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APPLICATION OF MULTI-CRITERIA OPTIMIZATION TO CHOOSE VARIANTS OF HARDWARE ARCHITECTURE FOR THE SWPL-1 HELMET-MOUNTED DISPLAY SYSTEM

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Abstract

The paper presents the structure and basic properties of the SWPL-1 helmet-mounted flight parameter display system, constructed for the Mi-17 helicopter with analogue systems and on-board instruments. It describes the basic components of the SWPL-1 system and on board components cooperating with the SWPL-1 system necessary to ensure the imaging system's operation (including the ADU-3200 central unit for aerodynamic data and the GPS-155XL satellite signals receiver). It presents the architecture, the principle of operation, and the main constituents of the SWPL-1 helmet-mounted flight parameter system, as well as the standards of data transmission used in digital communication between the SWPL-1 system and on-board systems (installed on the Mi-17 helicopter). It describes the scope and manner of pilot and navigation data presentation as well as control of drive unit operation parameters in detail. It presents selected optimization methods for tasks executed in the helmet mounted system's life cycle. The particular stages of the life cycle were described in detail, from the earliest stages of needs identification, through the analytic and conceptual phase, then the implementation stage, and ending with the operation stage. It introduces tasks for optimization and related methods into the process of creating the new system at every stage of its implementation. It presents one of the methods of multi-criteria optimization based on the experts' assessment of choice of a variant of the helmet-mounted flight parameter display system's hardware architecture in detail.

Keywords: *transport, avionics, helmet-mounted display systems, hardware architecture, multi-criteria optimization*

1. Introduction

The article presents the selected results of the works related to the design of a helmet-mounted flight parameter display system and its integration with existing on-board equipment of the aircraft. These results are based on practical experience gained in the process of creation and implementation into production and operation of the first Polish SWPL-1 helmet-mounted flight parameter display system.

The SWPL-1 helmet-mounted flight parameter display system [1] is dedicated to crews of the following helicopters: Mi-17-1V, Mi-17 T/U, Mi-17 AE and other versions of the Mi-17 helicopter. The system allows for observation of the area while controlling the helicopter's flight parameters [2]. It receives and processes information from on-board systems and presents them on helmet-mounted displays in the form of graphic symbols or in digital form. The SWPL-1 system visualises the flight parameters necessary to carry out the combat mission for a crew commander (the first pilot) and the second pilot.

The article presents one of the optimisation methods of tasks performed in the life cycle phases of the helmet-mounted system [1]. The particular life cycle phases were considered from the earliest stages of needs identification, through the analytical and conceptual phase, then the implementation stage, and ending with the operation stage.

Within the framework of works related to the SWPL-1 system, an original way, resulting from the experience gained during design and construction of the system, of using optimisation methods at individual stages of design and development of the SWPL-1 helmet-mounted flight parameter display system.

The optimisation methods were selected depending on the problem being solved. In the SWPL-1 system's initial life phases, when its hardware structure was not yet determined, the majority of optimisation tasks came down to optimal choices with defined criterion functions. The example of the original approach to the issue of optimisation was to use multi-criteria optimisation based on the assessment of variants related to the helmet-mounted system's hardware architecture solutions in order to choose the best variant, with own adaptation of Yager's method [3, 6].

The presented method of the multi-criteria optimisation was used in the analytical and conceptual phase of the system's life cycle. This phase is shown in Fig. 1.

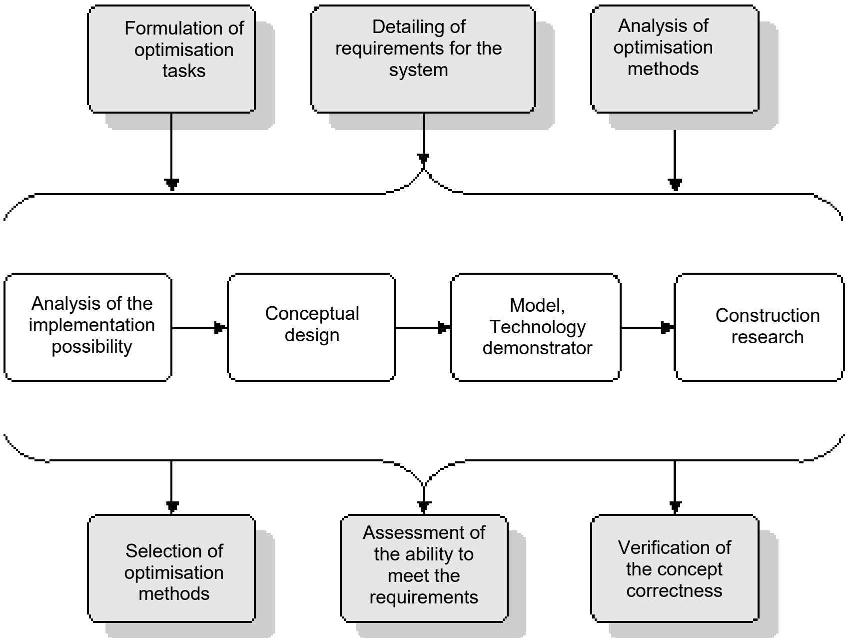

Fig. 1. Analytical and conceptual phase of the SWPL 1 system

2. Variants of the hardware architecture

For the helmet-mounted flight parameter display system's hardware architecture, two following variants were taken to the assessment:

Variant No. 1:

- cluster, single-processor architecture with the predominance of software solutions,
- architecture slightly using ready solutions and requiring the design and implementation of own solutions,
- architecture dedicated to the fulfilment of only these requirements, which were defined by a future user.

Variant No. 2:

- multi-processor, distributed architecture, with hardware and software solutions of signal processing algorithms,
- architecture using ready solutions of the packages of printed circuit boards, and introducing own solutions only to solve unusual problems,
- redundant architecture from the perspective of the ability to meet the future user's requirements.

Some of the architecture possibilities may not be used. A set of variants of the hardware architecture was defined as follows:

$$\mathbf{WR} = \{WR_1, WR_2\}, \tag{1}$$

where: WR_1 – variant No. 1; WR_2 – variant No. 2.

3. Optimisation criteria

A set of criteria was determined on the basis of deterministic point criteria:

$$\mathbf{K} = \{K_1, K_2, ..., K_6\}, \tag{2}$$

where: K_1 – estimated implementation cost according to the assumed architecture, K_2 – estimated cost of drawing up the construction documentation, K_3 – estimated cost of the hardware creation, K_4 – estimated value of the MTBF reliability indicator, K_5 – hour completion time, K_6 – calendar completion time.

A group of experts, who evaluate various architecture types, was defined as follows:

$$\mathbf{EK} = \{EK1, EK2, EK3\}, \tag{3}$$

where: $EK1$ – expert 1, $EK2$ – expert 2, $EK3$ – expert 3.

Each of these experts determined the validity matrix of criteria, where individual criteria were compared in pairs by **Saaty method** [3], [4], [5]. The set of **A** validity matrix was as follows:

$$\mathbf{A} = \{\mathbf{A}_{Ek}\} = \{\mathbf{A}_{E1}, \mathbf{A}_{E2}, \mathbf{A}_{E3}\}, \tag{4}$$

where: $\mathbf{A}_{E1}$ – validity matrix of criteria from expert 1, $\mathbf{A}_{E2}$ – validity matrix of criteria from expert 2, $\mathbf{A}_{E3}$ – validity matrix of criteria from expert 3.

Individual experts compare particular criteria in pairs. The assignment of values of a_{ij} elements of the matrix: $\mathbf{A}_{E1}, \mathbf{A}_{E2}, \mathbf{A}_{E3}$ in order to assess the validity of individual criteria was adopted on a scale from 1 to 10. The example of the assessment matrix of the validity of criteria was presented in the tabular form.

Tab. 1. Example of assessing the validity of criteria

ASSESEMENT MATRIX OF THE VALIDITY OF CRITERIA A_{E1} – THE ASSESSMENT OF EXPERT No. 1							
CRITERIA		*K1*	*K2*	*K3*	*K4*	*K5*	*K6*
Estimated cost of implementation in accordance with the assumed architecture	*K1*	1.0000	0.5000	0.5000	0.2000	5.0000	0.1250
Estimated cost of the design documentation preparation	*K2*	2.0000	1.0000	3.0000	0.5000	5.0000	0.2500
Estimated cost of the software creation	*K3*	2.0000	0.3333	1.0000	0.1429	4.0000	0.3333
Estimated value of MTBF reliability ratio	*K4*	5.0000	2.0000	7.0000	1.0000	10.0000	0.5000
Hourly implementation period	*K5*	0.2000	0.2000	0.2500	0.1000	1.0000	0.1000
Calendar implementation period	*K6*	8.0000	4.0000	3.0000	2.0000	10.0000	1.0000

The partial matrices $\mathbf{A}_{E1}$, $\mathbf{A}_{E2}$, $\mathbf{A}_{E3}$ obtained from individual experts are the basis to determine the cumulative matrix $\mathbf{A}_E$, the elements of which are averaged according to the relationship (5).

$$a_{Eij} = \frac{a_{E1ij} + a_{E2ij} + a_{E3ij}}{3}. \tag{5}$$

4. Adaptation of Yager's method to the issue of selecting the hardware architecture variant

The first step of the adaptation of Yager's method is to determine eigenvalues of the $\mathbf{A}_E$ matrix. The eigenvalues understood as the roots of the characteristic equation obtained from the $\mathbf{A}_E$ matrix according to the following formula:

$$\det\left[s \times \mathbf{I} - \mathbf{A}_E\right] = 0, \tag{6}$$

where: s – Laplace’s operator; $\mathbf{I}$ – identity matrix.

In the considered case, the values are as follows:
$s1$ = 6.4971,
$s2$ = -0.0662 + 1.2934i,
$s3$ = -0.0662 – 1.2934i,
$s4$ = -0.1589 + 0.9370i,
$s5$ = -0.1589 – 0.9370i,
$s6$ = -0.0470.
where: i – imaginary unit.

The determination of eigenvalues is necessary to check the condition that should be met by the $\mathbf{A}_E$ matrix. The condition is as follows

$$CI = \frac{s_{\max} - m}{m - 1} \le 0.1, \tag{7}$$

where: $s_{\max}$ – maximum value of its own module from the set of solutions of the characteristic equation; m – matrix rank $\mathbf{A}_E$ and at the same time, the number of criteria.

In the considered case CI = 0.0994, which is met by the condition (7).

The next step is to determine the weighting factors for individual criteria. The weighting factors create the own $\mathbf{Y}$ vector of the matrix equation

$$\mathbf{A}_E \bullet \mathbf{Y} = s_{\max} \cdot \mathbf{Y}. \tag{8}$$

Components (coordinates) of the $\mathbf{Y}$ vector must satisfy the condition

$$\sum_{i=1}^{m} y_i = m. \tag{9}$$

The matrix equation (8) can be transformed to the form

$$\left[\mathbf{A}_E - s_{\max} \cdot \mathbf{I}\right] \bullet \mathbf{Y} = 0 \tag{10}$$

or:

$$\mathbf{A}_W \bullet \mathbf{Y} = 0, \tag{11}$$

where:

$$\mathbf{A}_W = \begin{bmatrix} -5.4971 & 0.6111 & 0.4444 & 0.2056 & 5.0000 & 0.1204 \\ 2.0000 & -5.4971 & 2.6667 & 0.4444 & 4.6667 & 0.2333 \\ 2.3333 & 0.3889 & -5.4971 & 0.1429 & 4.0000 & 0.3611 \\ 5.0000 & 2.3333 & 7.0000 & -5.4971 & 9.3333 & 0.6667 \\ 0.2000 & 0.2167 & 0.2500 & 0.1074 & -5.4971 & 0.1037 \\ 8.3333 & 4.3333 & 3.0000 & 1.6667 & 9.6667 & -5.4971 \end{bmatrix}. \tag{12}$$

In the considered example, the main determinant of the **A**W matrix is $\det|\mathbf{A}_W| = 0$, it means that the system of equations (11) is homogeneous. The homogeneous system of equations has obviously zero solutions, which, in this case, we are not interested in. The zero value of the main determinant also means that the system of equations (11) has infinitely many solutions. Therefore, it is important to use the additional condition (9) for components of the own **Y vector.** The additional condition in the considered case will be as follows:

$$y_1 + y_2 + y_3 + y_4 + y_5 + y_6 = 6\,. \tag{13}$$

By determining (13) e.g. the coordinate y_6 from the equation and substituting it to the matrix equation (11), we will obtain the matrix equation in the following form:

$$\begin{bmatrix} a_{11}-a_{16} & a_{12}-a_{16} & a_{13}-a_{16} & a_{14}-a_{16} & a_{15}-a_{16} \\ a_{21}-a_{26} & a_{22}-a_{26} & a_{23}-a_{26} & a_{24}-a_{26} & a_{25}-a_{26} \\ a_{31}-a_{36} & a_{32}-a_{36} & a_{33}-a_{36} & a_{34}-a_{36} & a_{35}-a_{36} \\ a_{41}-a_{46} & a_{42}-a_{46} & a_{43}-a_{46} & a_{44}-a_{46} & a_{45}-a_{46} \\ a_{51}-a_{56} & a_{52}-a_{56} & a_{53}-a_{56} & a_{54}-a_{56} & a_{55}-a_{56} \\ a_{61}-a_{66} & a_{62}-a_{66} & a_{63}-a_{66} & a_{64}-a_{66} & a_{65}-a_{66} \end{bmatrix} \times \begin{bmatrix} y_1 \\ y_2 \\ y_3 \\ y_4 \\ y_5 \end{bmatrix} = \begin{bmatrix} -6\cdot a_{16} \\ -6\cdot a_{26} \\ -6\cdot a_{36} \\ -6\cdot a_{46} \\ -6\cdot a_{56} \\ -6\cdot a_{66} \end{bmatrix}, \tag{14}$$

where: a_{ik} – matrix elements **A**W.

In the general form, the matrix equation (14) can be written in the following form

$$\mathbf{A}_K \times \mathbf{Y} = \mathbf{B}_K\,. \tag{15}$$

If the matrix equation (15) results in the fact that the number of equations is larger than the number of unknowns, then, by using the Rouché-Capelli theorem, it is crucial to study, if the system of equations determined by the matrix equation (15) has one solution. In this case, the necessary and sufficient condition includes equality of the $\mathbf{A}_K$ matrix and $\mathbf{A}_{KB}$ matrix ranks completed by the column of the $\mathbf{B}_K$ vector. In the considered example, this condition is not satisfied because

$$R(\mathbf{A}_{KB}) \neq R(\mathbf{B}_K)\,. \tag{16}$$

Failure to satisfy this condition and the fact that the common matrix rank is equal to the number of unknowns leads to the conclusion that there is no exact solution. The occurred issue can be solved in many ways. It is important to search for solutions best bringing the matrix equation accomplishment (15) closer in terms of the adopted optimisation criterion.

As an indicator of optimisation, in this case, it is possible to adopt, e.g. one of two functionals described by the following relationships:

$$Q_1 = \sum_{i=1}^{6} \left[f_i\left(y_1, y_2, y_3, y_4, y_5\right) \right]^2, \tag{17}$$

$$Q_2 = \sum_{i=1}^{6} \left| f_i\left(y_1, y_2, y_3, y_4, y_5\right) \right|, \tag{18}$$

where: $f_i\left(y_1, y_2, y_3, y_4, y_5\right)$ – function that specifies the difference between the left and right side of the equation for a given *i* row of the matrix equation (15).

The solution to the problem will be to find the minimum value of the functional, and to determine the optimal values of coordinates: y_1, y_2, y_3, y_4, y_5 of the **Y** vector. The missing element y_6 of the vector must be then calculated on the basis of the equation (13).

The own vector's components are, at the same time, coordinates of the weighting vector for individual criteria.

$$\mathbf{W} = col\left[w_1, w_2, ..., w_6\right] = col\left[y_1, y_2, ..., y_6\right]. \tag{19}$$

The next step is evaluation by experts of individual variants of the hardware architecture. It was found that the point scale of assessing the variants will be within the closed interval <0, 10> and the numbers from this interval will be integers. The point ratings, assigned to individual (i) variants of the architecture, in relation to the j criterion, provided by the e expert, will be marked as:

$$S_{ij}(e) \text{ for } i = 1, 2 \text{ and } j = 1,2, \dots ,6. \tag{20}$$

In the first step of normalisation, it is important to create the following sums:

$$S_j(e) = \sum_{i=1}^{2} S_{ij}(e). \tag{21}$$

Therefore, there will be so many sums specified by the relationship (21), as many criteria are adopted. Each sum $S_j(e)$ is a sum of point ratings assigned to all variants for the j criterion by the e expert.

Then, on the basis of the experts' assessments, the assessment matrices of the hardware architecture variants were determined, the example of which was presented in the tabular form.

Tab. 2. Example of the matrix of ratings of the architecture variants by the Expert No. 1.

ASSESSEMENT MATRIX OF THE ARCHITECTURE WRE1 – THE ASSESSMENT OF EXPERT No. 1							
ARCHITECTURE VARIANTS		*K1*	*K2*	*K3*	*K4*	*K5*	*K6*
Variant No. 1 of architecture	*WR1*	4	3	5	4	1	3
Variant No. 2 of architecture	*WR2*	2	6	6	7	3	8
The sum of point ratings for individual variants in relation to K_j criterion	S_j	6	9	11	11	4	11

In the next step, it is important to create total standardised ratings, as average values of ratings of individual experts

$$c_{ij} = \frac{\sum_{e=1}^{3} c_{ij}(e)}{3}. \tag{22}$$

Tab. 3. Example of the matrix for total standardised ratings

MATRIX OF TOTAL STANDARDISED RATINGS C – THE AVERAGE EVALUATION OF EXPERTS							
ARCHITECTURE VARIANTS		*K1*	*K2*	*K3*	*K4*	*K5*	*K6*
Variant No. 1 of architecture	*WR1*	0.6905	0.3064	0.3864	0.5805	0.2722	0.3631
Variant No. 2 of architecture	*WR2*	0.3095	0.6936	0.6136	0.4195	0.7278	0.6369
Weight vector of criteria	w_j	0.3831	0.7688	0.5247	1.8736	0.1481	2.3017

Total standardised ratings were presented in the following form:

$$\begin{bmatrix} k_1 = c_{11}|_{WR1} + c_{21}|_{WR2} \\ k_2 = c_{12}|_{WR1} + c_{22}|_{WR2} \\ k_3 = c_{13}|_{WR1} + c_{23}|_{WR2} \\ k_4 = c_{14}|_{WR1} + c_{24}|_{WR2} \\ k_5 = c_{15}|_{WR1} + c_{25}|_{WR2} \\ k_6 = c_{16}|_{WR1} + c_{26}|_{WR2} \end{bmatrix} = \begin{bmatrix} k_1 = 0.6905|_{WR1} + 0.3095|_{WR2} \\ k_2 = 0.3064|_{WR1} + 0.6936|_{WR2} \\ k_3 = 0.3864|_{WR1} + 0.6136|_{WR2} \\ k_4 = 0.5805|_{WR1} + 0.4195|_{WR2} \\ k_5 = 0.2722|_{WR1} + 0.7278|_{WR2} \\ k_6 = 0.3631|_{WR1} + 0.6369|_{WR2} \end{bmatrix}. \tag{23}$$

Then, we determined standardised decisions by raising each component of subsequent standardised ratings to the power of the appropriate weight:

$$d = \sum_{i=1}^{2} c_{ij}^{w_j}\Big|_{WRi}, \tag{24}$$

where: $d = \{d_1, d_2, d_3, d_4, d_5, d_6\}$.

The standardised decisions can be presented as follows:

$$\begin{bmatrix} d_1 = c_{11}^{w1}|_{WR1} + c_{21}^{w1}|_{WR2} \\ d_2 = c_{12}^{w2}|_{WR1} + c_{22}^{w2}|_{WR2} \\ d_3 = c_{13}^{w3}|_{WR1} + c_{23}^{w3}|_{WR2} \\ d_4 = c_{14}^{w4}|_{WR1} + c_{24}^{w4}|_{WR2} \\ d_5 = c_{15}^{w5}|_{WR1} + c_{25}^{w5}|_{WR2} \\ d_6 = c_{16}^{w6}|_{WR1} + c_{26}^{w6}|_{WR2} \end{bmatrix} = \begin{bmatrix} d_1 = 0.8677|_{WR1} + 0.6381|_{WR2} \\ d_2 = 0.4028|_{WR1} + 0.7548|_{WR2} \\ d_3 = 0.6072|_{WR1} + 0.7740|_{WR2} \\ d_4 = 0.3609|_{WR1} + 0.1964|_{WR2} \\ d_5 = 0.8247|_{WR1} + 0.9540|_{WR2} \\ d_6 = 0.0971|_{WR1} + 0.3540|_{WR2} \end{bmatrix}. \tag{25}$$

In the last stage of optimisation, based on the matrix of standardised decisions, I created the optimal arrangement of variants from the perspective of adopted assessment criteria.

$$D = D|_{WR1} + D|_{WR2}, \tag{26}$$

where: $D|_{WR1} = \min_{i=1;j=1...6} c_{ij}^{w_j} = \min_{i=1...6;j=1} d_{ij}$ and $D|_{WR2} = \min_{i=2;j=1...6} c_{ij}^{w_j} = \min_{i=1...6;j=2} d_{ij}$.

The smallest element of $WR1$ variant column includes $D_{WR1} = 0.0971$ element.

The smallest element of $WR2$ variant column includes $D_{WR2} = 0.1964$ element.

In the light of the above, the optimum arrangement can be presented in the form of:

$$D = 0.0971|_{WR1} + 0.1964|_{WR2}. \tag{27}$$

The best variant, that is best meeting all the criteria adopted for the assessment, is the one, which corresponds to the largest component of the optimum arrangement:

$$WR_{i(opt)} = \max_{i=1,2} D|_{WRi}. \tag{28}$$

In the considered case, ***WR*2 variant is the best one** of the hardware architecture of SWPL-1 flight parameter display system.

5. Summary

The presented adaptation of Yager's multi-criteria optimisation method for the issue of choosing the optimal variant of the hardware architecture of the designed SWPL-1 system is fully useful at the stage of performing the conceptual design. The use of this method in the early stage of the analytical and conceptual phase of the system's life cycle gives measurable economic effects in the form of a reduction in the cost of the system implementation.

A very important element of this method is the right selection of experts. The experts should have extensive experience in the design of such systems and wide interdisciplinary knowledge. The number of experts should be greater than two, but not large due to the cost of performing the expert study.

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