NVD through the following generalized functional dependence:

$$Q = f\,(R, W_{ob}, f\#, F, AS_{ob}, AA_{ob}, AD_{ob}, AC_{ob}, AS_{oc}, AA_{oc}, AD_{oc}, AC_{oc}, ER, T, C). \quad (3.41)$$

3.3. Optimization Models for Selection of NVD Elements

Mathematical models are designed to help us make “better” decisions. Optimization models attempt to capture some key components to build a reasonable replica of the real system and provide a systematic and quantitative way to evaluate the selected decisions. In the simplest case, an optimization problem consists of maximizing or minimizing a real function by systematically choosing input values from within an allowed set and computing the value of the function. The generalization of optimization theory and techniques to other formulations comprises a large area of applied mathematics. More generally, optimization includes finding “best available” values of some objective function for given set of constraints. Optimization problem searches the best solution from all feasible solutions. Optimization problems can be divided into two categories depending on whether the variables are continuous or discrete. An optimization problem with discrete variables is known as a combinatorial optimization problem.

Often the design process of the real technical systems relies on the proper choice of their elements and/or subsystems. The designed technical systems usually have to satisfy many preliminary (and sometimes conflicting) requirements for the systems operational characteristics. The traditional approach to the design process is to make some intuitive choice of the needed components based on the experience, then to build a prototype and to test it against design goals. If the design goals are not satisfied a new choice is done, new prototype is built and tested. That “trials and errors” method continues until the preliminary design requirements are met. Those kinds of design processes based on the proper element choosing can be formalized as some combinatorial problems and some proper mathematical optimization methods can be used to reduce “trials and errors”, time and costs in the technical systems design. Mathematical optimization will not only reduce the design errors but can also be used for creating CAD systems eliminating to some degree need of human-expert design solutions. Depending on functional description of the optimization problem, different optimization techniques can be used – linear programming, nonlinear programming, discrete optimization, etc. When the design goal is formalized the first decision is to make a choice between the single objective and multiobjective optimization. The multiobjective optimization seems to be the natural choice but there are many practical problems where the single objective optimization gives satisfactory results with less computational efforts. Various mathematical models have been proposed to optimize the technical systems. For some technical systems there exist sets of elements or modules which have been already optimised and have different performance characteristics reflecting in their price, quality and availability. The question is which of them to use to satisfy the given preliminary requirements of the designed system as a whole.

The main idea is to propose flexible and intelligent choice of the needed elements or modules and to get as close as possible the desired characteristics of the designed system. As mentioned before, the most important element of NVD is its optoelectronic channel, because its parameters, price and weight are crucial parameters influencing the price and weight of the device as whole. The wide diversity of existing basic elements for the optoelectronic channel of NVD put the question for proper choice that is capable to optimize certain NVD parameters. In this regard it is necessary to develop appropriate optimization models. As generalized and sufficient for practical needs, the so called *quality of NVD* parameter can be considered as optimization criterion. NVD quality can be defined in different ways, depending on the area of application and user requirements, but there are quality indicators that are valid for all types of

NVD. One of them, which should be considered in determining the quality of NVD, is the *working range*. Similar quality indicators include parameters of NVD – *price*, *weight* and other user-defined requirements. Optimization quality criterion for NVD including the parameters as: *field of view, f-number, focus range, objective and eyepiece aberrations, eye relief, weight* and *price* of optoelectronic channel and the NVD *working range*, can be formulated. Using this quality criterion, deterministic and stochastic multi-objective optimization models could be formulated. These models are used to formulate appropriate optimization problems. In the deterministic model, the external surveillance conditions are considered as variables with known values. In the stochastic model, the parameters of the external surveillance conditions are considered as probabilistic variables involved via their mathematical expectation.

3.3.1. Deterministic Optimization Model for NVD Design

Essential characteristic of deterministic optimization is that it assumes the data as known for the given problem. In deterministic optimization model, the external surveillance conditions are considered deterministic with known values. Optimization models for NVD design will focus on the design of optoelectronic channel which parameters influence the quality of NVD as a whole. In order to make a choice for multiple elements of optoelectronic channel satisfying the given quality criteria, the proper binary integer variables (x, y, z, a_p, b_q^p) are introduced and used to select the relevant NVD optoelectronic channel elements – *IIT, objective, eyepiece* and *batteries*. Deterministic optimization model for design of optoelectronic channel of NVD is based on functional dependency (3.41) for which some criteria are to be maximized (*working range, battery lifetime duration, field of view, f-number* and eye *relief*) while rest of them are minimized (*objective focus range, and objective* and *ocular aberrations*):

$$
\begin{aligned}
&max\,\{R, BL, W_{ob}, f\#, ER\} \\
&min\,\{F, AS_{ob}, AA_{ob}, AD_{ob}, AC_{ob}, AS_{oc}, AA_{oc}, AD_{oc}, AC_{oc}\}
\end{aligned}
\qquad (3.42)
$$

(3.43a) $$R^d = \sqrt{0.07\tau_a EKA'^d_{ob} K_{IIT} K_{ob}} ,$$

(3.43b) $$R^r = \sqrt{0.07\tau_a EKA'^r_{ob} K_{IIT} K_{ob}} ,$$

(3.43c) $$R^i = \sqrt{0.07\tau_a EKA'^i_{ob} K_{IIT} K_{ob}} ,$$

(3.44) $$K_{IIT} = \sum_{i=1}^{m} x_i K_i^{IIT} ,$$

(3.45) $$K_{ob} = \sum_{j=1}^{n} y_j K_j^{ob} ,$$

(3.46) $$\sum_{i=1}^{m} x_i = 1, x_i \in \{0, 1\},$$

(3.47) $$\sum_{j=1}^{n} y_j = 1, y_j \in \{0, 1\},$$

(3.48) $$L_B = \frac{n\sum_{p=1}^{t} a_p \sum_{q=1}^{k_p} b_q^p C_B^q}{\sum_{i=1}^{m} x_i I_{IIT}^i} ,$$

(3.49) $$\sum_{p=1}^{t} a_p = 1,$$

(3.50) $$\sum_{p=1}^{t}\left(a_p - \sum_{q=1}^{k_p} b_q^p \right) = 0 ,$$

(3.51) $$\sum_{j=1}^{n} y_j F_j^{ob} = \theta \sum_{k=1}^{l} z_k F_k^{oc} ,$$

(3.52) $$\sum_{j=1}^{n} y_j W_j^{ob} \le \sum_{k=1}^{l} z_k W_k^{oc} ,$$

(3.53) $$AS_{ob} = \sum_{j=1}^{n} y_j AS_j^{ob} ,$$

(3.54) $$AA_{ob} = \sum_{j=1}^{n} y_j AA_j^{ob} ,$$

(3.55) $$AD_{ob} = \sum_{j=1}^{n} y_j AD_j^{ob} ,$$

(3.56) $$AC_{ob} = \sum_{j=1}^{n} y_j AC_j^{ob} ,$$

(3.57) $$f\# = \sum_{j=1}^{n} y_j f_j^{\#} ,$$

(3.58) $$F = \sum_{j=1}^{n} y_j F_j ,$$

(3.59) $$W_{ob} = \sum_{j=1}^{n} y_j W_j^{ob} ,$$

(3.60) $$ER = \sum_{k=1}^{l} z_k ER_k ,$$

(3.61) $$AS_{oc} = \sum_{k=1}^{l} z_k AS_k^{oc} ,$$

(3.62) $$AA_{oc} = \sum_{k=1}^{l} z_k AA_k^{oc} ,$$

(3.63) $$AD_{oc} = \sum_{k=1}^{l} z_k AD_k^{oc} ,$$

(3.64) $$AC_{oc} = \sum_{k=1}^{l} z_k AC_k^{oc} ,$$

(3.65) $$W_{oc} = \sum_{k=1}^{l} z_k W_k^{oc} ,$$

(3.66) $$\sum_{k=1}^{l} z_k = 1, z_k \in \{0, 1\},$$

(3.67) $$T_{IIT} = \sum_{i=1}^{m} x_i T_i^{IIT} ,$$

(3.68) $$T_{ob} = \sum_{j=1}^{n} y_j T_j^{ob} ,$$

(3.69) $$T_{oc} = \sum_{k=1}^{l} z_k T_k^{oc} ,$$

(3.70) $$T_{bat} = N\left(\sum_{p=1}^{t} a_p \left(s_p \sum_{q=1}^{k_p} b_q^p H_B^q + \sum_{p=1}^{t} t_p \right)\right),$$

(3.71) $$T = T_{IIT} + T_{ob} + T_{oc} + T_{bat},$$

(3.72) $$C_{IIT} = \sum_{i=1}^{m} x_i C_i^{IIT} ,$$

(3.73) $$C_{ob} = \sum_{j=1}^{n} y_j C_j^{ob} ,$$

(3.74) $$C_{oc} = \sum_{k=1}^{l} z_k C_k^{oc} ,$$

(3.75)
$$C_{bat} = n\left(\sum_{p=1}^{t} a_p\left(s_p\sum_{q=1}^{k_p} b_q^p C_{bat}^q + \sum_{p=1}^{t} k_p\right)\right),$$

(3.76)
$$C = C_{IIT} + C_{ob} + C_{oc} + C_{bat}.$$

The parameters of external surveillance conditions (τ_a – atmosphere transmittance, E – ambient night illumination, K – contrast between target and background, A'_{ob} – reduced target area is considered as deterministic constants with known values. The single choice of IIT, objective and ocular is realized by using the binary integer variables (3.46), (3.47) and (3.66). The single choice of the electrical battery type without combining of the different battery types and subtypes for each $p \in \{1, 2, \ldots, t\}$ is realized by using the binary variables a_p while the binary variable b^p_q is used to determine particular battery of q-subtype and p-type. The $s_p = 1$ for the 3 V batteries and $s_p = 2$ for the 1.5 V batteries. The relation (3.51) is used to provide the needed device magnification ($\theta = 1$ in case of NVG, $\theta > 1$ for other NVD with magnification).

3.3.2. Generalized Deterministic Model for NVD Optimal Design

Combinatorial optimization problems can be viewed as searching for the best element of some set of discrete items. The basic idea of the generalized optimization model for the design of NVD is to realize flexible intelligent choice of the needed modules for optoelectronic channel, i.e. to determine which combination of modules best conform the given requirements to the designed NVD, where the external surveillance conditions are considered as constants with known values. This idea is realized by using the generalized combinatorial optimization model for the design of NVD as (**Mustakerov, Borissova, 2007**):

(3.77)
$$max\ F(P) = (f_1(P), f_2(P), \ldots, f_q(P))$$

subject to

(3.78)
$$P = \sum_{j_i=1}^{J_i} P^i_{j_i,k_i} x^i_{j_i} ,$$

(3.79) $$g(P) = (g_1(P), g_2(P), \ldots, g_m(P)),$$

(3.80) $$\sum_{j_i} x^i_{j_i} = 1,\ x \in \{0,1\},$$

(3.81) $$P^{Li}_{j_i,k_i} \le P^i_{j_i,k_i} \le P^{Ui}_{j_i,k_i},\ i = 1, \text{n}.$$

In this formulation $f_1(P), f_2(P), \ldots, f_q(P)$ are the q objective functions (performance criteria) of the design variables vector (optimization parameters) $P = \{ P^i_{j_i,k_i} \mid i=1,\ldots,n,\ j_i \in \{J_i\},\ k_i \in \{K_i\}\} \in R^n$ of the all elements used in design process. R^n is the parameter's space of n elements to choose from, j_i are the types number of *i-th* element, k_i are the parameters of the *i-th* element of type j_i and $P^i_{j_i,k_i}$ is k_i-*th* parameter of *i-th* element of type j_i. $P' = \{ P^t_{s,r} \mid t \in \{i\},\ r \in \{k_i\},\ s \in \{j_i\}\}$ is the solution vector of the chosen elements parameters as a result of optimal combinatorial choice. The optimal choice is done by using restrictions (3.78) based on binary integer variables $X = \{ x^i_{j_i} \}$, subject to (3.80). Realistic optimal design involves not only objective functions, but also constraints, which represent limitations in the design variables space. For example, $P^{Li}_{j_i,k_i}$ and $P^{Ui}_{j_i,k_i}$ denote the lower and upper bounds on the design variables and the relation functions $(g_1(P), g_2(P), \ldots, g_m(P))$ describe some specific physical, technical or user restrictions on the modelled system. For example, there exist technical systems where the choice of some element i of type j_i restricts the choice of the other elements types to some subsets of the common elements set. The parameters of external surveillance conditions are considered as constants with known values.

Using the formalized optimization methods in design process gives the possibility to research, analyze and forecast the parameters of the designed device.

3.3.3. Stochastic Optimization Model for Design of Optoelectronic Channel of NVD

Stochastic models take advantage of the fact that probability distributions governing the data are known or can be estimated; the goal is to find some policy that is feasible for all (or almost all) the possible data instances and optimizes the expected performance of the model. An essential specific of the NVD design is the necessity of considering the external surveillance conditions. The *external ambient night, the contrast between background and surveillance target, the atmosphere transmittance* and the *surveillance target type* directly influence on the one of the most important NVD operational characteristics – *working range*. The NVD design could not be satisfactory if the external surveillance conditions uncertainty is not considered. As it is known the stochastic optimization problems try to model uncertainty in the data by assuming that the input is specified by a probability distribution. In case of NVD design, the expected surveillance conditions in the particular location and specific probability distribution laws should be taken into account.

Atmosphere transmittance. The earth is enveloped by a layer of atmosphere consisting of a mixture of gases and other solid and liquid particles (about 78% nitrogen, 21% oxygen and the remaining one percent consists of the inert gases, carbon dioxide and other gases). The propagation of light through the atmosphere depends upon several optical interaction phenomena as transmission, absorption, emission and scattering of light as it passes through the atmosphere. All of these interactions can be described as interactions into distinct optical phenomena of molecular absorption, Rayleigh scattering, Mie or aerosol scattering, and molecular emission. The atmosphere contains various solid and liquid particles such as aerosols, water drops, and ice crystals, which are highly variable in space and time. Scattering by particles similar to, or larger than the wavelength of light is typically treated by the Mie theory. Rayleigh scattering applies to particles that are small with respect to wavelengths of light. The strong wavelength dependence of the scattering

$(\sim\lambda^{-4})$ means that shorter (blue) wavelengths are scattered more strongly than longer (red) wavelengths. This results in the indirect blue light coming from all regions of the sky. Rayleigh scattering is a good approximation of the manner in which light scattering occurs within various media for which scattering particles have a small size parameter.

Numerical calculations of absorption in a real atmosphere requires knowledge for the gas composition of the atmosphere, the corresponding height above the ground, meteorological conditions and many other climatic factors (**Sospedra et al., 2004).** The transmission of the atmosphere is highly dependent upon the wavelength of the spectral radiation. The atmospheric propagation of optical radiation is influenced by particulate matter suspended in the air such as dust, fog, haze, cloud droplets and aerosols. Earth's atmospheric transmittance over 1 nautical mile sea level path is shown in **Fig. 3.4** (http://web.archive.org/web/20010913094914/http:/ewhdbks.mugu.navy.mil/transmit.gif).

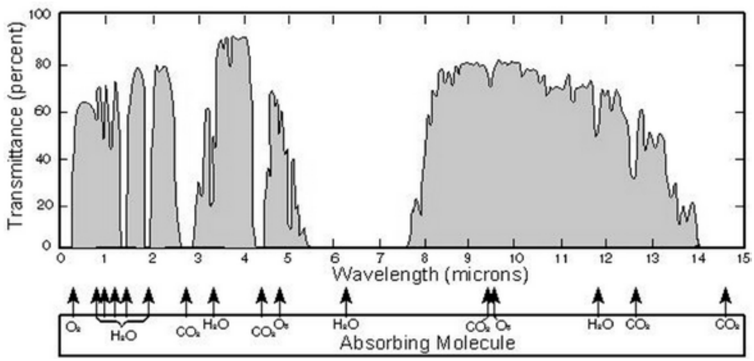


Fig. 3.4. Atmosphere transmittance over 1 nautical mile sea level

From 1933 to late 1940s, total transmittance remained stable at around 0.74 to 0.75, followed by the decreasing phase to the mid-1980s when it reached 0.69. It then turned into the increasing phase till the early 2000s marking the level of 0.71 (**Indiso, 1970; Ohkawara, 2012**).

The random nature of the atmosphere transmittance can be considered in stochastic optimization model, using its corresponding mathematical expectation (**Borissova, Mustakerov, 2009**):

(3.82) $$T_a^{st} = \sum_{i=1}^{p} P_{\tau_a}^i \tau_a^i ,$$

where: $\sum_{i=1}^{p} P_{\tau_a}^i = 1$.

Contrast between background and target. The NVD working range depends on the contrast between a surveillance target and its background. It could be considered as a stochastic parameter due to the color differences between targets (even of the same type) and the background changing when the target moves. The random behavior of the contrast could be also expressed by its mathematical expectation (**Borissova, Mustakerov, 2009**):

(3.83) $$K^{st} = \sum_{j=1}^{t} P_K^j K^j ,$$

where: $\sum_{j=1}^{t} P_K^j = 1$.

Ambient night illumination. There are variety conditions influencing the night illumination (moon phase, stars light, existing clouds, etc.). Some typical values of ambient night illumination can be described as follows: full moon (0.1 lx), half moon (0.5 lx), quarter moon (0.01 lx), starlight (0.001 lx) and overcast night (0.0001 lx) (**Ryer, 1997**). In the stochastic NVD model, the random nature of ambient night illumination is taken into account by its mathematical expectation (**Borissova, Mustakerov, 2009**):

(3.84) $$E^{st} = \sum_{k=1}^{h} P_E^k E^k ,$$

where: $\sum_{k=1}^{h} P_E^k = 1$.

Surveillance target area. The surveillance target area or more precisely the so called *reduced target area* A'_{ob} is another essential external surveillance parameter directly influencing on the NVD working range. A common practice is to consider the surveillance target area as known value in the cases when the surveillance object is of a particular type, a standing man for example. Generally speaking, the different objects have different dimensions and even for the known type of the surveillance targets their area is not fixed constant. When the target is the human figure, it should be taken into account that the size of the object cannot be accepted as determined dimensions. In the most general case, the man dimensions depend on the race and gender (**Steckel & Prince, 2001**). To be more correct the target area should be considered also as a stochastic parameter expressed by its mathematical expectation (**Borissova, Mustakerov, 2009**):

(3.85) $$A_{ob}^{st} = \sum_{m=1}^{l} P_{A_{ob}}^m A_{ob}^m ,$$

where: $\sum_{m=1}^{l} P_{A_{ob}}^m = 1$.

Taking into account the stochastic nature of the external surveillance conditions parameters (*atmosphere transmittance, ambient night illumination, contrast between background and target*, and *surveillance target area*), the formulated deterministic optimization model can be considered as a stochastic using the mathematical expectations for the parameters expressed by the relations (3.82), (3.83), (3.84) and (3.85). In this case, the same quality criteria for NVD optoelectronic channel can be used:

(3.86)
$$\max\{R, BL, W_{ob}, f\#, ER\}$$
$$\min\{F, AS_{ob}, AA_{ob}, AD_{ob}, AC_{ob}, AS_{oc}, AA_{oc}, AD_{oc}, AC_{oc}\}$$

subject to the relations that determine the specifics and parameters of NVD optoelectronic channel (3.43)-(3.76).

3.3.4. Generalized Stochastic Model for NVD Optimal Design

An essential feature in the design of NVD is the necessity to consider the external surveillance conditions. *Ambient night illumination, contrast between the background and surveillance target, atmosphere transmittance* and *type of surveillance target* directly affect the most important parameter – the NVD working range. These external parameters are random variables that depend on many correlated factors such as geographical location, weather conditions, environmental parameters, etc. (**Волков, 2001; Волков et al., 2000**). During the design process of NVD, the stochastic external conditions should be involved by their probabilistic laws of distribution. Therefore, the following generalized formulation of the stochastic model for NVD design can be represented as (**Borissova, Mustakerov, 2009**):

(3.87)
$$\max F(P) = (f_1(P), f_2(P), \ldots, f_q(P)),$$

subject to

(3.88)
$$P = \sum_{j_i=1}^{J_i} P^i_{j_i,k_i} x^i_{j_i} ,$$

(3.89)
$$g(P) = (g_1(P), g_2(P), \ldots, g_m(P)) ,$$

(3.90)
$$\sum_{j_i} x^i_{j_i} = 1, \ x \in \{0,1\},$$

(3.91)
$$P^{Li}_{j_i,k_i} \le P^i_{j_i,k_i} \le P^{Ui}_{j_i,k_i} , \ i = 1, n,$$

(3.92)
$$E(L) = \sum_k E^k_L L^k ,$$

(3.93)
$$E(\tau_a) = \sum_l E^l_{\tau_a} \tau_a{}^l ,$$

(3.94) $$E(K) = \sum_e E_K^e K^e \,,$$

(3.95) $$E(A'_{ob}) = \sum_t E_{A'_{ob}}^t A'^t_{ob} \,,$$

where (3.92)-(3.95) represent the relevant mathematical expectations of external surveillance conditions.

3.4. Deterministic Optimization Tasks for Selection of NVD Optoelectronic Channel Elements

The design of technical systems can be realized by seeking the best in some sense parameters via formulation and solving corresponding optimization problems. Based on the defined above deterministic and stochastic optimization models, proper optimization tasks can be formulated and solved. The specifics of modeling of NVD optoelectronic channel determine the nonlinear nature of these tasks while the necessity of an optimal choice requires introducing and using of binary integer variables.

For deterministic tasks, the parameters that define the external surveillance conditions (atmosphere transmittance, ambient night illumination, contrast, observed target area) participate as deterministic variables with known numerical values.

Task D1. This task is considered as a basic task of the deterministic model of optoelectronic channel, which can be modified by the addition of some restrictions and/or limits for variables and can be transformed according to the user's requirements. The purpose of this task is to find such a combination of modules for NVDs that maximize the NVD *working range, electrical battery supply power lifetime duration, field of view, objective f-number, eye relief,* and to minimize the *objective focus range, distortion, weight* and *cost* using the following criteria:

(3.96) $$\max \{R, LB, W_{ob}, f\#, ER\}$$
$$\min \{F, AD_{ob}, T, C\},$$

subject to (3.43) – (3.76) and known constants of the external surveillance conditions.

Task D1a. This is a modification of Task D1, where the objective function excludes the component for price to assess the impact of price on the final decision:

(3.97)
$$max\ \{R, W_{ob}, f\#, ER\}$$
$$min\ \{F, AD_{ob}, T\},$$

subject to the same constraints as in the task D1.

Task D2. To refine more precisely the DM preferences a "restricted" choice problem can be formulated. It is possible to add restrictions on some parameter values to comply with the DM preferences. The NVD optimal choice problem (3.96) s.t. (3.43)-(3.76) can be extended by adding of restrictions for some NVD parameters. Task D2 is modified Task D1 with additional restriction about the NVD working range by using one of the additional restrictions:

(3.98a)
$$\sqrt{0.07\tau_a EKA'_{ob} K_{IIT} K_{ob}} \geq R^D{}_{min}\ ,$$

(3.98b)
$$\sqrt{0.07\tau_a EKA'_{ob} K_{IIT} K_{ob}} \geq R^R{}_{min}\ ,$$

(3.98c)
$$\sqrt{0.07\tau_a EKA'_{ob} K_{IIT} K_{ob}} \geq R^I{}_{min}\ ,$$

where $R^D{}_{min}$, $R^R{}_{min}$ and $R^I{}_{min}$ are the given minimum values for distance of detection, recognition and identification.

Task D3. It is a modified Task D1 with additional restriction about the NVD price by using the additional restriction:

(3.99)
$$C_{min} \leq C \leq C_{max}\ ,$$

where C_{min} and C_{max} are the given lower and upper limit for the price of optoelectronic channel of NVD.

Task D4. It is a modified Task D1 with additional restriction about the NVD weight by using the additional restriction:

(3.100)
$$T \leq T_{max}\ ,$$

where T_{max} is the given upper limit for the weight of optoelectronic channel of NVD.

These tasks reflect some typical practical requirements when designing the NVD optoelectronic channel. The proposed deterministic mathematical optimization model of optoelectronic channel of NVD, allows introducing of other practical requirements for optoelectronic channel by formulation of tasks, including additional restrictions or combinations of the additional constraints imposed on the tasks D2, D3 and D4.

3.5. Stochastic Optimization Tasks for Selection of Elements of NVD Optoelectronic Channel

Stochastic selection of elements for NVD optoelectronic channel takes into account the external surveillance conditions as stochastic variables. Considering that fact these optimization tasks are formulated similarly to the deterministic tasks.

Task S1. This is a basic task of the stochastic model of optoelectronic channel. The purpose of this task is to find such a combination of NVD modules that maximize the NVD *working range, electrical battery supply power lifetime duration, field of view, objective f-number, eye relief*, and to minimize the *objective focus range, distortion, weight* and *cost* while considering external surveillance conditions as stochastic variables:

$$\begin{aligned} &max\ \{R, BL, W_{ob}, f\#, ER\} \\ &min\ \{F, AD_{ob}, T, C\}, \end{aligned} \qquad (3.101)$$

subject to (3.43)-(3.76) and mathematical expectations (3.82)-(3.84) for the external surveillance conditions.

Task S1a. It is modified Task S1, where the objective function excludes the component for price to assess the impact of price on the final decision:

$$\begin{aligned} &max\ \{R, BL, W_{ob}, f\#, ER\} \\ &min\ \{F, AD_{ob}, T\}, \end{aligned} \qquad (3.102)$$

subject to the same restrictions as in the task S1.

Task S2. It is modified Task S1 with additional restriction about the NVD working range by using one of the additional restrictions:

(3.103a) $$\sqrt{0.07T_a^{st}E^{st}K^{st}A'^{st}_{ob}K_{IIT}K_{ob}} \geq R^D{}_{min},$$

(3.103b) $$\sqrt{0.07T_a^{st}E^{st}K^{st}A'^{st}_{ob}K_{IIT}K_{ob}} \geq R^R{}_{min},$$

(3.103c) $$\sqrt{0.07T_a^{st}E^{st}K^{st}A'^{st}_{ob}K_{IIT}K_{ob}} \geq R^I{}_{min},$$

where $R^D{}_{min}$, $R^R{}_{min}$ and $R^I{}_{min}$ are the given minimum values for distance of detection, recognition and identification.

Task S3. It is modified Task S1 with additional restriction about the NVD price:

(3.104) $$C_{min} \leq C \leq C_{max},$$

where C_{min} and C_{max} are the given lower and upper limit for the price of optoelectronic channel of NVD.

Task S4. It is modified Task S1 with additional restriction about the NVD weight:

(3.105) $$T \leq T_{max},$$

where T_{max} is the specified the maximum acceptable weight for the NVD optoelectronic channel.

To satisfy other practical requirements, other optimization problems can be formulated, implementing additional restrictions and limits for various parameters of optoelectronic channel. Formulated deterministic and stochastic optimization problems enable optimal choice of modules for the NVD optoelectronic channel conforming to differing requirements for the working range, weight and cost of designed device. Described models (deterministic and stochastic) and the corresponding optimization tasks can be integrated into suitable methods for design of optoelectronic channel of NVD.

Chapter 4

Methods for Designing of NVD

The design methods based on the use of standardized modules contributes the systems innovation by providing a new system configuration. Due to the use of standard components, modular design reduces costs. The traditional approach to the design process is to build a prototype and to test it against design goals. This process is accompanied by essential costs of time and money. The definition of methods for design of NVD enabling preliminary theoretical evaluation of device parameters will contribute to decreasing of the above costs and is of great importance.

Formulated deterministic and stochastic models of NVD optoelectronic channel developed in Chapter 3 are used in NVD design methods. Three methods are described – method of *iterative choice,* method of *rational choice* and method of *optimal choice*.

4.1. Method of Iterative Choice of NVD Modules

The iterative method for choice of modules is implemented in developed software system “NVGpro” (**Borissova, Mustakerov, 2006**). The basic stages of this method are shown in **Fig. 4.1**.

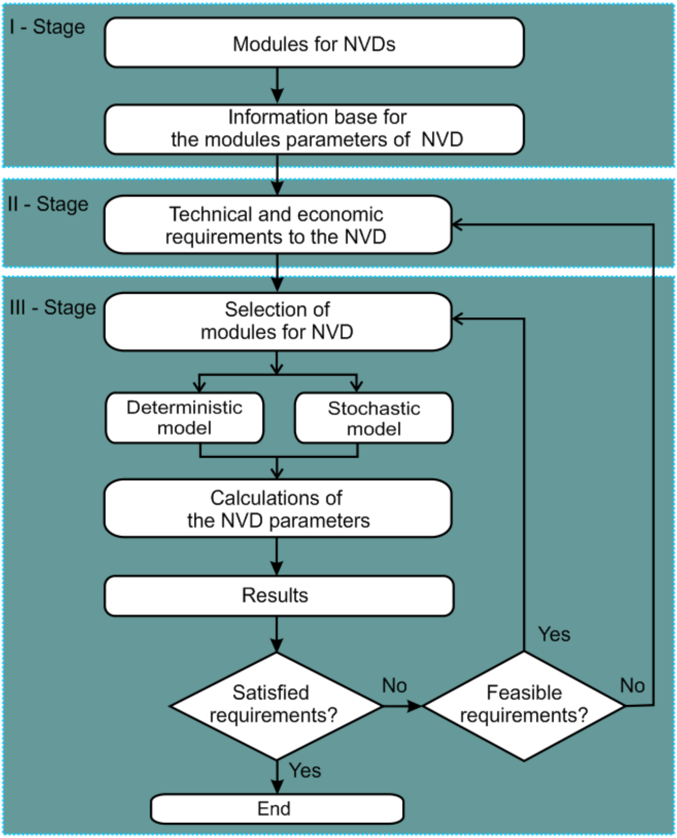


Fig. 4.1. Stages of iterative method for choice of NVD modules

The first stage of the iterative method is determination of the necessary modules for NVD design and developing of an information base for the relevant parameters. The second major st ep is to determine the technical and economic requirements about the designed device. At this stage, user requirements about the parameters of NVD (working range, field of view, weight, price, etc.) should be established. The third stage consists in selection of the basic NVD modules including the objective, IIT, eyepiece, and electrical batteries for the power supply. This selection is done by the decision maker (DM). When particular design device and parameter values of the external surveillance conditions are selected, the parameters of designed NVD can be calculated by deterministic or stochastic model.

In case of stochastic model, the mathematical expectations of external surveillance conditions are used. Next, the obtained results should be evaluated by the DM. If they do not comply with the expected DM requirements, some changes in the selected modules or external surveillance conditions should be done. Thus, by consistent implementation of the selection process and calculation of theoretical parameters of the designed NVD, the "virtual" designing continues until the requirements of DM about NVD parameters are satisfied.

4.2. Method of Rational Choice of NVD Modules

The concept of the rational choice method coincides largely with that used in multicriteria optimization for rational or satisfactory assessment. Rational decision-making means that decision maker (DM) does not optimize any particular objective function but instead tries to reach some satisfactory levels of certain criteria. In the most general case, the resulting solutions are not optimal but can be considered as rational or satisfactory solutions. This method does not use optimization, but allows selecting the "satisfactory" modules for designed NVD and calculates the corresponding theoretical estimations for the parameters of designed NVD. A schematic presentation of the design process of NVD by using the method of rational choice is shown in **Fig. 4.2** (**Borissova, Mustakerov, 2007**).

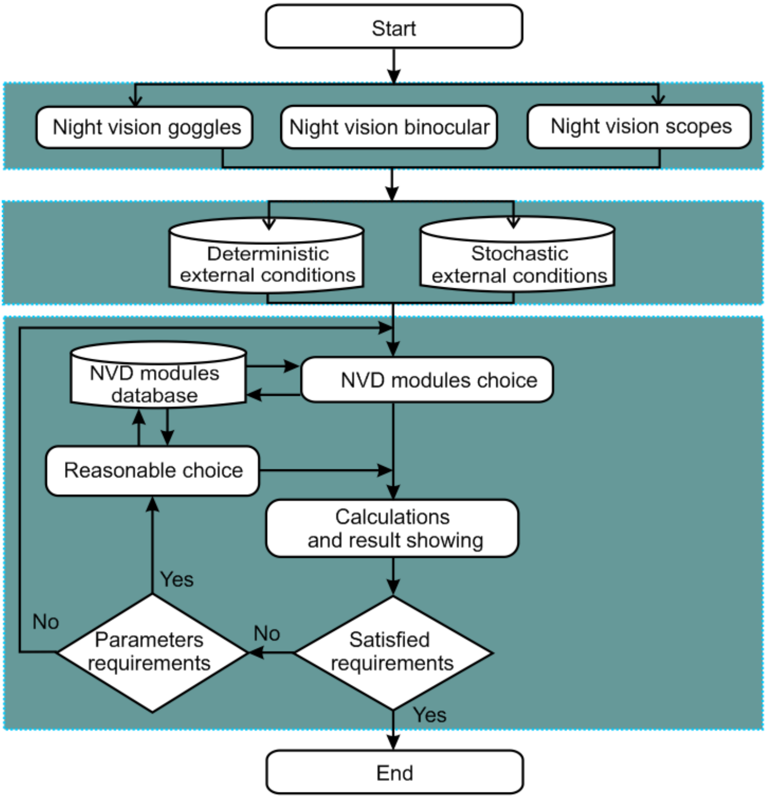


Fig. 4.2. NVD design using the rational choice method

An essential feature of this method is that DM can specify additional requirements for some of the parameters of the designed device as upper or lower limits of their values. Satisfying of the specified limits is realized by the following algorithmic scheme for implementation of the method – **Fig. 4.3** (**Borissova, Mustakerov, 2006**).

The algorithmic realization of the automatic rational choice is based on calculating of the results for all possible modules combinations taking into account the existing dependencIes between them.

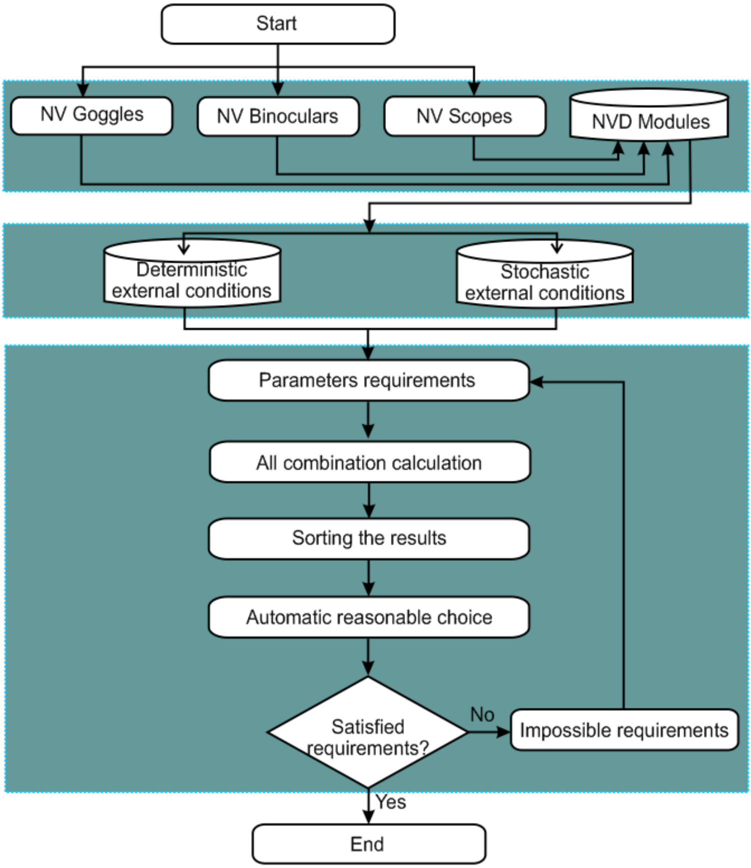


Fig. 4.3. Algorithmic implementation of the rational choice method

Then the arrays with results of calculations are sorted in increased order. The search for modules starts from the beginning of the relevant sorted array until a value greater or equal to the given one (for the case of maximization) is found as shown in **Fig. 4.4a** (**Mustakerov, Borissova, 2007**).

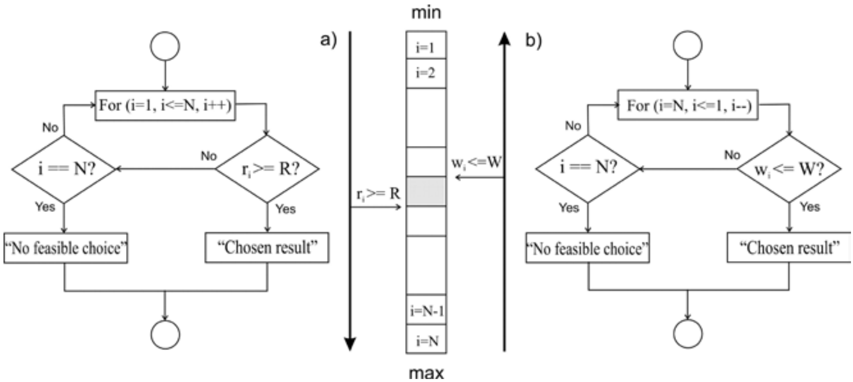


Fig. 4.4. Algorithmic realizations of the automatic reasonable choice:
a) for working ranges and magnification; b) for weight and price

If the desired value is for weight or price (i.e. a case of minimization) the search starts in the opposite direction - from the largest value until a smaller or equal value is found (Fig.4.4b). The modules combination found as a result of the reasonable choice is used to calculate the optoelectronic channel parameters. If the search is unsuccessful, i.e. there is no feasible modules combination, a proper message is shown and new limits for parameters are to be given.

4.2.1. A Generalized Algorithm for NVD Design by Iterative and Rational Choice Approaches

As the NVDs are not under mass production a possible approach is to offer to DM different virtual designs before actual producing of the device for his preliminary estimation and approval. This can be done by algorithm for preliminary assessment of NVDs design. It is developed taking into account the NVDs specific and DM requirements. The basic modules of passive night vision devices (NVDs) can be reduced to objective, image intensifier tube (IIT), ocular and power supply (**Fig. 4.5**).

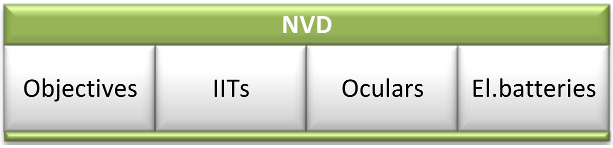


Fig. 4.5. Basic NVD modules

There exist different types of devices by application – night vision goggles (NVG), night vision binoculars (NVB), night vision scopes (NVS) and all of them have to be considered with their specific modules relations and compatibility. Practical experience shows the most essential parameters to be considered in NVD design: *working range, field of view, magnification, electrical battery power supply lifetime, weight* and *price*.

The theoretical NVDs *working range* estimation can be calculated by the proposed formula (2.53) (**Borissova, Mustakerov, 2006**).

The NVDs *magnification* α is represented by the relation of objective and ocular focal length and the magnification β of IIT (if exists)

(4.1)
$$\alpha = \beta \frac{f_{ob}}{f_{oc}}.$$

In case of NVGs, the overall magnification $\alpha = 1$ (i.e. no magnification), while the NVBs and NBSs have magnification $\alpha > 1$.

NVDs *field of view* is defined by the relation of objective and ocular focal length taking into account the IIT screen diameter. The objective field of view can be determined by the ratio:

(4.2)
$$f_{ob} = D_{IITph}\left(2tg(\omega/2)\right)^{-1},$$

where f_{ob} is the objective focal length in millimeters, ω is field of view in degrees, D_{IITph} is diameter of IIT photocathode in millimeters.

Electrical battery power supply lifetime L_B depends on the electrical load of IIT I_{IIT} and on battery capacity C_B:

(4.3)
$$L_B = \frac{C_B}{I_{IIT}}.$$

The typical supply voltage needed for the IIT is 3.0 V. There exists two basic categories that can be used – AA type batteries with supply voltage 1.5 V and button (coin) cell type with 3.0 V supply voltage. Different number of serial and/or parallel connected batteries can be used and the corresponding formula for battery capacity C_B, is (**Borissova, 2006**):

(4.4) $$C_B = n\sum_{p=1}^{t} a_p \sum_{q=1}^{k_p} b_q^p C_B^q \,,$$

where n – number of the parallel connected batteries accordingly to the capacity requirement, a_p – binary variable for battery p-type, b_q^p – binary variable for battery q-subtype of p-type battery, C_B^q – the capacity of the p-type and q-subtype battery.

Let us assume that there are t-type electrical batteries with supply voltage 1.5 V or 3 V. Each t-type battery could have k_p-subtypes with different capacity to choose from, so the electrical battery power supply weight could be defined as:

(4.5) $$W_{battery} = n\left(\sum_{p=1}^{t} a_p \left(s_p \sum_{q=1}^{k_p} b_q^p H_B^q + \sum_{p=1}^{t} t_p \right)\right),$$

where H_B^q – weight of the p-type and q-subtype electrical battery, t_p – single p-type electrical battery power supply weight, s_p = 1 for 3 V batteries and s_p = 2 for the 1.5 V batteries.

The electrical battery power supply price $Price_{battery}$ depends on the chosen battery type and on the number of batteries n:

(4.6) $$P_{battery} = n\left(\sum_{p=1}^{t} a_p \left(s_p \sum_{q=1}^{k_p} b_q^p P_B^q + \sum_{p=1}^{t} k_p \right)\right),$$

where P_B^p – price of the p-type and q-subtype electrical battery, k_p – single p-type electrical battery power supply price.

A good approximation of the NVDs *weight* and *price* could be estimated as a sum of relevant values for IIT, objective, ocular and electrical battery power supply as:

(4.7) $$Weight_{NVD} = W_{IIT} + W_{ob} + W_{oc} + W_{battery},$$

(4.8) $$Price_{NVD} = P_{IIT} + P_{ob} + P_{oc} + P_{battery}.$$

The described mathematical model can be integrated into a suitable algorithm for determining a preliminary theoretical evaluation of the parameters of the designed device (**Borissova et al., 2013**). The proposed algorithm concerns integration between defined sets of modules as input data, processing data by the described formulas and delivering the output information – theoretical evaluation of the parameters for the designed device. The generalized flowchart of the proposed algorithm for assessment of NVD design parameters is shown in **Fig. 4.6**.

The proposed algorithm starts with defining of external surveillance conditions – ambient light illumination, target type, contrast between background and target, and atmosphere transmittance. Due the specifics of the NVDs it is important to take into account different external surveillance conditions in the design process. The most important NVDs parameter – the working range, is influenced essentially by external surveillance conditions. Different values of external surveillance conditions are to be considered to reflect the different expected application surveillance conditions of the designed device. On the second stage the type of designed night vision device (NVG, NVB or NVS) is chosen. The third stage represents two algorithm branches – iterative and rational modules choice.

The iterative modules choice allows the DM to make his own selection of NVDs modules. Depending on the NVDs type chosen on stage 2 the corresponding formulae are used. Taking into account the given on the previous stages surveillance conditions, device type and sets of modules, the designed device parameters are calculated and shown: the NVDs working range (calculated as detecting, recognition and identification ranges) weight, price, and electrical battery power supply lifetime duration.

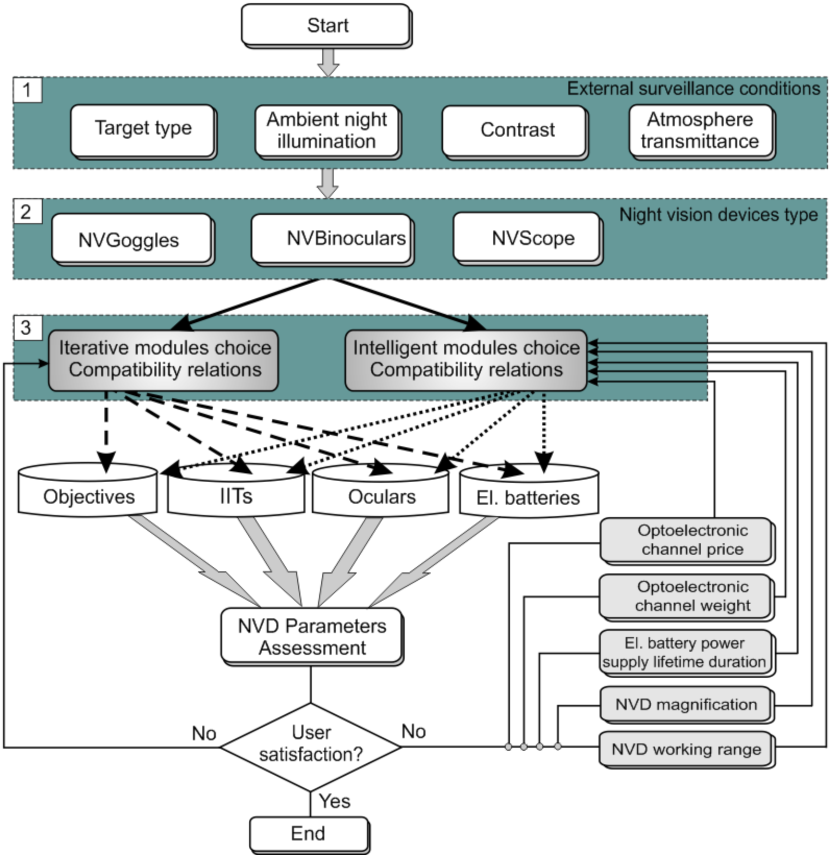


Fig. 4.6. Flowchart of the algorithm for assessment of NVD design parameters

If the DM is not satisfied with some of calculated NVDs parameters, he can select other modules via iterative branch of the algorithm. This interactive design process ends when the DM is satisfied with the designed device parameters estimations.

The second branch of the algorithm is used when the DM does not want to continue searching of satisfactory modules combination but relies on the intelligent rational modules choice. This rational choice of modules allows the DM to set up some preliminary requirements about the designed device parameters. The main idea of rational modules choice is to find compatible modules combinations while satisfying DM requirements for some NVDs parameters. The algorithmic realization of the rational modules choice is based on determining of device parameters for all feasible modules combinations. Then the resulted arrays are sorted in increased order. If given values of working range (detection or recognition or identification range) or magnification are to be met, the search goes toward increasing values of the sorted arrays until a value greater or equal to the given one is found. If weight or price required values are searched then the search starts from the largest value and goes on until a smaller or equal to the given by DM value is found. If different parameters values required by DM are met by different modules combinations the corresponding messages are shown to DM to assist his further actions – to accept some combination or to modify some of the required parameters values.

To support the assessment of designed NVDs parameters a Web-based software architecture implementing the proposed algorithm is developed – **Fig. 4.7**. The proposed architecture is based on using of AJAX technology on the client-side. AJAX (Asynchronous JavaScript and XML) is one of the most popular rich Internet application technologies. The main idea behind the architecture of the AJAX engine is the reuse every time when it is needed, some asynchronous processing or a smart way to refresh information on the current web page without reloading it (**Hertel, 2007**). Using the AJAX technology enables web applications to call the web server without leaving the actual page and in the background without notice of the user (through XMLHttpRequest). This avoids loading the same form or page including the html code multiple times, reduces the network traffic and increases the user acceptance. In practice, AJAX engine is realized as JavaScript functions that are called whenever information needs to be requested from the server. When the AJAX engine receives the server response, it goes into action, often parsing the data and making updates of the presented to the user information.

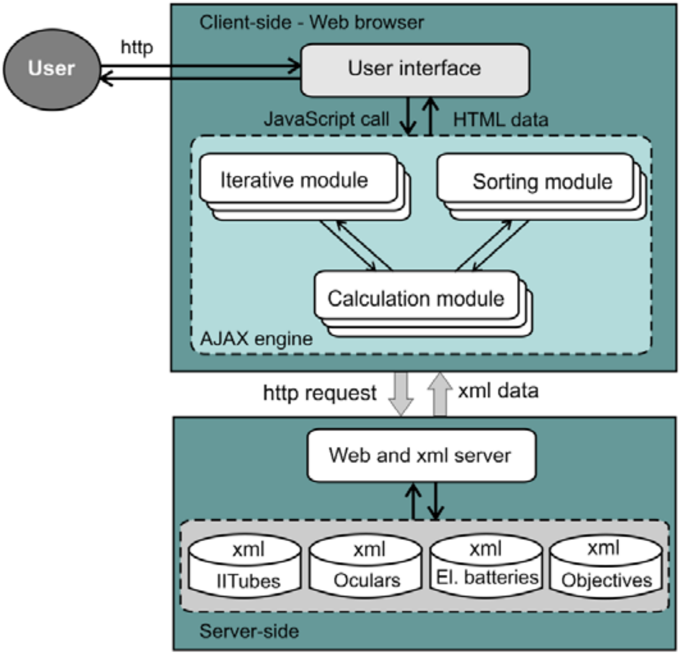


Fig. 4.7. Web-based architcture of system for NVD design

Because this process involves transferring less information than the traditional web application model, user information updates are faster.

The advantage of client-side architecture is the independence from the server-side technology. The server-side is realized by a mixture of technologies, such as HTML, script languages (JavaScript) and JSP technology. The databases for modules and their parameters, and all files of the web-based system for design assessment of NVDs are stored on the server-side. The server-side code creates and serves the page and responds to the client asynchronous requests. The graphical user interface of a prototype of web-based system for design assessment of NVDs based on the described architecture is shown in **Fig. 4.8**.

Fig. 4.8. Graphical user interface of web-based system for assessment of design of NVDs

Three radio buttons allow the DM to select only one type of NVDs (NVG, NVB or NVS). Drop-down lists allow DM to select NVDs modules. When a particular module is selected the lists of other modules are updated according their compatibility relation. Another group of drop-down lists are used to set external surveillance conditions. Each selection of a module visualizes its corresponding parameters within text fields. This information assists DM in process of selection. After device modules and external surveillance conditions are selected, the parameters of designed device are calculated and shown in corresponding text fields. This accomplishes the design of device via iterative branch of the developed algorithm. The rational design branch of the proposed algorithm is realized when DM enters some required values for the device parameters in the corresponding text fields. Then these requirements are processed by module "calculation" to define feasible modules combination satisfying all given DM preferences. When such a combination is found it is shown to the DM for approval or for another search.

If a feasible module combination satisfying all given DM preferences does not exist a proper message is shown. The used JavaScript functions call AJAX engine which sends request to server's databases and retrieves server response. Then passing the AJAX, the data on web page is displayed without reloading a page. After each request only small amount of data is transferred between client and web server.

4.3. Method for Optimal Design of NVD

The method of optimal choice implements the formulated optimization problems, i.e., the chosen configuration of modules is optimal in the sense of preliminary defined quality criteria for NVD design. This method is based on solution of deterministic or stochastic nonlinear mixed-integer single-criterion optimization problems. The stages of the method for optimal choice of NVD modules are shown in **Fig. 4.9**.

The first two stages coincide with stages in iterative and rational method for selecting of modules for NVD. At the third stage user (DM) selects (or modifies) a formulated in the previous paragraphs optimization problems using the deterministic or stochastic model of the external surveillance conditions. The formulated task is solved by appropriate optimization software. The resulting solution is analyzed by the DM and if results do not meet the requirements, another optimization task or modified optimization task are to be solved again. This process is repeated until the results meet the given requirements. In this case, DM has the opportunity to predetermine the limits of some parameters involved in the model.

Individual stages can be automated through the development of specialized software to facilitate interactive user interaction in the implementation of the methods.

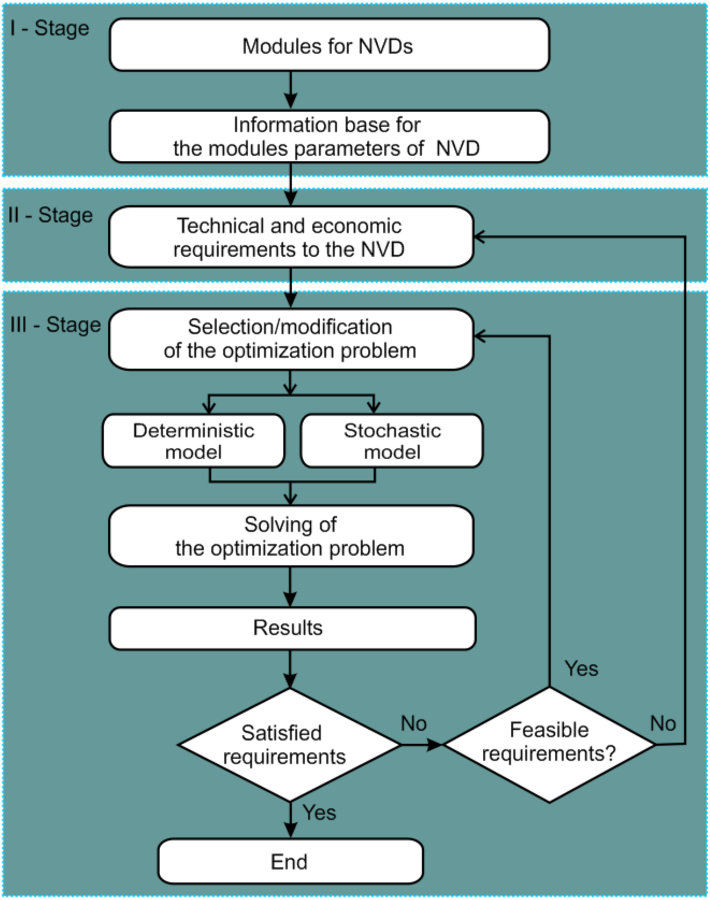


Fig. 4.9. NVD design using the optimal choice method

A generalized algorithmic implementation of the method of optimal choice of NVD modules is shown in **Fig. 4.10** (**Borissova, Mustakerov, 2007**).

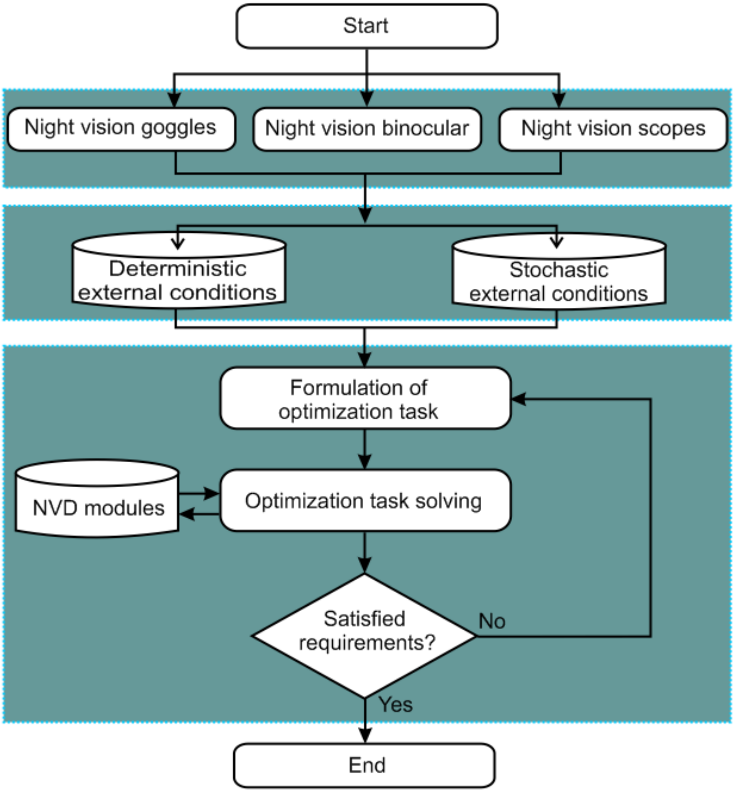


Fig. 4.10. Algorithmic implementation of the optimal choice method

The described method provides an optimal choice of components for the NVD and also uses iterative procedures for determining the parameters of the designed NVD under the control of DM. An essential feature of this method is that the resulting solutions are optimal accordingly to the given criteria and DM requirements and limitations in the optimization problem.

4.3.1. Multi-objective E-constraints Method for Optimal Choice of NVD Modules

Multi-objective optimization gives the DM a possibility to formulate his requirements as independent criteria that have to be optimized. This approach is characterized by different solution philosophies and goals when setting and solving them. The goal may be a representative set of Pareto optimal solutions, and/or quantity of the trade-offs in satisfying the different objectives, and/or a single solution that satisfies many subjective preferences of DM to be found. Multiobjective optimization problems are usually solved by utilizing scalarization. Via scalarization, the problem is transformed into a single objective optimization problem involving possibly some parameters or additional constraints. In most scalarizing functions, preference information of the decision maker is taken into consideration. After the scalarization phase, the widely developed theory and methods of single objective optimization are available (**Miettinen, Makela, 2002**). Two major requirements are set for a scalarization function in order to provide method completeness (**Sawaragi et al., 1985**):

1) it should be able to cover the entire set of Pareto optimal solutions;
2) every solution found by means of scalarization should be (weakly) Pareto optimal.

Multicriteria nonlinear mixed-integer optimization task for optimal choice of modules for NVD optoelectronic channel can be formulated as follows:

$$\begin{aligned} &max\ \{R, W_{ob}, f\#, ER\} \\ &min\ \{AD_{ob}, T, C, FR\}, \end{aligned} \tag{4.9}$$

subject to (3.43)-(3.76) for deterministic case or mathematical expectations for external surveillance conditions (3.82)-(3.85) in stochastic case.

One commonly used method for multicriteria optimization problems solving is so called *e-constraints method*. The e-constraints method optimizes one of the objective functions using the other objective functions as constraints, incorporating them in the constraint part of the model. By progressively changing the constraint values, different points on the Pareto-front could be sampled. By calculating the extremes of the Pareto-front the range of different objective functions could be calculated and constraint values selected accordingly. The method enables an even spread on the Pareto-front as long as the Pareto-front is continuous.

As input data for optimization tasks parameters of 5 different IITs (**Table 4.1**), 5 objectives (**Table 4.2**), 5 oculars (**Table 4.3**), and external surveillance conditions values as shown in **Table 4.4**, are used.

Table 4.1. IITs parameters

#	IIT	S_Σ, A/lm	δ, lp/mm	M	Weight, [g]	Price, [$]
1	DEP Gen II	0.000450	50	16	85	660
2	DEP SHD-3	0.000600	54	20	80	1500
3	DEP XD-4	0.000700	58	24	80	2000
4	DEP XR-5	0.000800	70	28	80	5600
5	ITT MX - 10160B	0.002100	72	36	85	5900

Table 4.2. Objectives parameters

#	Objective	1/k	$f_{об}$, mm	τ_o	FOV, deg	Distortion, %	Minimum focus range, cm	Weight, [g]	Price, [$]
1	NVD Prilep	1.20	25.17	0.80	43	7.0	25.0	82	340
2	AN/PVS-5C	1.05	26.80	0.86	40	4.5	25.0	95	380
3	AN/PVS-5A	1.40	25.00	0.81	40	8.0	25.5	83	300
4	NVG-500	1.09	26.60	0.77	40	5.0	25.0	92	290
5	D-2V	1.40	26.00	0.80	37	8.0	25.0	85	300

Table 4.3. Oculars parameters

#	Ocular	$f_{ок}$, [mm]	W_{ok}, [deg]	ER, [mm]	Weight, [g]	Price, [$]
1	NVD Prilep	25.17	43.0	15	62	150
2	NVG-500	26.60	40.5	15	75	100
3	M-963	26.00	41.0	15	60	160
4	M-953	25.00	40.0	25	68	140
5	M-915	26.80	41.0	15	70	150

Table 4.4. External surveillance conditions

External surveillance conditions	Atmospheric transmittance	Night illumination	Contrast	Reduced target area for		
				detection	recognition	identification
deterministic	0.700	0.010	0.200	0.700	0.276	0.131
stochastic	0.575	0.0135	0.275	0.642	0.253	0.120

Using the e-constraints method and data from **Tables 4.1, 4.2, 4.3** and **4.4**, the following scalarization problems are formulated and solved sequentially (**Borissova, 2006**):

Scalarization problem R that implements the criterion for a *maximum detection range* is:

(4.10) $$max\ R^D$$

subject to relations according to **Tables 4.1, 4.2, 4.3** and **4.4**, restrictions (3.40)-(3.71) and new additional restrictions for the rest of criteria:

(4.11) $$35 \leq W_{ob},$$

(4.12) $$1 \leq f\#,$$

(4.13) $$FR \leq 30,$$

(4.14) $$AD_{ob} \leq 9,$$

(4.15) $$20 \leq ER\ ,$$

(4.16) $$T \leq 300,$$

(4.17) $$C \leq 7000.$$

Solving the task R determines the detection range that is set up as a constraint in other scalarization tasks according to the rules of e-constraints method.

Scalarization problem $\mathbf{W_{ob}}$ implements the criterion for maximum *field of view*:

(4.18) $$max\ W_{ob}$$

subject to relations (3.40)-(3.71), restrictions (4.12)-(4.17) and new additional restriction for detection range:

(4.19) $$400 \leq R^D.$$

Solving the task $\mathbf{W_{ob}}$ determines the field of view that will be used on next step of e-constraints method.

Scalarization problem f# implements the criterion for maximum *f-number*:

(4.20) $$max\ f\#$$

subject to relations (3.40)-(3.71), restrictions (4.13)-(4.17), (4.19) and new additional restriction for field of view:

(4.21) $$40 \leq W_{ob}.$$

Solving the task **f#** determines the objective *f-number* that is set up as a constraint on next step.

Scalarization problem FR implements criterion of minimum *objective focus range*:

(4.22) $$max\ (-FR)$$

subject to relations (3.40)-(3.71), restrictions (4.14)-(4.17), (4.19), (4.21) and new additional restriction:

(4.23) $$1 \leq f\#.$$

Solving the task **FR** determines the minimum objective focus range that is set up as a constraint in following scalarization tasks.

Scalarization problem $\mathbf{AD_{ob}}$ implements criterion of minimum *objective distortion*:

(4.24) $$max\ (-AD_{ob})$$

subject to relations (3.40)-(3.71), restrictions (4.15)-(4.17), (4.19), (4.21), (4.23) and new additional restriction:

(4.25) $$FR \leq 30.$$

Solving the task $\mathbf{AD_{ob}}$ determines the objective distortion that is set up as a constraint in other scalarization tasks.

Scalarization problem ER implement criterion for maximum *distance of the eyepiece exit pupil*:

(4.26) $$max\ ER$$

subject to relations (3.40)-(3.71), restrictions (4.16)-(4.17), (4.19), (4.21), (4.23), (4.25) and new additional restriction:

(4.27) $$AD_{ob} \leq 7.$$

Solving the task **ER** determines the eye relief that is set up as a constraint in other scalarization tasks.

Scalarization problem T implements criterion of a minimum *weight* of optoelectronic channel:

(4.28) $$\max(-T)$$

subject to relations (3.40)-(3.71), restrictions (4.17), (4.19), (4.21), (4.23), (4.25), (4.27) and new additional restriction:

(4.29) $$10 \le ER.$$

Solving the task **T** determines weight of the optoelectronic channel that is set up as a constraint in other scalarization tasks.

Scalarization problem C implements criterion for a minimum *price* of optoelectronic channel:

(4. 30) $$\max(-C)$$

subject to relations (3.40)-(3.71), restrictions (4.19), (4.21), (4.23), (4.25), (4.27), (4.29) and new additional restriction:

(4.31) $$T \le 250\ .$$

The final solution of the formulated multicriteria optimization problem by the e-constraints method is the solution of last scalarization subproblem C. The results from scalarization problems solutions on each step of e-constraints method implementation for deterministic external surveillance conditions case are shown in **Table 4.5**.

Table 4.5. Results of solutions by the e-constraints method for deterministic external surveillance conditions

NVD parameters as criteria	**Scalarization Tasks**							
	R	**W_{ob}**	**f#**	**FR**	**AD_{ob}**	**ER**	**T**	**C (final solution)**
FOV, degree	40	43	40	40	40	40	43	40
f#	1.05	1.2	1.05	1.05	1.05	1.09	1.2	1.05
FR, mm	25	25	25	25	25	25	25	25
AD_{ob}, %	4.5	7	4.5	4.5	4.5	5	7	4.5
ER, mm	15	15	15	15	15	15	15	15
R^d, m	651	552	413	404	413	414	552	404
Weight, g	250	229	245	245	245	247	229	245
Price, $	6430	6390	2530	2030	2530	5990	6390	2030

The changes of detection range (**Fig. 4.11**) and price of optoelectronic channel (**Fig. 4.12**) compared to the obtained values in particular scalarization task solving in case of standing man as a target and deterministic external surveillance conditions are shown in **Fig. 4.11** and **Fig. 4.12**.

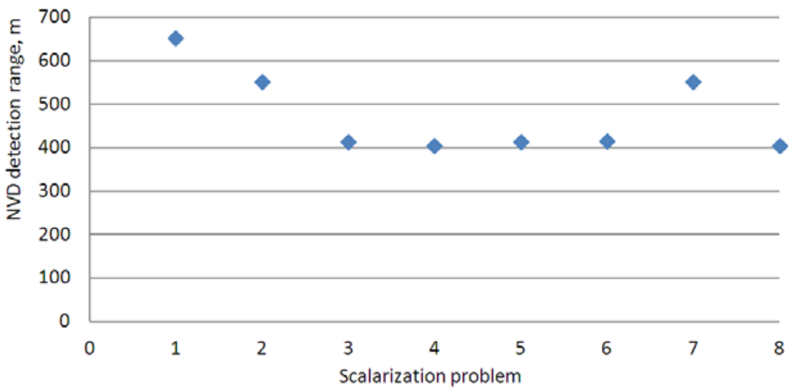


Fig. 4.11. Changes in NVD detection range by the scalarization tasks solutions

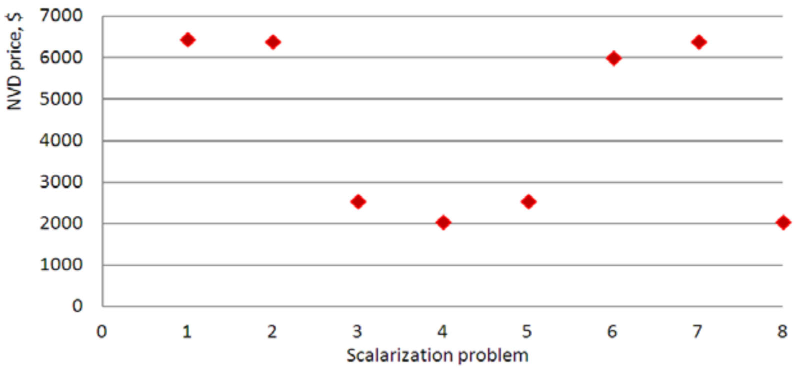


Fig. 4.12. Changes in price of NVD by the scalarization tasks solutions

The e-constraints method is used also for stochastic case of external surveillance conditions and the corresponding results are shown in Table 4.6.

Table 4.6. Results of solutions by the e-constraints method for stochastic external surveillance conditions

NVD parameters as criteria	**Scalarization Tasks**							
	R	**Wob**	**1/k**	**FR**	**AD_{ob}**	**ER**	**T**	**C (final solution)**
FOV, degree	40	43	40	40	40	40	43	40
f#	1.05	1.2	1.05	1.09	1.05	1.09	1.2	1.05
FR, mm	25	25	25	25	25	25	25	25
AD_{ob}, %	4.5	7	4.5	5	4.5	5	7	4.5
ER, mm	15	15	15	15	15	15	15	15
R^d, m	768	651	530	708	530	708	413	530
Weight, g	250	229	245	250	245	252	229	245
Price, $	6430	6390	6130	6290	6130	6290	6390	6130

The variations in detection range (**Fig. 4.13**) and price of optoelectronic channel (**Fig. 4.14**) compared to the obtained values in particular scalarization task solutions in case of standing man as a target and stochastic external surveillance conditions are illustrated.

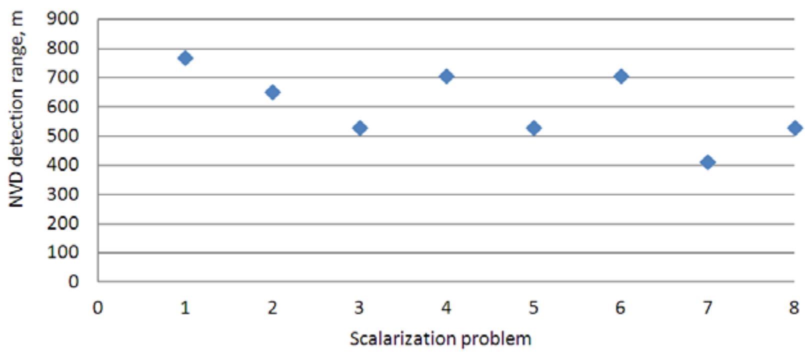


Fig. 4.13. Changes in NVD detection range by the scalarization tasks solutions

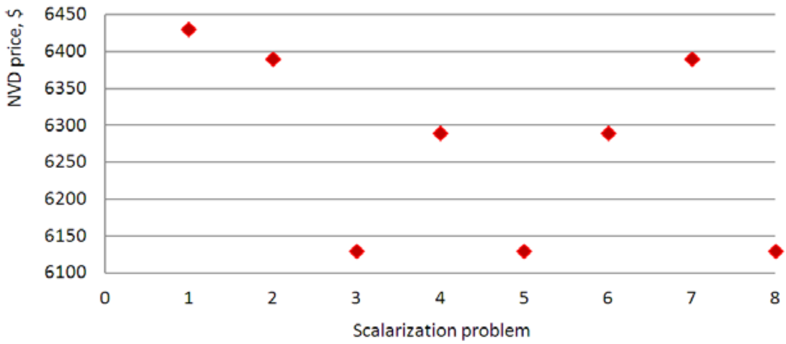


Fig. 4.14. Changes in price of NVD by the scalarization tasks solutions

It is known that the use of different methods for multicriteria problems solving often leads to a variety of Pareto-optimal solutions. The choice of a particular method depends on the specifics of the problem and how to set the DM's preferences with respect to intended decision.

Chapter 5

Selection of NVD by Optimization Models Formulation

As a result of a technological development there exist a constantly growing number of different NVD types and models with different values of parameters. The user preferences should be dominant for the importance of the NVD parameters and their values. Most of the offered NVD have specifications datasheets with information about the NVD essential parameters and that information can be used to make an intelligent choice. Some flexible objective approach based on a quantative evaluation is needed to make a choice considering the NVD parameters importance and values according to to the different user's preferences.

5.1. Multicriteria Optimization Model for Selection of NVD

When choosing the NVD, the user acts as a decision maker and should consider all the relevant costs and benefits of the options for the set of devices to choose from and to adequately address all of his/her preferences. The preferred device should be that which comes close to the decision maker's objectives which may often conflict. In practice, it is unlikely that some device will perform best against all objectives and can be clearly preferred; each one will demonstrate different advantages and disadvantages. Describing the balance between objectives, and identifying the preferred option is a complex problem. This problem can be approached as multicriteria combinatorial optimization problem characterized by the presence of many conflicting preferences (criteria) about the NVD parameters values. In many practical cases the choice is usually done intuitively based on the decision-maker experience. For example, choosing of the NVD, using the latest technological solutions, reflects on higher prices to pay. It is reasonable to look for the “user best” device among the offered NVD, i.e., whose parameters values are best according to to the user’s point of view. There are considerable advantages in making an explicit decision-aiding framework ensuring that all concerns are identified and addressed and the reasons behind a particular choice are made clear. The advantages of such a structured approach are particularly apparent where there are many alternative devices with numerous different parameters values.

The NVD effectiveness depends on various device parameters. For example, the user may define requirements for a wide field of view and bigger magnification, and these two parameters are inversely proportional to each other. This determines the need to build a mathematical model for selection of the most appropriate device for a particular user, taking into account the given requirements to the device parameters.

5.1.1. Generalized Multicriteria Optimization Model for Selection of NVD

Using of the multicriteria optimization allows to model in a natural way the decision maker’ preferences to express in an explicit manner a choice between options involving a number of often conflicting objectives. Through the aggregation of disparate information onto a common index of utility, the multicriteria techniques aim to provide a rational basis for classifying choices. The multicriteria optimization give the option to identify the preferences and trade-offs between the benefits and disbenefits of all alternatives. The problem of NVD choice by flexible adjusting to the user preferences could be formulated as multicriteria optimization problem if the parameters of the different NVD are considered as objective functions. In other words, the choosing of a proper NVD means choosing of a device with parameters values as close to the user expected values as possible. Some of the NVD parameters values reflect in better NVD performance when increasing, while the other – when decreasing. The generalized multicriteria optimization problem definition can be formulated as (**Mustakerov, Borissova, 2007**):

$$\begin{aligned} &max\ P(\mathrm{x}) = P_1(x), P_2(x), \ldots, P_j(x))^{\mathrm{T}}, \\ &min\ N(\mathrm{x}) = N_1(x), N_2(x), \ldots, N_k\,(x))^{\mathrm{T}}, \end{aligned} \tag{5.1}$$

subject to

$$P_j(\mathrm{x}) = \sum_{i=1}^{I} P_{ij} x_i\ , j = 1, 2,\ldots, \mathrm{J}\ , \tag{5.2}$$

$$N_k(\mathrm{x}) = \sum_{i=1}^{I} N_{ik} x_i\ , k = 1, 2,\ldots, \mathrm{K}\ , \tag{5.3}$$

$$\sum_{i=1}^{I} x_i = 1\ ,\ x_i \in \{0, 1\}\ , \tag{5.4}$$

where $P_1(x), P_2(x), \ldots, P_J(x)$ are the J objective functions expressing the NVD parameters that should be maximized, i.e., bigger values increase NVD performance; $N_1(x), N_2(x), \ldots, N_K(x)$ are the K objective functions of the NVD parameters that should be minimized, i.e., lower values increase NVD performance; P_{ij} and N_{ik} represents the j-th respectively k-th parameters values of the i-th device and are known constants; x = (x_1, x_2, …, x_I) are binary integer variables corresponding to the indexes i = 1, 2, …, I, of each particular NVD considered to be a candidate for the “user best” NVD as a result of multicriteria optimal choice.

There should be pointed out that such formulation of the multicriteria optimization problem is a formulation of linear integer combinatorial choice problem. The result of its solution is a choice of one particular NVD from a defined set of NVD with predetermined and known parameters values. The above formulation has no additional restrictions on the parameters values and all choices of a particular NVD are feasible. The Pareto optimal choice depends on the decision-maker preferences.

5.1.2. Numerical Application of Multicriteria Optimization for Selection of NVD without Additional Restrictions

The night vision goggles are the most widely used devices type both for military and civil applications. To illustrate the proposed approach applicability some practically proven parameters with values data for real binoculars type NVG are collected from the Internet (see **Table 5.1**). Other NVG parameters could also be considered but these ones shown in **Table 5.1** are adequate to demonstrate the proposed multicriteria model for selection of NVD.

Considering the NVG parameters from **Table 5.1** as users' criteria for a preferable choice, a multicriteria optimization problem can be formulated as: to choose such a device which has the highest resolution, largest field of view, the longest work duration and the greatest working distance and smallest focal length, weight and price.

The requirements described above are represented mathematically in the following way (**Borissova et al., 2008**):

$$(5.5) \qquad \begin{aligned} &max\ P(\mathrm{x}) = P_1(x), P_2(x), P_3(x), P_4(x))^{\mathrm{T}}, \\ &min\ N(\mathrm{x}) = N_1(x), N_2(x), N_3(x), N_4\ (x))^{\mathrm{T}}, \end{aligned}$$

subject to

$$(5.6) \qquad P_j(\mathrm{x}) = \sum_{i=1}^{15} P_{ij} x_i\ ,\ j = 1, 2, 3, 4,$$

$$(5.7) \qquad N_k(\mathrm{x}) = \sum_{i=1}^{15} N_{ik} x_i\ ,\ k = 1, 2, 3, 4,$$

$$(5.8) \qquad \sum_{i=1}^{15} x_i = 1,\ x_i \in \{0, 1\},$$

where $P_1(x)$, $P_2(x)$, $P_3(x)$, $P_4(x)$ are the NVG resolution, field of view, battery lifetime duration and working range which values should be chosen as big as possible; P_{i1}, P_{i2}, P_{i3}, P_{i4} are resolution, field of view, battery lifetime duration and working range values of the *i*-th device from **Table 5.1**; $N_1(x)$, $N_2(x)$, $N_3(x)$, $N_4(x)$ are the NVG objective focus range, length, weight and price which values should be chosen as low as possible; N_{i1}, N_{i2}, N_{i3}, N_{i4} are objective focus range, length, weight and price values of the ***i***-th device; $x = (x_1, x_2, \ldots, x_{15})$ are binary integer variables corresponding to each of the fifteen NVG shown in **Table 5.1**.

Table 5.1. NVD parameters

#	NVD	Resolution lp/mm	FOV deg	BL hours	Detection range, m	Min. FR cm	Length mm	Weight g	Price $
		P1	P2	P3	P4	N1	N2	N3	N4
1	ATN Cougar Gen 1	40	30	15 (10-20)	150	100	137	800	629
2	NZT-22 Gen 1	40	36	15	120	25	180	740	1350
3	MV-221G Gen 2+	32	40	40	125	25	114	482	2699
4	ATN Night Cougar-2 Gen 2+	36 (32-40)	30	15 (10-20)	150	100	137	800	2695
5	ПН-9К Gen 2+	34 (30-38)	36	10	180	25	127	750	4943
6	ATN Night Cougar CGT Gen 2+	50 (45-54)	30	15 (10-20)	250	100	137	800	3696
7	ATN Night Cougar HPT Gen 2+	59 (54-64)	30	15 (10-20)	300	100	137	800	4519
8	Dipol 221H Gen 2+	59	40	30	300	25	117	650	6052
9	ATN Night Cougar-3 Gen 3	64	30	15 (10-20)	300	100	137	800	4889
10	ATN Night Cougar-3A Gen 3	68 (64-72)	30	10-20 (15)	325	100	137	800	5629
11	ATN Night Cougar-4 Gen 4	68 (64-72)	30	15 (10-20)	325	100	137	800	9299
12	ATN PS-23 Gen 2+	41 (36-45)	40	35	200	25	151	700	2420
13	ATN PS-23 Gen CGT	50 (45-54)	40	35	200	25	151	700	3995
14	ATN PS-23 Gen 3	64	40	35	300	25	151	700	5685
15	ATN PS-23 Gen 4	72	40	35	350	25	151	700	11149

The widely used approach for solving multiobjective optimization problems is to transform a multiple objective (vector) problem into single-objective (scalarization) problems. Among decision methods, weighted-sum aggregation of preferences is by far the most common, as it is a direct specification of importance weights. The *weighted sum* method transforms multiple objectives into an aggregated scalarization objective function by multiplying each objective function by a weighting coefficient and summing up all contributors to look for the Pareto solution (**Marler, Arora, 2010**). NVG parameters in task formulation (5.5)-(5.8) are quite different by nature and values and could not be aggregated as comparable objectives. Thus the normalization is needed for objectives of different units to be comparable criteria and their weights correctly to represent their relative importance (**Marler, Arora, 2005**). The following normalization scheme is chosen:

(5.9) $$P_j^* = \frac{P_j - P_{j\min}}{P_{j\max} - P_{j\min}}$$ about maximizing criteria,

(5.10) $$N_k^* = \frac{N_{k\max} - N_k}{N_{k\max} - N_{k\min}}$$ about minimizing criteria.

This normalization scheme supplies parameters values between 0 and 1 based on the maximal and minimal objective values of the parameters (**Marler**, **Arora, 2004**). The normalization not only transforms data to have comparable values but also transforms the problem to a maximizing problem (Ibid.). The defined *max* and *min* values for each of the objectives (criteria) and their differences are shown in **Table 5.2**.

Table 5.2. Objective's min and max values and their differences

Criterion / Value	***P1***	***P2***	***P3***	***P4***	***N1***	***N2***	***N3***	***N4***
max	72	40	40	350	100	180	800	11149
min	32	30	10	120	25	114	482	629
(*max–min*)	40	10	30	230	75	66	318	10520

The *weighted sum* method requires multiplying each of the normalized objective functions by some weighting coefficients and summarizing them into a single objective function. Following this requirement the following optimization choice problem is defined:

$$\max\,(w_1P_1^*(x) + w_2P_2^*(x) + w_3P_3^*(x) + w_4P_4^*(x) + \\ + w_5N_1^*(x) + w_6N_2^*(x) + w_7N_3^*(x) + w_8N_4^*(x)) \tag{5.11}$$

subject to

$$P_j^*(x) = \sum_{i=1}^{15} P_{ji}^* x_i\,, \quad j = 1, 2, 3, 4; \tag{5.12}$$

$$N_k^*(x) = \sum_{i=1}^{15} N_{ki}^* x_i\,, \; k = 1, 2, 3, 4; \tag{5.13}$$

$$\sum_{i=1}^{15} x_i = 1\,, \; x_i \in \{0, 1\}; \tag{5.14}$$

$$\sum_{i=1} w_i = 1\,, \; 0 \le w_i \le 1, \tag{5.15}$$

where w_i = (1, 2,…, 8) are weighting coefficients for each of the objective functions. If $\sum_{i=1}^{8} w_i = 1$ and $0 \le w_i \le 1$, the weighted objectives sum is said to be a convex combination of objectives.

The solution of the transformed single objective optimization problem determines one particular Pareto optimal point. When weights are changed the *weighted sum* method defines different single objective optimization problem with different Pareto solutions points. Using of the *weighted sum* method is based on the decision-makers composite measure of importance across all the device parameters values, i.e., all criteria are weighted according to how important each is regarded in relation to the others. The weights represent a preference set for a particular DM and probably they will change with the different decision makers. For the goal of numerical experimentation some practical preferences of four imaginary users are chosen:

1) User 1 has equal preferences for all NVG parameters.
2) User 2 puts more weight on the price and weight then the other NVG parameters.
3) User 3 is interested in better NVG resolution but stresses much more on the NVG detection range and is less interested in the price and other parameters.
4) User 4 is equally keen on better NVG resolution, detection range and lower weight and price and is not interested at all in other parameters.

The corresponding sets of weight coefficients are shown in **Table 5.3**.

Table 5.3. Sets of weight coefficients

DM	w_1	w_2	w_3	w_4	w_5	w_6	w_7	w_8
DM-1	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125
DM-2	0.10	0.10	0.10	0.10	0.10	0.10	0.20	0.20
DM-3	0.20	0.10	0.10	0.30	0.05	0.10	0.10	0.05
DM-4	0.25	0.0	0.0	0.25	0.0	0.0	0.25	0.25

Four numerical tasks corresponding to the sets of weight coefficients from **Table 5.3** are formulated. Each table row defines particular optimization task – Task 1 (for set 1), Task 2 (for set 2), Task 3 (for set 3) and Task 4 (for set 4) following the model:

$$\max \Big(w_1 \sum_{i=1}^{15}\left(\frac{P_{i1}-32}{40}\right)x_i + w_2 \sum_{i=1}^{15}\left(\frac{P_{i2}-30}{10}\right)x_i + w_3 \sum_{i=1}^{15}\left(\frac{P_{i3}-10}{30}\right)x_i + w_4 \sum_{i=1}^{15}\left(\frac{P_{i4}-120}{230}\right)x_i + w_5 \sum_{i=1}^{15}\left(\frac{100-N_{i1}}{75}\right)x_i + w_6 \sum_{i=1}^{15}\left(\frac{180-N_{i2}}{66}\right)x_i + w_7 \sum_{i=1}^{15}\left(\frac{800-N_{i3}}{318}\right)x_i + w_8 \sum_{i=1}^{15}\left(\frac{11149-N_{i4}}{10520}\right)x_i\Big) \tag{5.16}$$

subject to

(5.17) $$\sum_{i=1}^{15} x_i = 1, \; x_i \in \{0, 1\},$$

(5.18) $$\sum_{i=1} w_i = 1, \; 0 \le w_i \le 1,$$

where P_{i1}, P_{i2}, P_{i3}, P_{i4}, are resolution, field of view, battery lifetime duration and working range values of the ***i***-th device from **Table 5.1**; N_{i1}, N_{i2}, N_{i3}, N_{i4} are objective focus range, length, weight and price values of the ***i***-th device and w_1, w_2, w_3, w_4, w_5, w_6, w_7 and w_8 are weight coefficients with values from corresponding row of **Table 5.3**. The task solutions define Pareto optimal choices shown in **Table 5.4**.

Table 5.4. Pareto optimal "unrestricted" NVG choices

Tasks	Resolu-tion, lp/mm	FOV, deg	BL, hours	R^d, m	FR, cm	Length mm	Weight g	Price, $	Chosen NVG from Table 5.1
Task 1	59	40	30	300	25	117	650	6052	No 8
Task 2	32	40	40	125	25	114	482	2699	No 3
Task 3	72	40	35	350	25	151	700	11149	No 15
Task 4	64	40	35	300	25	151	700	5685	No 14

The chosen devices satisfy the user amd meet user requirements of different parameters defined by their numerical weights. Four different choices are available as results of optimization tasks solution. If some user is not satisfied with the result of the choice he/she can try another weight coefficients combination. Due to the fact that this choice is done from a known finite discrete set of devices any weights combination satisfying (5.18) could be used to get a feasible Pareto optimal choice. In conclusion, the solved four numerical examples demonstrate the applicability of the proposed choice approach by adjusting to the different users' preferences choice strategy.

5.1.3. Multicriteria Optimization Model for Selection of NVD with Additional Restrictions

To refine more precisely the user preferences it is possible to add restrictions on some parameter values to comply with tighter DM preferences, i.e., to formulated a "restricted" choice problem. This means to extend the problem (5.5)-(5.8) by adding of restrictions for some NVG parameters. For example, price not to be bigger than some upper limit $Price_{max}$ and/or detection range above some lower limit $Det.Range_{min}$ and/or resolution with lower limit $Resolution_{min}$. Combinations of similar restrictions could define different optimization tasks denoted here as Tasks 1e, 2e, 3e and 4e (**Borissova et al., 2008**):

Task 1e. This modification of task 1 from section 5.1.2 has additional restrictions for lower limit of resolution and upper price limit:

$$\sum_{i=1}^{15} P_{i1} x_i \geq Resolution_{min} = 50, \qquad (5.19)$$

$$\sum_{i=1}^{15} N_{i4} x_i \leq Price_{max} = 5500; \qquad (5.20)$$

Task 2e. This task is similar to the task 2 with added restriction for the upper price limit:

$$\sum_{i=1}^{15} N_{i4} x_i \leq Price_{max} = 2500; \qquad (5.21)$$

Task 3e. This task is similar to the task 3 with additional three limitations about resolution, working range and price:

$$\sum_{i=1}^{15} P_{i1} x_i \geq Resolution_{min} = 50, \qquad (5.22)$$

$$\sum_{i=1}^{15} P_{i4} x_i \geq Range_{min} = 220, \qquad (5.23)$$

(5.24) $$\sum_{i=1}^{15} N_{i4}x_i \leq Price_{max} = 4000;$$

Task 4e. This task is similar to task 4 with two additional restrictions about the working range and price:

(5.25) $$\sum_{i=1}^{15} P_{i4}x_i \geq Range_{min} = 200,$$

(5.26) $$\sum_{i=1}^{15} N_{i4}x_i \leq Price_{max} = 5000.$$

The solutions of the formulated extended tasks (Tasks 1e, 2e, 3e, 4e) defining different NVG choices are shown in **Table 5.5**.

Table 5.5. Pareto-optimal "restricted" choices of NVG

Tasks	Resolu-tion, lp/mm	FOV deg	BL hours	R^d m	FR cm	Length mm	Weight g	Price $	Chosen NVG from Table 5.1
Task 1e	50	40	35	200	25	151	700	3995	No 13
Task 2e	41	40	35	200	25	151	700	2420	No 12
Task 3e	50	30	15	250	100	137	800	3696	No 6
Task 4e	64	30	15	300	100	137	800	4889	No 9

The "restricted" NVG choice approach allows more precisely refining of the user preferences by adding of restrictions for some NVG parameters. This is illustrated by solutions of Tasks 1e, 2e, 3e and 4e where different parameters numerical limits result in different devices choices.

The differences between the chosen devices in **Table 5.4** and **Table 5.5** demonstrate the influence of the additional parameters restrictions. Unlike the "unrestricted" choices described in section 5.1.2 introducing of some parameters restrictions or combinations of restrictions could result to unfeasible optimization tasks. It is evident that if those additional restrictions are unrealistic or their combinations cannot be satisfied by any particular device the choice will be impossible. It is the decision maker's expertise that could help to resolve that unfeasibility. Usually the software for optimization tasks solving provides some post optimization analysis that could help to define the unfeasible restrictions which should be changed appropriately.

Fig. 5.1 illustrates the comparison between the choice without restrictions and choice with restrictions.

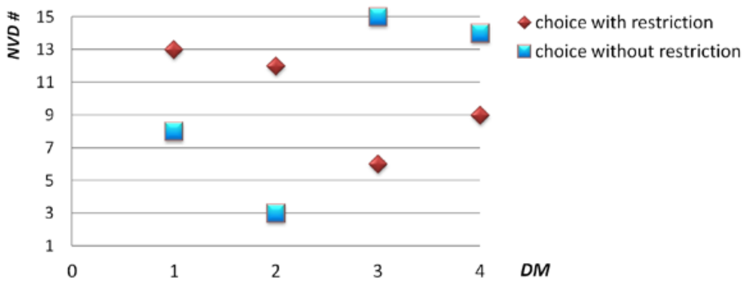


Fig. 5.1. Comparison between the choice without restrictions and choice with restrictions

The multicriteria optimization technique is decision aiding tools that do not replace the role of the decision-maker or its responsibility for the decision taking but is a good tool to supply reasonable alternatives to make a smart choice.

5.2. Multicriteria Optimization Model for Selection of NVD Taking into Account the External Surveillance Conditions

For more realistic selection of NVD it could be done by taking into account not only the user's preferences toward the parameters importance but as well the conditions under which the device will be used. The NVD catalog data are given for certain fixed external surveillance conditions. It is well known that the external surveillance conditions (ambient night illumination, atmosphere transmittance, contrast between the background and target, and type of surveillance target) directly affect the performance of NVD. Taking into account the changeable nature of surveillance conditions, the parameters of the devices measured in real conditions may differ from their catalog values.

There exist four external surveillance conditions (ESC) parameters that directly affect the NVD performance – *ambient light illumination, atmospheric transmittance*, *contrast between background* and *the surveillance target and surveillance target area*. The local weather patterns and an understanding of the effects on NVD performance are important for successful night vision observing. It is reasonable to describe shortly the ESC specifics and how they influence the NVD performance.

The visibility through the NVD is significantly affected by the illumination levels. The current night vision enhancement technology development has significantly improved the needed light-level requirements and the operational light level depends on the used image intensifier tube type. The most popular passive NVD use the natural illumination supplied by the moon and stars and the typical values used are 0.1 lx for full moon, 0.05 lx for half moon, 0.01 lx for quarter moon, 0.001 lx for starlight and 0.0001 lx for overcast. The NVD require some light to operate and provide less benefit in very low ambient light conditions.

Atmospheric conditions and consistence directly reflects to the air transmittance which is important factor to the image enhancement night vision technology. The light is absorbed, scattered, or refracted, either before or after it strikes terrain depending on the aerial media consistence and can reduce the usable energy available to the NVD. The NVD observing distance decreases by the low atmospheric transmittance. The atmospheric transmittance is limited in the range of 0.69 до 0.804 (**Indiso, 1970, Ohkawara, 2012**).

The contrast between the background and target is important to correctly interpret the NVD image. Any terrain that contains varying albedos (forests, cultivated fields, etc.) will likely increase the level of contrast in a NVD image. The contrast is defined as the difference in brightness between an object and its surrounding background and an object with 5% contrast is defined as "low contrast" and difficult to "see", whereas an object with 90% contrast is "high contrast" and easy to "see". The contrast between the background and surveillance target varies from 0.05 to 0.50.

Usually the surveillance target area is considered as known value in the cases when the surveillance object is of a particular type. For example, a standing man target area could be calculated using typical man height values between 1.6 m and 1.9 m and width of (0.60÷0.75) m. Generally speaking, the different objects have different dimensions and even for the known type of the surveillance targets their area is not fixed constant. The larger the object is, the easier is to see it. Different types of working range (detection, recognition and identification) are increased when that parameter has bigger values (**Borissova et al., 2006**).

NVD choice is usually based on some preliminary user requirements about the NVD performance parameters. The device working range is a function of the ESC and that dependence should be considered when trying to make a smart choice. To take into account the influence of the external surveillance conditions the developed in (**Borissova, Mustakerov, 2008**) model is modified by introducing the device working range as a function of the chosen device parameters and the values of expected external surveillance conditions instead of choosing of the working range among the known constant values (**Borissova, 2008**):

(5.27) $$\begin{aligned} &max\, P(\mathrm{x}) = P_1(x), P_2(x), \ldots, P_j(x))^{\mathrm{T}}, \\ &min\, N(\mathrm{x}) = N_1(x), N_2(x), \ldots, N_k\,(x))^{\mathrm{T}}, \end{aligned}$$

subject to

(5.28) $$R(x) = \sum_{i=1}^{I} x_i \sqrt{0.07 E \tau_a K A_t^* \frac{D_{in}^i f_{ob}^i \tau_{ob}^i \delta^i S^i}{\Phi_{\min}^i M^i}}\,,$$

(5.29) $$P_j(x) = \sum_{i=1}^{I} P_{ij} x_i\,,\ j = 1, 2, \ldots, \mathrm{J},$$

(5.30) $$N_k(x) = \sum_{i=1}^{I} N_{ik} x_i \,, \; k = 1, 2, \ldots, K,$$

(5.31) $$\sum_{i=1}^{I} x_i = 1 \,, \; x_i \in \{0, 1\},$$

where $R(x)$ is the calculated NVD working range using the values for: E – ambient light illumination in lx, τ_a – atmospheric transmittance, K – contrast, A_t^* – reduced target area in m^2, D_{in} – diameter of the inlet pupil in m, f_{ob} – objective focal length in mm, τ_{ob} – objective transmittance, S – IIT luminous sensitivity in A/lm, δ – IIT limiting resolution in lp/mm, $\Phi_{min.}$ – IIT photocathode limiting light flow in lm, M – IIT signal-to-noise ratio; $P_1(x), \ldots, P_J(x)$ are other the NVD parameters that should be maximized; $N_1(x), N_2(x), \ldots, N_K(x)$ are the NVD parameters that should be minimized; P_{ij} and N_{ik} represents the parameters values of each particular device as known constants; x = ($x_1, x_2, \ldots, x_I$) are binary integer variables corresponding to each device used to realize the choosing mechanism.

Other requirements about the NVD parameters could be added as additional objective functions or restrictions within the formulated model (5.27)-(5.31) to reflect different user requirements.

The expected ESC values for ambient night illumination, atmospheric transmittance, contrast between background and target and the target area are shown in **Table 5.6**.

Table 5.6. Expected external surveillance conditions (ESC)

ESC	**Light illumination E, lx**	**Atmospheric transmittance, τ_a**	**Contrast, K**	**Target area, A_t^*, m^2**
Set 1	0.01 (¼ moon)	0.75	0.20	0.758
Set 2	0.001 (starlight)	0.80	0.30	

The applicability of the proposed approach for NVD choice is illustrated by a numerical example of binocular NVG (night vision goggles) choice. The real parameters data of 10 particular NVG are shown in **Table 5.7**.

Table 5.7. NVG parameters data

No	Type of NVG	Resolution, lp/mm	Lens system	f, mm	Objective transmittance	SNR	IIT luminous sensitivity, A/lm	FOV, deg	Weight g	Price, $
1	Night Optics D-2MV	40	1:1.2	26	0.78	12	0.00024	40	482	650
2	Rigel 3250	30	1	35	0.78	12	0.00022	30	430	699
3	ATN Cougar-2	32-40	1:1.4	35	0.78	16	0.00031	30	800	3071
4	ATN Cougar CGTI	40-51	1:1.4	35	0.78	15	0.00035	30	800	3696
5	ATN Night Cougar-3	64	1:1.4	35	0.78	20	0.00087	30	800	4884
6	ATN Night Cougar-4	68	1:1.4	35	0.8	25	0.00115	30	800	9932
7	ATN PS-23-2	36-45	1:1.2	24	0.8	13	0.0007	40	700	3550
8	ATN PS-23-CGT	45-54	1:1.2	24	0.8	17	0.0011	40	700	4195
9	ATN PS-23-3	55-72	1:1.2	24	0.8	22	0.0016	40	700	5895
10	ATN PS-23-4	64-72	1:1.2	24	0.8	24	0.0019	40	700	12995

The proposed model (5.27)-(5.31) and data from **Table 5.6** and **Table 5.7** are used to define multicriteria optimization tasks solved by *weighted sum* method. This method requires *a priori* information about the user's preferences for different objectives importance, i.e., the weight coefficients values. The practical experience shows that some of the most preferable objectives from the user's point of view are the NVG *working range*, *price* and *weight* and in some cases other NVG parameters (for example – *field of view*). Two combinations of weight coefficients for objectives are chosen expressing the user preferences as shown in **Table 5.8**.

The weight coefficients combination (a) expresses the user importance ranking as: 1st – working range; 2nd – price; 3rd and 4th – field of view and weight. The combination (b) ranking is: 1st – device price; 2nd – working range; 3rd – field of view, and 4th – weight. Any other user preferences can be expressed by different weight coefficients.

Table 5.8. Objectives weight coefficients

DM preferences	Working range w1	Field of view w2	Price w3	Weight w4
DM-1	0.50	0.10	0.30	0.10
DM-2	0.25	0.20	0.50	0.05

The *weighted sum* method converts the multiobjective optimization problem to a single objective problem by introducing weights w_i to each normalized objective function and defining a scalarization objective function as (Borissova, 2008):

$$\max\left(w_1R^*(x) + w_2FOV^*(x) + w_3C^*(x) + w_4W^*(x)\right) \tag{5.32}$$

subject to

$$R^*(x) = \frac{\sum_{i=1}^{10} x_i \sqrt{0.07E\tau_a KA_t^* \frac{D_{in}^i f_{ob}^i \tau_{ob}^i \delta^i S^i}{\Phi_{\min}^i M^i}} - R_{\min}}{R_{\max} - R_{\min}}, \tag{5.33}$$

$$FOV^*(x) = \frac{\sum_{i=1}^{10} FOV_i x_i - FOV_{\min}}{FOV_{\max} - FOV_{\min}}, \tag{5.34}$$

$$C^*(x) = \frac{C_{\max} - \sum_{i=1}^{10} C_i x_i}{C_{\max} - C_{\min}}, \tag{5.35}$$

$$W^*(x) = \frac{W_{\max} - \sum_{i=1}^{10} W_i x_i}{W_{\max} - W_{\min}}, \tag{5.36}$$

(5.37) $$\sum_{i=1}^{10} x_i = 1,\ x_i \in \{0,\ 1\},$$

(5.38) $$\sum_{i=1} w_i = 1,\ 0 \le w_i \le 1,$$

where w_i are objective functions weight coefficients shown in **Table 3** and $R^*(x)$, $FOV^*(x)$, $C^*(x)$ and $W^*(x)$ are normalized objective functions.

Using *weighted sum* method and the information from **Tables 5.6**, **5.7** and **5.8** four transformed single criterion optimization tasks are solved corresponding to the given ESC and weight coefficients combinations. The tasks solutions and the chosen devices are shown in **Table 5.9**.

Table 5.9. Optimization choice results

External surveillance conditions (ESC)	Preferences	R, m	FOV, degree	C, $	W, g	Chosen NVG of Table 5.6
Set 1	DM-1	748	40	5895	700	No 9
	DM-2	335	40	650	482	No 1
Set 2	DM-1	187	40	5895	700	No 9
	DM-2	84	40	650	482	No 1

As it is seen from **Table 5.9** the different sets of ESC do not affect the devices choice but define different working ranges under different ESC. It is important to know what working range values to expect when choosing a proper device for particular ESC. If the user does not accept the expected working range values he could introduce some lower limit to consider. It is added as restriction to problem (5.33)-(5.38). For example, the restriction:

(5.39) $$R(x) \ge 500$$

added to (5.33)-(5.38) leads to choosing of other device as shown in **Table 5.10**.

Table 5.10. Optimization choice results with restrictions

External surveillance conditions	Preferences	R ≥ 500, m	FOV, degree	C, $	W, g	Chosen NVG of Table 5.6
Set 1	DM-1	748	40	5895	700	No 9
	DM-2	623	40	4195	700	No 8

The choice of the device No 9 for objective weights combination (a) satisfies the restriction (5.39) and is not affected by adding that restriction. Changing the objectives weight coefficients and introducing different user preferences as additional restrictions will refine the choice. Because of the discrete combinatorial nature of the NVG choice it is possible to have unfeasible problem when introducing such a kind of restrictions. In cases like that the introduced restrictions should be weakened as needed to get feasibility. For example, the task (5.33)-(5.38) is infeasible, i.e., it is impossible to satisfy (5.39) for the set 2 of ESC and the restriction (5.39) could be changed as $R(x) \geq 100$, for example. The post-optimization analysis provided by the most optimization software packages can be used to help in cases like that.

The comparison between the chosen devices from **Table 5.6** in the case of external surveillance condition defined as *set-1* for both decision makers (DM-1 and DM-2) are shown in **Fig. 5.2**.

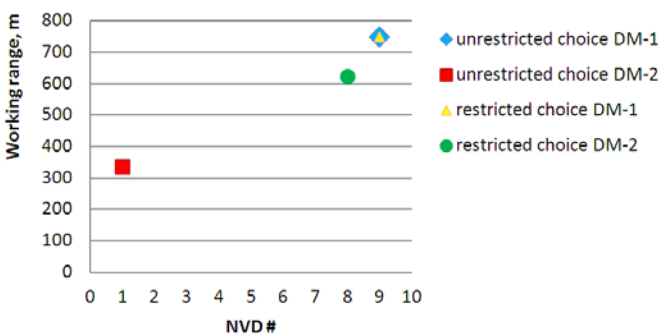


Fig. 5.2. Comparison between the choice without restrictions and choice with restrictions

Fig. 5.2 shows how different external surveillance condition together with DM preferences can influence to the choice of particular device. For example, comparing the selected device in case of DM-2 preferences, the "unrestricted" problem leads to choice of device #1, while modifying the problem by additional restriction about the NVD detection range bigger than 500 m under the same external surveillance condition defined as set-1, leads to choice of device #8.

The LINGO solver is used for optimization tasks solving. The solutions times of the described optimization problems are about few seconds using a typical PC. Other NVD parameters could be considered as objective functions to reflect the user requirements but the NVD working range is important if the external surveillance conditions are to be considered.

From a formal point of view, any Pareto-optimal solution is equally acceptable as is the solution of multicriteria optimization problem. In practice, only one solution is selected as a final decision and this is done by DM.

5.3. Multicriteria Optimization Model for k-Best NVD Selection

There are considerable advantages in making an explicit decision-aiding framework ensuring that all concerns are identified and addressed and the reasons behind a particular choice are made clear. The advantages of such a structured approach are particularly apparent where there are many alternative devices with numerous different parameters values. In some cases the user is interested in more than one alternative to make his final selection. To define k-best alternatives conforming to the given user preferences toward NVDs parameters a proper mathematical model is developed (**Borissova et al., 2013**). The aim of current model is to assist the user by selection of k-best devices in accordance to the importance of NVDs performance parameters. By a presented procedure for evaluation of deviation of each of k-best devices from the "ideal" solution this approach can contribute for more rational and efficient decision-making.

When choosing an NVD the user acts as a decision-maker (DM) and should consider all the relevant costs and benefits of the options for the set of devices to choose from. The preferred device should be this one which comes close to the decision maker's objectives, which often conflict. The performance of the NVDs depends on many parameters where the most essential are:

1) *working range* (*R*) of NVD depends on ambient light illumination, atmospheric transmittance, contrast between target and background, target area, diameter of the inlet pupil, objective focal length, objective transmittance, image intensifier tube (IIT) luminous sensitivity, IIT limiting resolution, IIT photocathode limiting light flow and signal-to-noise ratio;
2) *field of view* (*FOV*) is parameter defining the amount of visual information provided via the device. In principle, the larger the *FOV* is the more information is available;
3) *objective focus range* (*FR*) define the minimum focusing range of near objects;
4) *battery life* (*BL*) determine the operational time duration of devices according to used battery types and capacity and the current of image intensifier tube;
5) *weight* – currently most NVDs are portable devices and the weight is an important parameter that should be minimized.
6) *price* – a parameter that depends on used NVDs modules that is always worth to consider when making some decision choice.

The multicriteria approach fits to the situations in which users are not able to define a single goal function. On the other hand, mixed-integer optimization provides a powerful framework for mathematical modeling of many optimization problems that involve discrete and continuous variables. Therefore, the NVDs performance could be modeled as multicriteria mixed-integer optimization problem for determining of k-best selection of devices taking into account essential NVDs parameters (*working range, field of view, battery life*, *focus range, weight* and *price*) and external surveillance conditions as follows:

$$\max\{R, FOV, BL\} \quad \min\{FR, Weight, Price\} \tag{5.40}$$

subject to

$$R = \sum_{i=1}^{n} x_i \sqrt{0.07 E \tau_a K A_t^* \frac{D_{in}^i f_{ob}^i \tau_{ob}^i \delta^i S^i}{\Phi_{\min}^i M^i}}, \tag{5.41}$$

$$FOV = \sum_{i=1}^{n} FOV_i x_i, \tag{5.42}$$

$$BL = \sum_{i=1}^{n} BL_i x_i, \tag{5.43}$$

$$FR = \sum_{i=1}^{n} FR_i x_i, \tag{5.44}$$

$$Weight = \sum_{i=1}^{n} Weight_i x_i, \tag{5.45}$$

$$Price = \sum_{i=1}^{n} Price_i x_i, \tag{5.46}$$

$$\sum_{i=1}^{n} x_i = k, \ x_i \in \{0, 1\}, \tag{5.47}$$

$$1 < k < n, \tag{5.48}$$

where R is the NVD working range, E – ambient light illumination in lx, τ_a – atmospheric transmittance, C – contrast, A_t^* – reduced target area in m^2, D_{in} – diameter of the inlet pupil in m, f_{ob} – objective focal length in mm, τ_{ob} – objective transmittance, S – IIT luminous sensitivity in A/lm, δ – IIT limiting resolution in lp/mm, $\Phi_{min.}$ – IIT photocathode limiting light flow in lm, M – IIT signal-to-noise ratio; FOV – field of view, FR – objective focus range, BL – battery life (operational time duration of NVD), weight and price of NVD, x_i are binary integer variables corresponding to each device, k is integer decision variable determining the number of k-best devices to be found, and n is the number of devices to choose from.

The k-best alternatives are modeled by means of the decision variables x_i. The relation (5.47) of the decision variables is generalization of the classical optimization problem of finding a single solution. It contains as a special case the single-choice for $k = 1$. The inequality (5.48) is used to determine the number of best solutions, which can be 2, 3 or at most $(n – 1)$.

In relative ratio method for the multiple attributes decision making problems, a compromise alternative is determined based on the concept that the chosen alternative should be as close to the ideal solution as possible (**Li, 2009**). The selection process is based on evaluation of the alternatives with respect to the set of relevant criteria.

The problem of evaluation of alternatives in terms of their distance to the ideal solution can be seen as a "second-order" decision problem. After determining of k-best devices, when the user is interested to evaluate each of the chosen devices, the relative estimation between the "ideal" device and devices from the k-best set can be performed by following the procedure:

1) Determine the objective function value for an "ideal" (but nonexistent) device with all of its parameters at their optimal values;
2) Determine the objective function values for each device within the k-best set;
3) Determine the relative estimation for each device of k-best set compared to the "ideal" device.

To illustrate the applicability of the proposed approach, real parameters data for 10 night vision goggles are used as input data (**Table 5.11**) for a numerical example. To solve the formulated multicriteria problem (5.40)-(5.48) the normalization scheme (5.9) and (5.10) is used. Distinguish feature of this normalization scheme is that it provides the values for parameters between 0 and 1 based on the maximal and minimal objective values of each parameter. This normalization not only transforms data to have comparable values but also transforms the problem to a maximizing problem.

Table 5.11. NVD parameters

#	NVD	δ, lp/mm	f_{ob}, mm	D_{in}, mm	τ_{ob}	M	S, A/lm	FOV, degree	BL, hours	FR cm	Weight, g	Price, $
1	Night Optics D-2MV	40	26	21.67	0.78	12	0.00024	40	40	25	482	650
2	Rigel 3250	30	35	35	0.78	12	0.00022	30	30	25	430	699
3	ATN Cougar 2	32-40	35	25	0.78	16	0.00031	30	10-20	100	500	3071
4	ATN Cougar CGTI	45-54	35	25	0.78	15	0.00035	30	10-20	100	500	3696
5	ATN Night Cougar-3	64	35	25	0.78	20	0.00087	30	10-20	100	500	4884
6	ATN Night Cougar-4	64-72	35	25	0.80	25	0.00115	30	10-20	100	500	9932
7	ATN PS23-2	36-45	24	20	0.80	13	0.00070	40	60	25	700	3550
8	ATN PS23-CGT	45-54	24	20	0.80	17	0.00110	40	60	25	700	4195
9	ATN PS23-3	55-72	24	20	0.80	22	0.00160	40	35	25	700	5895
10	ATN PS23-4	64-72	24	20	0.80	24	0.00190	40	35	25	700	12995

The transformed by *weighted sum* method scalarization optimization problem for determining the k-best devices are defined as follows:

$$(5.49)\qquad max\left\{\begin{array}{l} w_1\dfrac{R-R_{\min}}{R_{\max}-R_{\min}}x_1+w_2\dfrac{FOV-FOV_{\min}}{FOV_{\max}-FOV_{\min}}x_2+w_3\dfrac{BL-BL_{\min}}{BL_{\max}-BL_{\min}}x_3+\\ +w_4\dfrac{FR_{\max}-FR}{FR_{\max}-FR_{\min}}x_4+w_5\dfrac{Weight_{\max}-Weight}{Weight_{\max}-Weight_{\min}}x_5+\\ +w_6\dfrac{Price_{\max}-Price}{Price_{\max}-Price_{\min}}x_6 \end{array}\right\}$$

$$(5.50)\qquad R=\sum_{i=1}^{10}x_i\sqrt{0.07E\tau_a CA_t^*\frac{D_{in}^i f_{ob}^i \tau_{ob}^i \delta^i S^i}{\Phi_{\min}^i M^i}},$$

(5.51) $$FOV = \sum_{i=1}^{10} FOV_i x_i \ ,$$

(5.52) $$BL = \sum_{i=1}^{10} BL_i x_i \ ,$$

(5.53) $$FR = \sum_{i=1}^{10} FR_i x_i \ ,$$

(5.54) $$Weight = \sum_{i=1}^{10} Weight_{\,i} x_i \ ,$$

(5.55) $$Price = \sum_{i=1}^{10} Price_i x_i \ ,$$

(5.56) $$\sum_{i=1}^{10} x_i = k \ , \ x_i \in \{0, 1\},$$

(5.57) $$1 < k < 10,$$

(5.58) $$\sum_{i=1}^{6} w_i = 1, \ 0 \le w_i \le 1,$$

where w_i are weighting coefficients for each of the normalized objective functions.

The proposed model defines k-best Pareto optimal solutions considering the importance of each criteria expressed by DM preferences. The applicability of the proposed approach is tested by four different sets of weighting coefficients reflecting four different DM types of preferences about importance of criteria as shown in **Table 5.12**.

Table 5.12. DM preferences

DM preferences	**Weighting coefficients**					
	w_1	w_2	w_3	w_4	w_5	w_6
DM-1	0.17	0.17	0.16	0.16	0.17	0.17
DM-2	0.30	0.03	0.04	0.03	0.30	0.30
DM-3	0.20	0.20	0.10	0.10	0.20	0.20
DM-4	0.30	0.00	0.00	0.10	0.30	0.30

First set of weighting coefficients (DM-1) expresses equivalent importance of all criteria – *detection range, field of view, battery life, focus range, price* and *weight.* The second set (DM-2) simulate the DM preferences emphasizing on *working range, weight* and *price*; the corresponding set for DM-3 reflect the preferences on *working range, field of view, weight* and *price* and DM-4 expresses the DM strong preferences about *working range, focus range, weight* and *price.*

The solutions of task (5.49)-(5.58) for different sets of weighting coefficients accordingly device numbering in **Table 5.12** for k = 3 and k = 5 best devices selections are illustrated in **Fig. 5.3**.

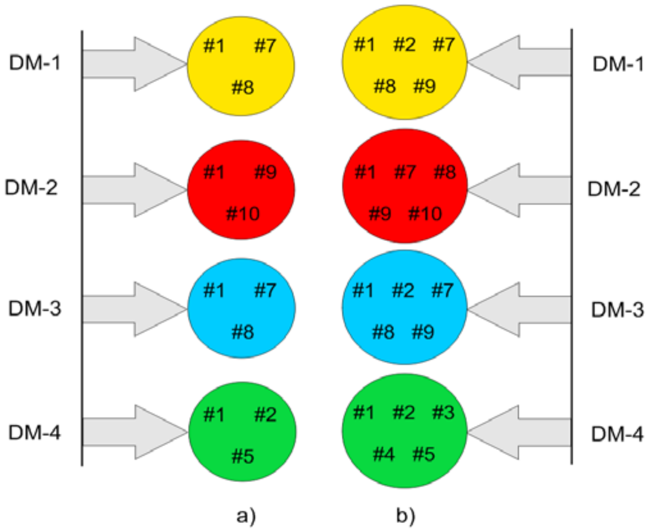


Fig. 5.3. k-best devices accordingly different DM preferences:
a) k = 3; b) k = 5

These groups of devices satisfy DM preferences expressed by defined weighted coefficients sets in **Table 5.12**. These k-best selections of devices could be the base from which the user can make his final choice decision. From the formal point of view, every Pareto-optimal solution is equally acceptable as solution to the multi-objective optimization problem. In practice, only one solution has to be chosen as final decision and this is realized by involvement of decision maker.

A proper procedure is proposed for helping the DM in taking of his final decision, by defining how far each of these k-best devices is from some imaginary "ideal" device:

- Step 1: Definition of an "ideal" device with "ideal" parameters, i.e., device whose parameters values have their optimal (maximal/minimal) values. Having in mind the normalization scheme, the objective function value of (12)-(14) for this "ideal" device is equal to 1.
- Step 2: Calculation of the objective function value for each of the selected k-best devices.
- Step 3: Subtract calculated value of objective function for each k-best device from objective function value of "ideal" device and determine in percentage the relative distance of devices from "ideal" one.

The results of execution of the described procedure for each of selected k-best devices are shown in **Table 5.13**, **Table 5.14**, **Table 5.15** and **Table 5.16**.

Table 5.13. Relative distances for DM-1 k-best devices

5-best devices selection	Objective function value	Relative distance in %
#1	0.629	37.02
#8	0.589	41.01
#7	0.584	41.56
#9	0.494	50.60
#2	0.457	54.27

Table 5.14. Relative distances for DM-2 k-best devices

5-best devices selection	Objective function value	Relative distance in %
#1	0.4545	54.55
#9	0.3567	64.33
#10	0.3541	64.59
#8	0.3538	64.62
#7	0.3300	67.00

Table 5.15. Relative distances for DM-3 k-best devices

5-best devices selection	Objective function value	Relative distance in %
#1	0.6037	39.63
#8	0.5175	48.25
#7	0.5110	48.90
#9	0.4539	54.61
#2	0.4204	57.96

Table 5.16. Relative distances for DM-4 k-best devices

5-best devices selection	Objective function value	Relative distance in %
#2	0.5306	46.94
#1	0.4723	52.77
#5	0.3578	64.22
#4	0.3550	64.50
#3	0.3116	68.84

Imposing the DM-1 preferences, where all NVDs parameters are considered as of equal importance, the results show that the device #1 has minimal deviation from the ideal solution followed by devices #8, #7 and #2. In case of DM-2 preferences minimal deviation from the ideal solution also has device #1 followed by devices #9, #10, #8 and #7. For DM-3 preferences the order of devices is #1, #8, #7, #9 and #2 and for DM-4 set of weightings the devices are ranked as #2, #1, #5, #4 and #3.

The relative distances for determined k-best devices for different sets of weighting coefficients (different DM preferences) comparing the alternatives in terms of their rank acceptability are shown in **Fig. 5.4**.

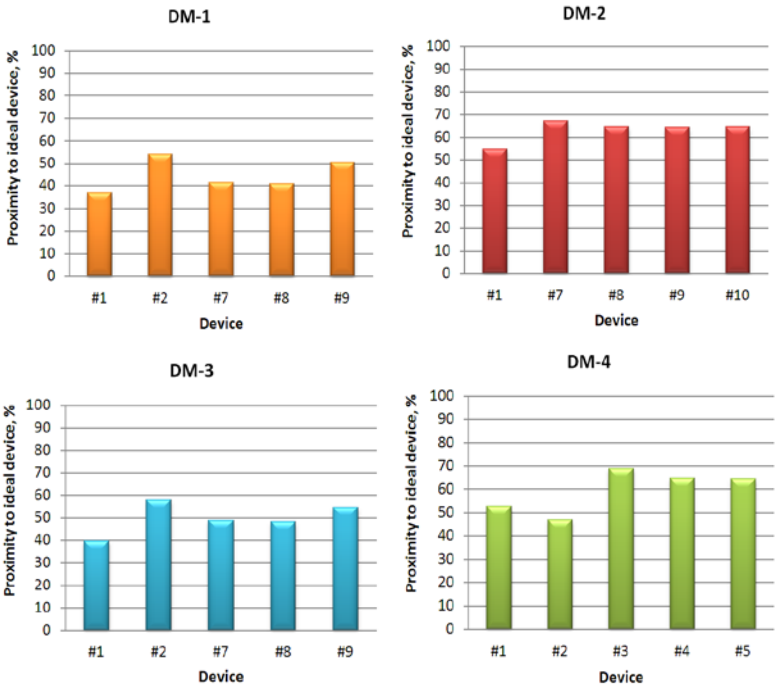


Fig. 5.4. Relative estimations of k-best NVDs for different DM preferences

As it is seen from **Fig. 5.4**, the proximity of devices to the "ideal" depends on given DM preferences. Some of the devices in particular k-best selections are close to the "ideal" then others and could be considered as a good reasonable choice. For example, for DM-1 selection of devices 1, 7, 8, the device #1 is closest to the "ideal" and devices #7 and #8 have almost the same deviation from the “ideal”. The same is valid for DM-3 k-best selections. Using the information of relative estimations for NVDs k-best selections to analyze the results, the DM could make his final choice in more informed and reasonable way. Increasing the number of devices and their diversity will increase the variety of choices but will also increase the tasks sizes and their computational complexity.

Despite the fact that mixed integer nonlinear problems are difficult to solve (in general they are NP-complete), the formulated optimization problem and its numerical results show quite acceptable solution times.

Chapter 6

Approaches for Determination of Surveillance Conditions in Relation to NVD Performance

The working range is one of the most significant parameter of night vision devices, given in catalogue datasheets. The NVD working range depends both on NVD parameters and external surveillance conditions. On the other hand, the NVD catalog data are given for certain fixed external surveillance conditions. It is interesting to explore different combinations of external surveillance conditions which correspond to given working range of night vision devices.

6.1. Multicriteria Model for Exploring Combinations of External Surveillance Conditions Conforming the Given NVD Working Range

From the user's point of view it is interesting to know what combinations of the external surveillance conditions values would correspond to the working range data listed in catalogue datasheets. To define such sets of external surveillance conditions values a multicriteria optimization problem is formulated (**Borissova, Mustakerov, 2009**):

(6.1)
$$\begin{cases} min\, E \\ min\, K \\ min\, \tau_a \end{cases}$$

subject to

(6.2)
$$\sqrt{\frac{0.07 D_{in} f_{ob} \tau_o S_\Sigma \delta E \tau_a K A'_{ob}}{M \Phi_{\min.ph}}} = R^* \text{ ,}$$

(6.3)
$$E^l \le E \le E^u \text{ ,}$$

(6.4)
$$\tau_a^l \le \tau_a \le \tau_a^u \text{ ,}$$

(6.5)
$$K^l \le K \le K^u \text{ ,}$$

where R^* is the given detection range in meters for standing man target, E^u, $\tau_a{}^u$, K^u are upper and lower E^l, $\tau_a{}^l$, K^l limits for the ambient light illumination, atmosphere transmittance and contrast.

The formulated multicriteria nonlinear optimization problem (6.1)-(6.5) is used to calculate combinations of values of the external surveillance conditions satisfying the equality (6.2). For the goal of numerical experiments the most widely used type NVD, i.e., night vision goggles (NVG) are considered with the following parameters:

- image intensifier tube *Gen. 3 US* with limiting resolution of δ = 68 lp/mm, photocathode sensitivity 0.0019 A/lm, signal-to-noise ratio M = 25 and photocathode sensitivity 4.10^{-13} lx,
- objective with inlet pupil diameter of D_{in} = 0.018 m, focal length f_{ob} = 26 mm and objective transmittance τ_o = 0.8,
- NVG detecting range R^* = 325 m.

The values of external surveillance conditions parameters in question are:

- night illumination E within interval $0.0001 \le E \le 0.01$,
- atmosphere transmittance τ_a within interval $0.65 \le \tau_a \le 0.80$,

- contrast K between surveillance target and background within interval $0.1 \le K \le 0.5$,
- the reduced target area for standing men is $A'_{ob} = 0.72$ m^2.

The use of the *weighted sum* method for solution of the formulated multicriteria optimization task leads to following single criterion task:

(6.6) $$min\ (w_1E' + w_2K' + w_3\tau_a'),$$

subject to

(6.7) $$0.0001 \le E \le 0.01,$$

(6.8) $$0.01 \le K \le 0.05,$$

(6.9) $$0.65 \le \tau_a \le 0.80,$$

(6.10) $$\sum_i w_i = 1,$$

where $E' = \dfrac{E - 0.01}{0.01 - 0.0001}$, $K' = \dfrac{K - 0.5}{0.5 - 0.1}$ and $\tau_a' = \dfrac{\tau_a - 0.80}{0.80 - 0.65}$ are the normalized objective functions.

As it was described previously the *weighted sum* method scalarizes a set of objectives into a single objective by pre-multiplying each objective with a user-supplied weight coefficient. The relative importance of each objective function is reflected by those coefficients w_i.

Three different cases of weight coefficients reflecting user requirements about the external surveillance conditions are investigated.

- *case 1.* This case is based on objective function (6.6) and restrictions (6.7)-(6.9) and considers the whole practical range of external surveillance conditions values.
- *case 2.* Here some of the external surveillance conditions are limited in given boundaries.
- *case 3.* This case is focused on combinations of external surveillance conditions where some of them are fixed with given values.

The optimization tasks solutions define external surveillance conditions combinations conforming to detection range of the given target for each of these cases. The results for case 1 are shown in **Table 6.1**.

Table 6.1. Weight coefficients and solution results for case 1

No	w_1	w_2	w_3	**E**, lux	**K**	τ_a	**R**, m
1	0.34	0.33	0.33	0.00400	0.166	0.65	325
2	0.60	0.30	0.1	0.00287	0.232	0.65	
3	0.10	0.60	0.30	0.00666	0.100	0.65	
4	0.30	0.10	0.60	0.00261	0.237	0.70	
5	0.10	0.10	0.80	0.00413	0.150	0.70	
6	0.10	0.80	0.10	0.00413	0.150	0.70	
7	0.80	0.10	0. 10	0.00159	0.387	0.70	

The solution results in **Table 6.1** give different combinations for ambient night illumination and contrast between background and target. The atmosphere transmittance has relatively small feasible interval which defines the lowest possible value. Different weight coefficients (reflecting the user importance about the particular external surveillance conditions) lead to different combination of values of external surveillance conditions conforming to the given NVG detecting range.

The results from second case when some limits for external surveillance conditions are imposed are shown in **Table 6.2**.

Table 6.2. Weight coefficients and solution results for case 2

No	w_1	w_2	w_3	**E**, lux	**K**	τ_a	**R**, m
1	0.34	0.33	0.33	0.00413	0.15	0.7	325
2	0.6	0.3	0.1	0.00319	0.194		
3	0.1	0.6	0.3	0.00413	0.15		
4	0.3	0.1	0.6	0.00261	0.237		
5	0.1	0.1	0.8	0.00413	0.15		
6	0.1	0.8	0.1	0.00413	0.15		
7	0.8	0.1	0. 1	0.00159	0.387		

When some preliminary information about the expected values of the external surveillance conditions exists they can be restricted within some narrower limits. That case is numerically tested for narrowed intervals for contrast K and atmosphere transmittance τ_a using the same sets of weight coefficients as in the first case. That reflects in the solutions of corresponding optimization tasks (see **Table 6.2**) that define different combinations of the surveillance conditions for the given NVG detecting range.

The results from third case when atmospheric transmittance is considered with some fixed value are shown in **Table 6.3**.

Table 6.3. Weight coefficients and solution results for case 3

No	$\mathbf{w_1}$	$\mathbf{w_2}$	**E**, lux	**K**	$\boldsymbol{\tau_a}$	**R**, m
1	0.5	0.5	0.00383	0.153	0.73	325
2	0.7	0.3	0.00251	0.236		
3	0.3	0.7	0.00585	0.100		

In some practical cases, some of the external surveillance conditions could be considered as known with fixed values. The proposed approach was tested with fixed value about the atmospheric transmittance $\tau_a = 0.73$ using three different combinations of weight coefficients. The solution's results define different combinations of night illumination and contrast values to balance the fixed atmospheric transmittance τ_a value for given working range (**Table 6.3**). It is possible to give fixed values for other external surveillance conditions to investigate the possible combinations satisfying the given NVG working range. Sometimes that could lead to unfeasible optimization task formulation. Changing the given fixed values and experimentation with them will help to overcome such kind of problems.

6.2. Method for Determining of Ambient Night Illumination and Contrast Feasible Range in Relation to NVDs Performance

The performance of passive NVDs is a function of internal and external parameters as (**Borissova, Mustakerov, 2008**; **Borissova, Mustakerov, 2009**):

- limiting resolution of IIT – a measure of how many lines of varying intensity (light to dark) can be resolved within a millimeter of screen area;
- signal-to-noise ratio – determines the low-light resolution capability and measures the light signal reaching the eye, divided by the perceived noise as seen by the eye (**Higginbotham, 2006**; **Riegler et al., 1991**);
- IIT photocathode's sensitivity – the ability of photocathode material to produce an electrical response when subjected to light photons (**Task, 1992**);
- optical system f-number – represents the ratio of the focal length of the lens to the diameter of the entrance pupil (**Borissova, Mustakerov, 2008**);
- ambient light illumination – the passive NVD uses available ambient light as starlight, moonlight and sky glow from distant manmade sources – city lights, etc. (**Marasco et al., 2003**);
- atmospheric transmittance – depends on the air temperature, atmospheric pressure, relative humidity, number and size distribution of atmospheric aerosols, concentration of abnormal atmospheric constituents such as smoke, dust, exhaust fumes, chemical effluents, and refractive indices of all types of aerosol in the optical path (**Indiso, 1970**; **Ohkawara, 2012**);
- contrast between the background and surveillance target – monochromatic contrast difference between the integrated target and background intensities;

- type of surveillance target (**Borissova, Mustakerov, 2006**; **Russell, Lombardo, 1998**).

Most of the internal parameters are shown in catalog datasheets. The NVD working range mentioned in catalog is defined under specific external surveillance conditions that in most cases are not specified. It is possible to investigate the feasible ranges of variation of the external surveillance conditions that correspond to the given NVD performance to help the user to compensate the missing or incomplete information.

The functional dependence of NVDs performance of internal parameters and external surveillance conditions is expressed analytically via the formulation proposed by the authors' (**Borissova,** & **Mustakerov, 2006**; **Borissova,** & **Mustakerov, 2009**):

(6.11)
$$R^2 = \left(\frac{0.07 D_{in} f_{ob} \tau_{ob} \tau_a S \delta E K A_{target}}{M \Phi_{min.ph}} \right),$$

where: R – working range in m; D_{in} – objective diameter inlet pupil in m; f_{ob} – objective focal length in mm, τ_a, τ_{ob} – atmosphere and objective transmittance, dimensionless; $\Phi_{min.ph}$ – image intensifier tube photocathode limiting light flow in lm; δ – IIT limiting resolution in lp/mm, S – IIT luminous sensitivity in A/lm, M – IIT' signal-to-noise ratio, dimensionless; E – ambient light illumination in lx; K – contrast, dimensionless; A_{target} – reduced target area in m^2 (**Borissova, Mustakerov, 2006**; **Russell, Lombardo, 1998**).

The atmosphere transmittance varies within narrow interval of (0.712-0.804) for spectral interval of NVD (**Indiso, 1970**). From 1933 to the late 1940s, the transmittance remained stable at around 0.74 to 0.75, in the mid-1980s it reached 0.69 and then began to increase till the early 2000s marking the level of 0.71 (**Ohkawara, 2012**). Because of that, the atmosphere transmittance could be considered as a constant.

The relation (6.11) can be used to define different combinations of external surveillance conditions corresponding to given NVDs performance. The values of minimal ambient light illumination and maximal contrast between target and background and vice versa represent two boundary points for particular target and working range. They cannot be determined from (1) because for known NVDs performance this formulation cannot be solved for two unknown variables. The theoretical minimal or maximal values of illumination and contrast in (1) could not be feasible for the given NVDs performance. The two boundaries of illumination and contrast under particular target and working range can be determined by using of multicriteria problem formulation.

One feasible boundary point corresponds to maximum of external ambient night illumination and minimum of contrast between target and background. It can be determined by solving the multicriteria **Problem 1**:

$$\text{(6.12)} \qquad \begin{cases} max\, E = \left(\dfrac{R^2 M \Phi_{min.ph}}{0.07 D_{in} f_{ob} \tau_{ob} S_{\Sigma} \delta \tau_a K A_{target}} \right) \\ min\, K = \left(\dfrac{R^2 M \Phi_{min.ph}}{0.07 D_{in} f_{ob} \tau_{ob} S_{\Sigma} \delta \tau_a E A_{target}} \right) \end{cases}$$

subject to

$$\text{(6.13)} \qquad E^l \le E \le E^u ,$$

$$\text{(6.14)} \qquad K^l \le K \le K^u ,$$

$$\text{(6.15)} \qquad A^l \le A_{target} \le A^u ,$$

where E^u, K^u, A^u and E^l, K^l, A^l are upper and lower boundaries for the ambient light illumination, contrast and reduced target area; R is given detection range in meters; M, $\Phi_{min.ph}$, D_{in}, f_{ob}, τ_{ob}, S_{Σ}, and δ are constants that depend on particular NVDs performance.

The other boundary point corresponding to minimal ambient night illumination and maximal contrast can be defined by solution of the **Problem 2:**

(6.16) $$\begin{cases} max\,\mathrm{K} = \left(\dfrac{R^2 M\Phi_{min.ph}}{0.07 D_{in} f_{ob} \tau_{ob} S_{\Sigma} \delta \tau_a E A_{target}} \right) \\ min\,E = \left(\dfrac{R^2 M\Phi_{min.ph}}{0.07 D_{in} f_{ob} \tau_{ob} S_{\Sigma} \delta \tau_a K A_{target}} \right) \end{cases}$$

subject to (6.13)-(6.15).

The formulated in this way **Problem 1** and **Problem 2** are integrated in the following algorithmic approach for determination of the feasible ranges of surveillance conditions in relation to NVDs performance as shown in **Fig. 6.1** (**Borissova et al., 2014**).

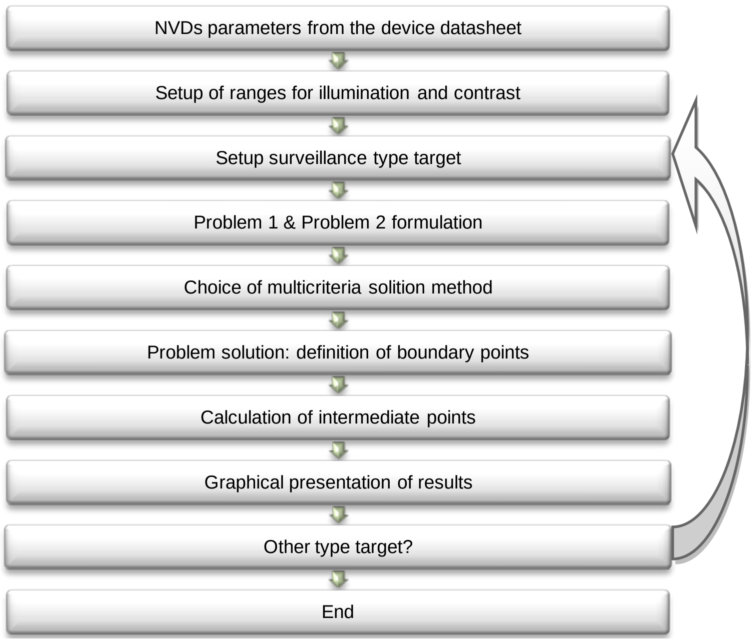


Fig. 6.1. Determination of the feasible ranges of surveillance conditions in relation to NVDs performance

At the first stage, the internal NVDs parameters data from the device datasheet are to be collected. At the next stage, the values for upper and lower boundaries of ambient light illumination and contrast are set up. Next, surveillance target type is defined (for example – standing man or jeep, or tank, etc.). Then, the **Problem 1** – for maximum of external ambient light illumination and minimum of contrast between target and background, and **Problem 2** – for minimal ambient light illumination and maximal contrast, are formulated.

The solutions of the formulated problems by a proper multicriteria optimization solution method define two boundary combinations of ambient light illumination and contrast, conforming to the given NVDs performance. The type of curve following the dependency from the equation (6.11) simplified as $E \sim 1/K$ or $K \sim 1/E$, and can be illustrated as shown in **Fig. 6.2**.

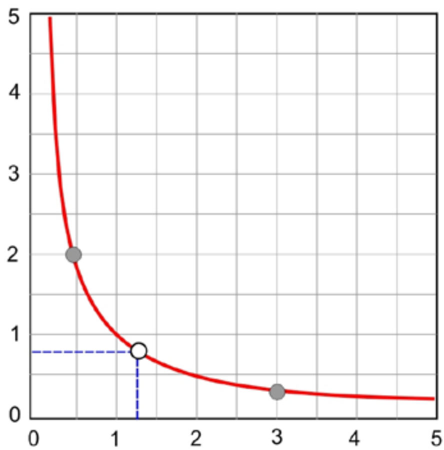


Fig. 6.2. Simplified dependency for E ~ 1/K (K ~ 1/E)

It is an example of rectangular hyperbola or so called reciprocal function ($y = 1/x$). The defined boundary points and some intermediate points calculated by (6.11) present graphically all feasible combinations of night illumination and contrast for given NVD performance. This graphical presentation can be used to define particular value for illumination (contrast) for some given value of contrast (illumination) – see **Fig. 6.2**. At the last stage, NVDs performance can be explored toward other surveillance target types if needed. Using this approach allows exploring different combinations of external surveillance conditions complying with the catalogue data for NVD performance.

The proposed approach for determination of the surveillance conditions in relation to NVDs performance is verified numerically for two types of NVDs – night vision goggles and weapon sight, with catalog data in **Table 6.4**.

Table 6.4. Night vision devices catalog data

Limiting resolution lp/mm	**Signal-to-noise ratio, *dimensionless***	**Photocathode sensitivity, A/lm**	**Objective inlet pupil diameter, m**	**Focal length, mm**	**Detection range, m**
Night Vision Goggles – MVP-MV14BGP*					
64	21	0.001350	0.018	25	300
Weapon Sight – MV-740**					
64	24	0.001800	0.018	100	425

* http://www.morovision.com/night_vision_goggles/MVP-MV-14BGP.htm
** http://morovision.com/weapons_sights/MVPA-MV-740-3P.htm

For both devices, objective transmittance is considered to be equal to 0.80, the minimal photocathode sensitivity of 3.4×10^{-12} A/lm and atmosphere transmittance of 0.71. The external surveillance conditions vary within following boundaries:

- night illumination E is changed within interval from overcast night sky illumination (starlight) to full moon illumination ($0.00013 \leq E \leq 0.013$ lux);
- contrast K between surveillance target type and background is limited within interval of $0.1 \leq K \leq 0.5$;
- reduced target area according to the Johnson' criteria (**Russell, Lombardo, 1998**) for different targets: 1) standing man

(A_{man} = 0.72 m^2), 2) jeep (A_{jeep} = 2,47 m^2); 3) truck (A_{truck} = 5.9 m^2), and 4) tank (A_{tank} = 10 m^2).

For the goal of methodology numerical verification, the *weighted sum* method (**Marler, Arora, 2010**) is chosen to solve the formulated multicriteria problems. The original **Problem 1** and **Problem 2** are transformed to single criterion tasks as:

Task 1:

$$max\ (w_1E' + w_2K') \tag{6.17}$$

subject to (6.13) – (6.15) and

$$\sum_i w_i = 1, \tag{6.18}$$

where $E' = \frac{E - E^{\min}}{E^{\max} - E^{\min}}$ and $K' = \frac{K^{\max} - K}{K^{\max} - K^{\min}}$ are normalized objectives (**Marler, Arora, 2010**).

Task 2:

$$max\ (w_1E' + w_2K') \tag{6.19}$$

subject to (6.13) – (6.15) and

$$\sum_i w_i = 1, \tag{6.20}$$

where $E' = \frac{E^{\max} - E}{E^{\max} - E^{\min}}$ and $K' = \frac{K - K^{\min}}{K^{\max} - K^{\min}}$ are normalized objectives (**Marler, Arora, 2010**).

The solutions results of **Task 1** and **Task 2** shown in **Table 6.5** define boundary points for illumination and contrast for 4 type of surveillance targets – *standing man*, *jeep*, *truck* and *tank*.

Table 6.5. The solution results for boundary points of night illumination and contrast

NVDs	Target type	Illumination, lux	Contrast, *dimensionless*	Given detection range, m
Night vision goggles MVP-MV14BGP	*Task 1: (max E, min K, w_1=0.50, w_2=0.50)*			
	standing man (A_{man} = 0.72)	0.0130000	0.44	300
	jeep (A_{jeep} = 2.47)	0.0130000	0.13	300
	truck (A_{truck} = 5.9)	0.0007045	0.10	300
	tank (A_{tank} = 10)	0.0041568	0.10	300
	Task 2: (min E, max K, w_1=0.50, w_2=0.50)			
	standing man (A_{man} = 0.72)	0.011547	0.50	300
	jeep (A_{jeep} = 2.47)	0.003365	0.50	300
	truck (A_{truck} = 5.9)	0.001409	0.50	300
	tank (A_{tank} = 10)	0.000831	0.50	300
	Task 1: (max E, min K, w_1=0.50, w_2=0.50)			
Weapon sight MV-740	*standing man (A_{man} = 0.72)*	0.001000	0.25	425
	jeep (A_{jeep} = 2.47)	0.007237	0.10	425
	truck (A_{truck} = 5.9)	0.003030	0.10	425
	tank (A_{tank} = 10)	0.001787	0.10	425
	Task 2: (min E, max K, w_1=0.50, w_2=0.50)			
	standing man (A_{man} = 0.72)	0.004965	0.50	425
	jeep (A_{jeep} = 2.47)	0.001447	0.50	425
	truck (A_{truck} = 5.9)	0.000606	0.50	425
	tank (A_{tank} = 10)	0.000357	0.50	425

The data from **Table 6.5** is used to represent graphically the dependency of night illumination and contrast for tested two types of night vision devices under 4 different surveillance target types as shown in **Fig. 6.3** and **Fig. 6.4**.

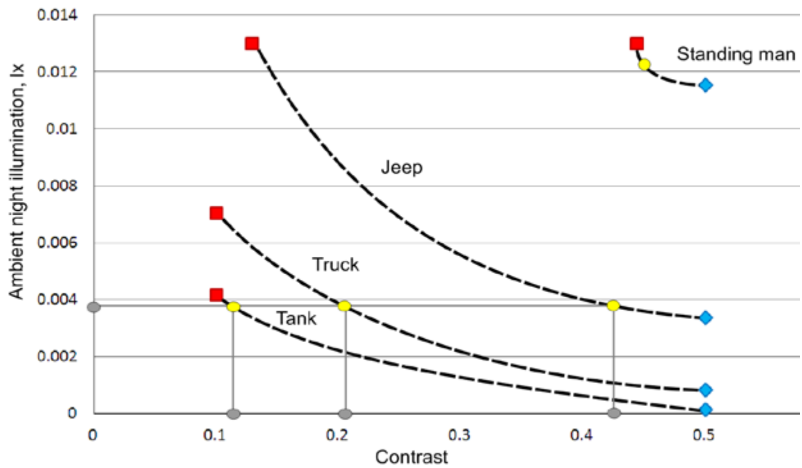


Fig. 6.3. The dependency of ambient night illumination and contrast for MVP-MV14BGP performance

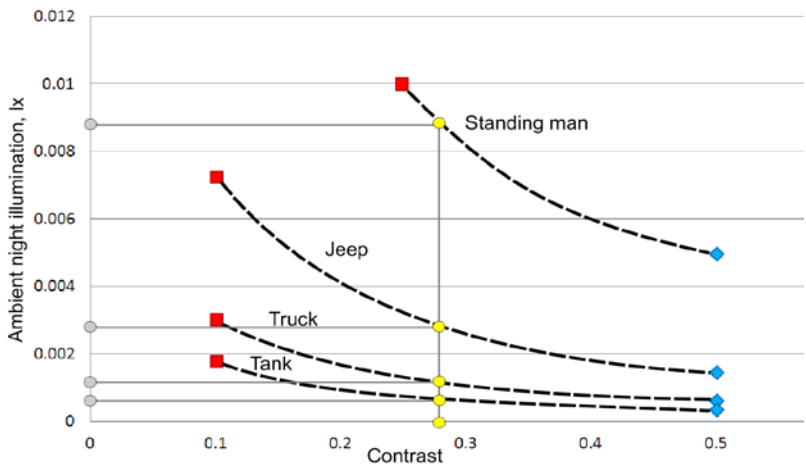


Fig. 6.4. The dependency of ambient night illumination and contrast for MV-740 performance

As could be seen from **Fig. 6.2** and **Fig 6.3** there exists more than one combination of night illumination and contrast for given type of target conforming to the given NVDs performance. Using these curves it is possible to estimate the effectiveness of particular NVD toward different combinations of night illumination and contrast. For example, if night illumination is 0.0038 (**Fig. 6.3**), the goggles detection range of 300 m can be provided for contrast of: 0.12 (tank), 0.21 (truck) and 0.42 (jeep). As it can be seen from **Fig. 6.3**, the detection of standing man is impossible for this value of illumination. If contrast is fixed to 0.28 (**Fig. 6.4**), the weapon sight detection range of 425 m is achieved for illumination of 0.0005 for tank, 0.001 for truck, 0.0024 for jeep and 0.0088 for standing man. If other values of illumination or contrast are to be considered, the performance of given NVD can be estimated roughly in advance by similar graphical representations. The exact estimations can be done by calculation of the corresponding intermediate points using the relation (6.11).

The described approach allows determining the theoretical estimations for the variation ranges of contrast and ambient night illumination under given type of surveillance target for a particular given device. Using the graphical representation of these variation ranges the effectiveness of NVD accordingly its catalog specifications can be assessed visually. Such assessments are important for the practical application of NVD as catalog data are often incomplete.

Conclusion

In the monograph the most popular passive NVD based on image intensifier technology are investigated. The different types of NVD and their elements are briefly introduced. The basic NVD parameters and their relation to each other are defined. A formula for theoretical estimation of NVD working range is proposed based on parameters of individual parameters of the optoelectronic channel modules and parameters of external surveillance conditions. The parameters of optoelectronic channel modules together with external surveillance conditions are used to formulate deterministic and stochastic optimization models. These models are the basis for deterministic and stochastic optimization tasks formulation to determine the Pareto-optimal combination of modules for NVD optoelectronic channel. Some of the proposed models are modified to take into account the DM preferences toward the designed device.

Three methods for designing of NVD are proposed – iterative, rational and optimal. The iterative method allows the DM to select the NVD modules and to evaluate the parameters of designed device. The concept of the rational choice method coincides largely with that used in multicriteria optimization for rational or satisfactory assessment. Rational decision making means that DM does not optimize any objective function but tries to reach the satisfactory levels of certain criteria. In the most general case, the resulting solutions are not optimal but can be considered as rational or satisfactory solutions. The method of optimal choice implements the formulated optimization problems and the defined configuration of modules is optimal in the sense of given quality criteria for optoelectronic channel of NVD.

The multicriteria models for selection of devices for night vision from a given set of devices – without additional restrictions and with given additional boundary limits for the device parameters are proposed. A multicriteria model for selection of NVD taking into account the external surveillance conditions is presented too. A multicriteria optimization model is used to assist the user choice by selection of k-best devices in accordance to the importance of NVDs performance parameters. By a presented procedure for evaluation of deviation of each of the k-best devices from the "ideal" solution this approach can contribute for more rational and efficient decision-making.

A multicriteria optimization model is formulated to determine sets of different combinations of the external surveillance conditions values for which the NVD working range shown in catalogue data can be valid. By the use of other formulation of multicriteria optimization model it is possible not only to obtain some to external surveillance conditions (ESC) values conforming to the NVD working range, but also to determine the boundary conditions for the ESC.

The described iterative and rational methods for selection and assessment of parameters of designed NVD are implemented in a Web-based application. The architecture of developed prototype application is based on using AJAX technology.

Future investigations of the NVD are to be considered on the developments and application of new fusion technology where thermal imaging and image intensification technology are being combined together.

List of Abbreviations

A_{in} – area of inlet pupil,
A_{ob} – target area,
A'_{ob} – reduced target area,
AS_{ob} – objective spherical aberration,
AA_{ob} – objective astigmatism,
AD_{ob} – objective distortion,
AC_{ob} – objective curvature of field,
AS_{oc} – ocular spherical aberration,
AA_{oc} – ocular astigmatism,
AD_{oc} – ocular distortion,
AC_{oc} – ocular curvature of field,
A^{st}_{ob} – mathematical expectation for target area,
$A^{st\prime}_{ob}$ – mathematical expectation for reduced target area
C_{IIT} – price of IIT,
C_{ob} – price of objective,
C_{oc} – price of ocular,
C – price of opto-electronics channel,
D_{phIIT} – diameter of the IIT photocathode,
D_{in} – diameter of inlet pupil,
DM – decision maker,
E – ambient night illumination,
ER – eye relief,
E^{st} – mathematical expectation for ambient night illumination,
FOP – fiber optic plate,
FOV – field of view,
FOM – figure of merit,
FR – focus range,
IIT – image intensifier tube,
K – contrast between target and background,
K_{IIT} – generalized parameter for IIT quality,
K_{ob} – generalized parameter for objective quality,
K^{st} – mathematical expectation for contrast,
L_b – background brightness,
M – signal-to-noise ratio,

MCP – microchannel plate,
NVB – night vision binoculars,
NVD – night vision devices,
NVG – night vision goggles,
NVS – night vision scopes,
Q – generalized criterion for NVD quality,
R – working range,
R^d – detection range,
R^{or} – orientation range,
R^r – recognition range,
R^i – identification range,
S – IIT luminous sensitivity,
T_{IIT} – weight of IIT,
T_{ob} – weight of objective,
T_{oc} – weight of ocular,
T – weight of opto-electronc channel,
T_a^{st} – mathematical expectation for atmosphere transmittance,
W_{ob} – objective field of view,
W_{oc} – ocular field of view,
Γ – magnification,
f_{ob} – objective focal length,
f_{oc} – ocular focal length,
$f\#$ – *f*-number,
Φ – light flow,
$\Phi_{b.eff}$ – effective background flow,
$\Phi_{ob.eff}$ – effective flow from the object,
$\Phi_{th.ph}$ – IIT threshold sensitivity,
$\Phi_{\Sigma eff}$ – total flow from object and background,
δ_{IIT} – IIT limiting resolution,
γ – device resolution,
$\varphi(\lambda)$ – spectral sensitivity,
$\rho_b(\lambda)$ – spectral reflectance of the background,
$\rho_{ob}(\lambda)$ – spectral reflectance of the object,
τ_a – atmosphere transmittance,
τ_o – optical transmittance

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Daniela Borissova

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Reviewed by:
Acad. Ivan Popchev
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Daniela Borissova received M.Sc. degree from the St. Kliment Ohridski University of Sofia with specialization in "Quantum Electronics and Laser Technology" in 1994, followed by Ph.D. from the Institute of Information Technologies at Bulgarian Academy of Sciences (BAS) in 2007. From 1994 she works at the Institute of Information and Communication Technologies at BAS where she is currently associate professor. She has specializations in Canada, Norway, Albania and the Czech Republic. Her main research interests are related to modeling and optimization of night vision devices, information systems, e-learning, web design and development of web-based applications.

The monograph is based on original research in the field of night vision devices (NVD) working on the principle of light amplification. Different types of NVD, their key elements and the NVD principle of action are discussed. An analysis of the basic components of these devices – image intensifier tube and optical systems has been done. A mathematical model of the night vision devices that describes the relationships between the elements of the devices is proposed. A theoretical approach for evaluation of the NVD parameters is described which is based on the deduced mathematical relationships. The developed optimization models are tested with numerical examples based on real data. The monograph can be useful both for professionals and for a wide range of readers interested in modern NVD.

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