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NIGHT VISION DEVICES DESIGN PROCESS MODELLING

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ABSTRACT. The paper focuses on problems concerning the modelling of the night vision devices (NVD) design process as a combinatorial choice. A NVD model is defined and used for virtual design simulation and for optimization tasks formulation. Two methods for the NVD virtual design process modelling are described - reasonable combinatorial choice and optimal combinatorial choice of the NVD basic modules - objective, image intensifier tube and ocular. As a result of the methods using some preliminary estimation of the NVD operational characteristics (working range under given external surveillance conditions, weight and price) are calculated. The reasonable combinatorial choice method acts as a designer simulation tool to try different modules combinations for different external surveillance conditions. The optimal combinatorial choice method uses formulated nonlinear mixed integer multiobjective or single objective optimization problems. Solving of the formulated optimization problems gives the Pareto optimal (or optimal) modules combination for the given restrictions and criteria. Both methods support the NVD design to reduce the traditional NVD design process "trial and errors" costs for multiple prototypes building and testing.

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1. INTRODUCTION

Modelling techniques are important tools for researchers, designers and users. They assist understanding the object, predicting its characteristics and reasoning on the solution taking processes. The modelling can serve different goals at different levels by using different background theories. Contemporary personal computers are many times more powerful than those of the past and are equipped with options as multi-core processors, gigabytes of RAM, hundreds of gigabytes hard disks storage and have hight level performance. Developing modelling methodologies using the capabilities of the modern personal computers will improve the quality of the decision making processes and will reduce the related time and money costs.

Technical systems design process is an example of time and money consuming decision making process. Part of the design process is intuitive, however analytical techniques as well as numerical optimization could be of great value and can permit vast improvement in it [1]. To optimize the technical systems design various mathematical models have been proposed [2, 3]. The night vision devices (NVD) are specific technical systems whose design is based on the designer experience and need costly prototypes building and testing [4]. The NVD modules or subsystems optimization is based on their physical, technical, performance, etc. characteristics [5, 6, 7, 8]. That means there exist sets of modules for the NVD that have been already optimised with different performance characteristics reflecting in their price, quality and availability. The designer has to decide which of them to use to satisfy the given design requirements. The NVD design process can be modeled and formalized as combinatorial choice problem and using proper mathematical methods can reduce the design process time and costs.

The current paper focuses on problems concerning the modelling of the NVD design process as reasonable or optimal choice of the main NVD modules (objective, image intensifier tube and ocular) taking into account their physical and functional relations, user requirements and the external surveillance conditions.

2. Night vision devices design process modelling problem

The NVD design is an iterative process. It starts with a choice of some NVD module, then calculating the parameters of the other modules based on the existing functional relations, choice of the remaining modules, building a prototype and testing it against the given performance specifications. If those specifications are not satisfied the whole process repeats until the satisfactory results have gotten. The prototype building stage is a needed stage to estimate if the design goals are met. The prototypes building needs availability of sets of modules with different parameters. Some of them probably would not be used but that is uncertain in advance and they should be available i.e. bought and stored. That design stage is the most time and money consuming stage. If it is possible to reduce the number of prototypes building and testing iterations while guaranteeing the satisfaction of the design goals it will reflect in decreasing the time and money cost of the overall design process. It could be done by means of proper mathematical tools to simulate virtually the NVD design process using the capabilities of the modern computers. When the desired NVD operational characteristics are expressed as functions of merit, i.e. as objective functions, it is possible to use optimization methods as a tool to get optimal solutions and to automate the design process.

3. Night vision devices design modelling methods

The proposed design process modelling is based on combinatorial choice of the NVD modules satisfying the given requirements. The most essential subsystem for the NVD operational characteristics is its optoelectronic channel consisting of objective, image intensifier tube (IIT) and ocular [9]. The practical experience shows that the NVD design should take into account also the external surveillance conditions - external ambient light, contrast between background and target, atmospheric transmittance and target area. The external surveillance conditions are stochastic by nature and that could be reflected into the developed NVD design modelling methods. For any given NVD design, the designer has to cope with different and sometime conflicting user requirements such as low cost and weight on one side and high device quality on the other side. Two different alternative methods are developed for the NVD design - reasonable combinatorial choice and optimal combinatorial choice.

The reasonable combinatorial choice is computer simulating of the iterative NVD design process, i.e. choice of modules observing the functional relations, calculating of the theoretical estimation of the NVD operational characteristics without prototype building and testing and repeating all steps in the computer environment until the design goals are met.

The NVD design by optimal combinatorial choice is based on automation of the iterative design by means of optimization techniques. It involves mathematical modelling of the designed device, formulating of optimization tasks, choosing of proper solving methods and relevant solving software. The solution of the optimization tasks gives the NVD modules combination which is optimal (or Pareto optimal) for the formulated objective functions and for the given restrictions.

3.1. NVD DESIGN BY REASONABLE COMBINATORIAL CHOICE METHOD

The reasonable combinatorial choice assists the designer to find a good from his point of view, i.e. reasonable combination of NVD modules taking into account the design restrictions, user requirements and the given external conditions. The algorithmic diagram of the reasonable combinatorial choice method for the NVD design is shown on Fig. 1.

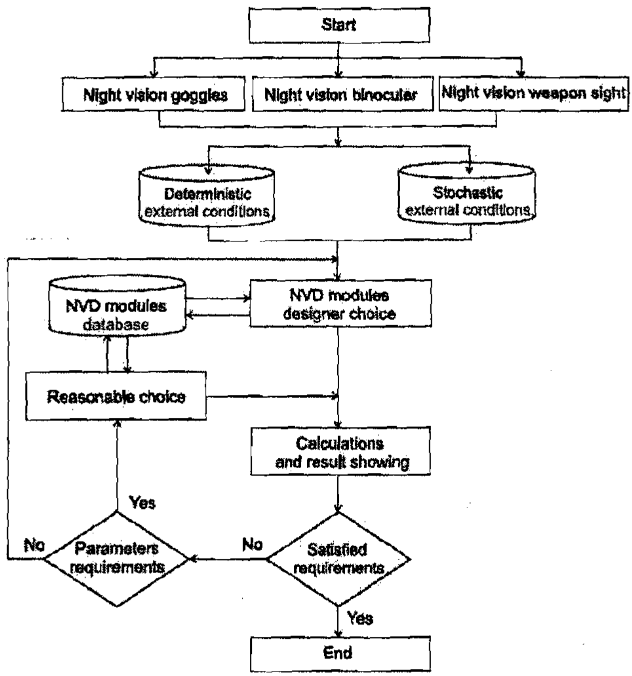

Figure 1: Algorithmic diagram of the NVD design by reasonable combinatorial choice method

The NVD can be of different types by construction - monoculars, binoculars or biocculars and by function - night vision goggles (without magnification), night vision binoculars (with magnification) and night vision weapon sights (monocular type with magnification). The most essential subsystem influencing the functional characteristics of the NVD is its optoelectronic channel consisting of objective, image intensifier tube (IIT) and ocular. It is indicative for the important operational characteristics as working range, the device price and weight and is considered in the paper as the example of the NVD design.

The crucial design decision is to choose proper optoelectonic channel modules taking into account their functional relations for the given NVD type considering the given external surveillance conditions. Using the chosen modules parameters some preliminary theoretical estimation of the NVD functional characteristics can be calculated.

From practical point of view the working range is one of the main NVD functional characteristic . The calculation of the NVD working range is based on the formula developed in [9, 10]:

$$R = \sqrt{\frac{0.07EK\tau_a A_{ob} D_{in} f_{ob} \tau_{ob} S\delta}{M\Phi_{min}}}[m] \quad (1)$$

where: E - ambient light illumination in lx, K - contrast, τ_a, τ_{ob} - atmosphere and objective transmittance, A_{ob} - target area in m^2, D_{in} - diameter of the objective inlet pupil in m, f_{ob} - objective focal length in mm, S - IIT luminous sensitivity in A/lm, δ - IIT limiting resolution in lp/mm, M - IIT signal to noise ratio and Φ_{min} - IIT photocathode limiting light flow in lm.

By using so called "reduced target area" A'_{ob} instead of A_{ob} different types of working range can be calculated, for example - the detection range, the recognition range and the identification range [9].

The NVD optoelectronic channel weight W and price P are calculated by summarizing the weight and price of its chosen modules:

$$W = W_{IIT} + W_{ob} + W_{oc} \quad (2)$$

$$C = C_{IIT} + C_{ob} + C_{oc} \quad (3)$$

where: W_{IIT}, C_{IIT} are the IIT weight and price; W_{ob}, C_{ob} are the objective weight and price and W_{oc}, C_{oc} are the ocular weight and price respectively.

On Fig. 1 the NVD design process starts with choosing of the NVD type and the external surveillance conditions. The NVD type is usually defined by the customer. The external surveillance conditions (ambient light, contrast between background and target, atmospheric transmittance and surveillance target) are given as deterministic values known for the expected geographic, climatic etc. conditions [9] or as stochastic values taken from the relevant probabilities distributions.

The next algorithmic step is to choose the main optoelectronic channel modules by the designer. As a result of that choice the NVD modules parameters become known and using them the operational characteristics are calculated. If the calculated operational characteristics do not meet the given requirements the designer has two alternatives. The first one is to make a new choice of modules and to evaluate the calculated results. That iterative process can be repeated until the design goals are met or are impossible to meet. The second alternative gives the designer option to define some preferred values for the device operational characteristics. That alternative is called "reasonable choice" i.e. automatic choice of modules combination to satisfy the given operational parameters values. The particular algorithmic realization of the reasonable choice does not use optimization techniques. The modules combination found satisfies the given requirements but is not guaranteed to be the best one.

It could be seen that the NVD design by reasonable choice is essentially an iterative computer simulation of the traditional design process extended with automatic NVD reasonable modules choice satisfying some designer requirements. Using of the reasonable choice method gives also theoretical estimation for the NVD operational characteristics without the need of prototype building and testing. The proposed NVD design method could be used also as an analysis tool to define parameters for some custom modules if the available ones are not appropriate.

The reasonable choice method is implemented in NVD design software system "NVDpro" [11].

3.2. NVD DESIGN BY OPTIMAL COMBINATORIAL CHOICE METHOD

Another alternative to the NVD design is using of optimal combinatorial choice method. The essence of this method is formulating and solving of optimization tasks. The algorithmic diagram of the NVD design by optimal combinatorial choice method is shown on Fig. 2.

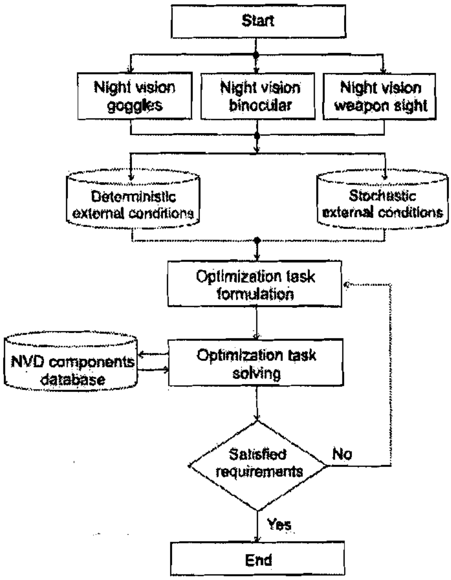

Figure 2: Algorithmic diagram of the NVD design by optimal combinatorial method

The NVD type and external condition choosing steps are the same as for the reasonable choice method. One of the core stages for NVD design by optimal combinatorial choice is optimization task formulation stage. It could implement a number of previously formulated single or multicriteria optimization tasks giving the designer the freedom to choose the most appropriate one or it can give the designer possibilities to formulate and try its own optimization task formulation.

All optimization tasks formulations are based on a mathematical models of the NVD described in [9, 10, 12, 13, 14]. As it was pointed out the opto-electronic channel is dominant for the operational characteristics of the NVD and its modelling can serve as a good example for the implementation of the proposed method. To formulate optimization tasks some functions of merit i.e. objective functions are used. The NVD quality parameters to consider as important from practical point of view are working range, weight, price, battery power supply, etc. [12, 13].

An example of a multicriteria optimization task formulation for the NVD design can be stated as:

$$maxF(P) = f_1(P),\ minF(P) = f_2(P),\ minF(P) = f_3(P), \quad (4)$$

s.t.

$$P^1 = \sum_{j_1=1}^{J_1} P^1_{j_1,k_1} x^1_{j_1}, \quad (5)$$

$j_1 = 1,..,J_1 -$ IIT' number, $k_1 -$ IIT' parameters vector,

$$P^2 = \sum_{j_2=1}^{J_2} P^2_{j_2,k_2} x^2_{j_2}, \quad (6)$$

$j_2 = 1,..,J_2 -$ objectives number, $k_2 -$ objectives parameters vector,

$$P^3 = \sum_{j_3=1}^{J_3} P^3_{j_3,k_3} x^3_{j_3}, \quad (7)$$

$j_3 = 1,..,J_3 -$ oculars number, $k_3 -$ oculars parameters vector,

$$g_1(P) = \sum_{j_2=1}^{J_2} P^2_{j_2,k_2} x^2_{j_2} - \alpha \sum_{j_3=1}^{J_3} P^3_{j_3,k_3} x^3_{j_3} = 0, \quad (8)$$

$$g_2(P) = \sum_{j_3=1}^{J_3} 2sin(\frac{P^3_{j_3,k_3}}{2}) x^3_{j_3} - \sum_{j_1=1}^{J_1} P^1_{j_1,k_1} x^1_{j_1} \geq 0, \quad (9)$$

$$\sum_{j_i} x^i_{j_i} = 1, \quad x \in [0,1] \quad (10)$$

$$P^{L_i}_{j_i,k_i} \leq P^i_{j_i,k_i} \leq P^{U_i}_{j_i,k_i} \quad (11)$$

where:

- $f_1(P) = \sqrt{\frac{0.07P^2_{j_2,1}P^2_{j_2,2}P^2_{j_2,3}P^1_{j_1,1}P^1_{j_1,2}E_1E_2E_3E_4}{P^1_{j_1,3}P^1_{j_1,4}}}$ is the NVD working range functional relation of the IIT parameters $P^1_{j_1,k_1}$ ($k_1 = 1,2,3,4$), of the objective parameters $P^2_{j_2,k_2}$ ($k_2 = 1,2,3$) and of the external surveillance conditions values E_e ($e = 1,2,3,4$), based on equation (1),
- $f_2(P) = P^1_{j_1,w_1} + P^2_{j_2,w_2} + P^3_{j_3,w_3}$ is the NVD weight functional relation of the parameters corresponding to the weights of the $j-th$ types of the IIT, objective and ocular,
- $f_3(P) = P^1_{j_1,c_1} + P^2_{j_2,c_2} + P^3_{j_3,c_3}$ is the NVD cost function of the parameters corresponding to the costs of the $j-th$ types of the IIT, objective and ocular,
- P^1, P^2, P^3 are constraints for the choice of the single IIT, single objective and single ocular by using of binary integer variables $x^i_{j_i}$ (10),
- $g_1(P)$ is equation for optical system magnification α, depending on the objective $P^2_{j_2,l_2}$ and ocular $P^3_{j_3,l_3}$ focal length,
- $g_2(P)$ describes specifics for the NVD relation between the IIT screen diameter $P^1_{j_1,d_1}$ and the ocular field of view $P^3_{j_3,d_3}$,
- relation (11) represents the existance of some upper $P^{U_i}_{j_i,k_i}$ and/or lower $P^{L_i}_{j_i,k_i}$ boundaries about the NVD parameters.

The functional relation $f_1(P)$ for the NVD working range determination is nonlinear, and the binary variables $x^i_{j_i}$ are integer which defines the formulated optimization task (4) - (11) as nonlinear mixed integer multicriteria problem.

Using different criteria (including single criterion formulations), different restrictions and relations relevant to the different practical applications will define other possible formulations.

The next core stage of the NVD design by optimal combinatorial choice is optimization tasks solving. There exist many proper methods and algorithms with proven reliability that can be used [15]. In case of multicriteria formulation (which is the closest to the real design problems) the solution is Pareto optimal i.e. the search is for the Pareto set of solutions, among which the decision-maker selects the final solution by trading off the objectives against each other. If the designer is not satisfied of the solution a feedback is provided to the optimization tasks formulation stage. It can be used not only in multicriteria case for decision-maker (designer) preferences changing but also for choosing different optimization tasks formulations or for editing of the existing formulations.

Some solutions of numerical examples for different optimization tasks formulations are shown in [9, 12, 13, 14] proving the applicability of the proposed optimal combinatorial choice method for the NVD design.

NVD design by means of optimization methods can be used also to analyze and forecast the parameters of the designed device. As a result of that analysis specific requirements for the needed modules parameters can be defined and used to tailor the customized modules to the particular practical needs.

4. Conclusion

An essential aspect of using modelling and computer simulation is the possibility to use effective mathematical methods and the impressive capabilities of the modern computers for the complex and difficult engineering tasks. The current paper presents two methods for night vision devices design process modelling and simulating in the computer environment.

The first proposed NVD design method - reasonable combinatorial choice, can be implemented as iterative design tool for virtual computer simulation of the NVD design process. It uses automatic feasible choice of modules satisfying the given NVD parameters requirements without using of optimization methods and the designer has to decide which NVD modules combination is the reasonable one for each particular practical need. The reasonable combinatorial choice method for the NVD design is implemented in a Web-based software system "NVDpro" [11].

The second NVD design method is optimal combinatorial choice of the NVD modules. It is based on mathematical model of the NVD optoelectronic channel and formulation of the relevant optimization tasks. The solutions of the formulated optimization tasks provide the best combination of the needed NVD modules to satisfy the preliminary requirements. When the optimization tasks are single criterion tasks their solution is guaranteed to be the optimal solution. For multicriteria formulations a set of Pareto optimal solutions is provided to the designer to choose the best one accordingly his preferences.

Both methods give some preliminary theoretical estimation of the designed NVD parameters reducing the number of the needed prototypes to build and test thus reducing the overall design time and costs. They can be used also for training and understanding of the NVD design process specifics. Implemented in the computer aided design (CAD) systems they increase design efficiency and can help the designers to get better NVD design solutions.

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