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Choice and analysis of the command and launch unit optimal solution for an anti-tank guided missile

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This paper describes the CLU working principles for an anti-tank guided missile which gunner can fire either from his shoulder or tripod. The main functional parts and design of the CLU are described for the case when CCD cameras are used as the sensors in a coordinator. The analysis and operational presentation of the CLU are made, as well as the software main functions related to the missile launching sequence control, picture acquisition and processing, flare pixel coordinates determination and the missile guidance and control. The CLU basic characteristics, the methods for their verification and the factors influencing them, are also defined.

Key words: **anti-tank missile, guided missile, guide missile, coordinator, flare, CCD camera, software, structural scheme.**

Notation and symbols

A/D	- analog to digital converter
BRM	- booster rocket motor
CCD	- charge coupled device
CLU	- command and launching unit
$D_{n,n}$	- gyroscope signal at every 45° of angular position
DSP	- digital signal processor
FPGA	- field programmable gate arrays
ICG	- impulsive command generator
IR	- infrared
K	- resultant command coefficient
$K_{\max}$, $K_{\min}$	- maximum and minimum command coefficients
LCD	- liquid crystal display
LED	- light emitted diode
LOK	- picture acquisition and processing program
LS	- line of sight
LT	- launching tube
NAL	- narrow angle lens
OS	- optical sight
PIC	- program for the impulsive command generation
PGC	- program for guidance and control
PTL	- pyrotechnic lock
SRM	- sustainer rocket motor
SRAM	- static random access memory
START	- program for the entry data readings
TB	- thermal battery
TBL	- test before launching
TBL1,TBL2	- test before launching
TV	- television
TVC	- thrust vector control
U_{k_1} , U_{k_2}	- impulsive command coefficients
V_n	- gyroscope vertical signal
WAL	- wide angle lens
a,b	- flare coordinates on the target
α,β	- sight angles of the lenses in vertical and horizontal direction
x	- distance passed by the missile
x_D	- proper distance from CLU up to the target
$x_{v_{\min}}$	- distance passed by the missile from the moment when guidance starts
h_{ref}	- reference flight height
h, y	- missile position metric coordinates in reference to the line of sight
m_h, m_y	- number of the camera working pixels in vertical and horizontal direction
n_h, n_y	- pixel coordinates of the flare image at the picture
f	- lens focus distance
η , ζ	- command coefficients in the vertical and horizontal plane
$\Delta\eta_k$, $\Delta\zeta_k$	- command coefficients increments in the vertical and horizontal plane
$\eta_{\min}$, $\zeta_{\min}$	- minimum command coefficients in the vertical and horizontal plane
$\eta_{\max}$, $\zeta_{\max}$	- maximum command coefficients in the vertical and horizontal plane
η^r	- Earth gravity force compensation coefficient
ζ^r	- Magnus force and momentum compensation coefficient
Δh_k , Δy_k	- linear errors of guidance in the vertical and horizontal plane
ε_h , ε_y	- angular errors of guidance in the vertical and horizontal plane
δ_h , δ_y	- lens resolutions in the vertical and horizontal direction
e_{h0}, e_{h1}, e_{h2}, f_{h1}, f_{h2}	- digital recursive filter coefficients in vertical plane

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e_{y0}, e_{y1}, e_{y2}, f_{y1}, f_{y2} - digital recursive filter coefficients in the horizontal plane

φ_1, φ_2 - "ON" angles of the first and the second pair of interceptors within TVC system

ψ_1, ψ_2 - "OFF" angles of the first and the second pair of interceptors within TVC system

Introduction

CLU is an optoelecronical device intended for the second generation anti-tank missiles launching and guidance to the line of sight defined by the gunner while aiming the target. The CLU, presented in this paper, has CCD cameras, measures the rocket angular deviation from the LS, calculates the angular and linear deviations, generates command signals proportional to the linear deviations and sends them to the missile which is to execute commands in order to achieve the desired flight corrections.

CLU can see the missile as a bright spot at the CCD camera picture, which, in fact, represents the image of the flare at the missile bottom and radiating light energy towards coordinator. In order to be protected against jamming, coordinator and flare are working in time synchronization which is established during the launching preparation phase. In odd half pictures of the CCD camera, the flare is turned on, together with the interferences at the background. In even half-pictures, the flare is turned off and the background with the interferences exists only. In a difference between odd and even half-picture, only the image of flare remains distinguished at the background. The act of the flare image coordinates determination is reduced to the bright spot center of gravity coordinates calculation, [1].

Then, the CLU generates command signals, in intensity proportional to the missile linear deviation from the LS and which satisfy phase and gain criteria of stability for the closed-loop control system. Utilizing the communication channel, CLU sends the command signals to the missile, which, in the form of the commands, are executed by the TVC system and brings the missile to the LS, [2], [3].

Design and functional parts of CLU

The CLU design is shown in Fig.1. The main functional parts of CLU are:

- Optoelectronic coordinator with two CCD cameras, the first one with WAL and the second with NAL.
- Electronical group for the video signal processing and the missile launching and flight control.
- OS for the target acquisition, identification and tracking.
- Trigger for the missile launching sequence initiation.

The CCD camera with WAL is tracking the missile from the moment when it enters the lens field of view (about 1 m from the LT front end) up to the moment when it reaches the distance $x_{v_{\min}}$ (about 50 m from the LT front end). On the CLU command, the missile tracking is taken over by the CCD camera with NAL from the distance $x_{v_{\min}}$ up to the target, [4].

OS is of optoelectronical structure and consists of low-illumination CCD camera with WAL, in optoelectronic coordinator, and LCD with simple ocular equipped with a rubber shock absorber for the gunner's eye focus distance adaptation according to his diopter, in the OS housing, Fig.2. Opto-electronical design of the OS solves the complex ergonomic problem of flexibility in order to compromise the sniper and telescope types depending upon the gunner's combat position during the firing.

The launching trigger has all of the necessary brakes and safeties in order to prevent any accidental firing. At the same time, it serves as the support when the missile has to be fired from the gunner's shoulder at various combat positions.

The CLU electronically structure comprises four cards of euro-format and mother board (MB-10). Those four cards are:

- missile launching sequence control (LA-10),
- CLU computer (AM-10),
- impulsive command generator (GIK-10) and
- CLU DC power supply (DC-10).

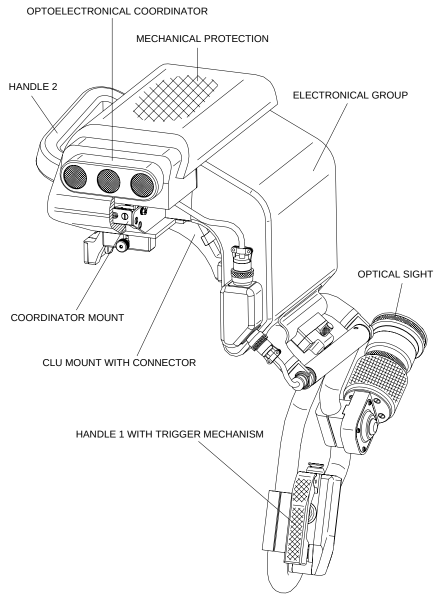


Figure 1. CLU general overview

Mechanical connection and locking of the CLU on to the LT and electrical connection between CLU and LT and missile within LT, is achieved by utilizing the CLU mount and connector. All parts of the CLU design are integrated with the CLU mount and ergonomically shaped. As a whole, it represents the compact functional entirety which is mechanically and environmentally protected during the handling and transporting.

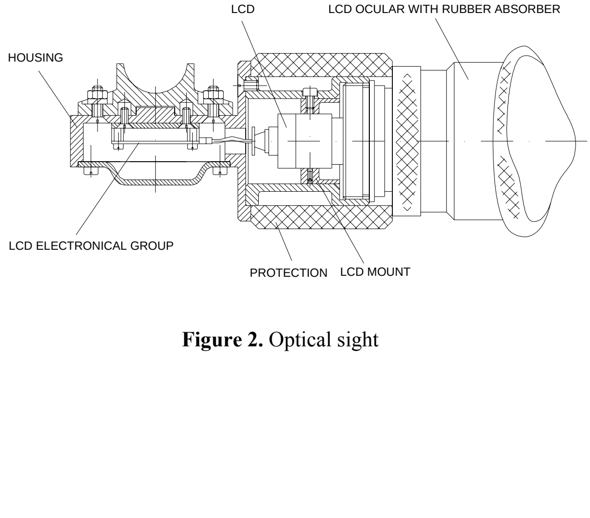


Figure 2. Optical sight

CLU computer

The main tasks of the CLU computer based on AM-10 card are:

1. FPGA circuit operation control in the sense of the picture parameters choice and selection (the number of points in line, numbers of lines, etc.). It also starts and stops the process of the video signal sampling.
2. CCD cameras video signal processing in order to calculate, in real time, coordinates of the flare during the missile flight utilizing an anti-jamming algorithm for the coordinator protection.
3. Calculation of the commands based upon the guidance law, determined in advance, and sending them to the GIK-10 card in the form of control words. The GIK-10 card generates the command signals to the missile at the moment when missile is able to execute them.
4. Missile launching sequence control via LA-10 card.

The block diagram of the AM-10 card and connection with other cards within the CLU electronical structure is shown in Fig.3 and it consists of four functional blocks: digital processor (DSP TMS-320 F240), programmable logical circuit FPGA for the video signal sampling process, block for CCD cameras video signal analogue processing and finally, block for DC power supply (+12V and +5V), [5].

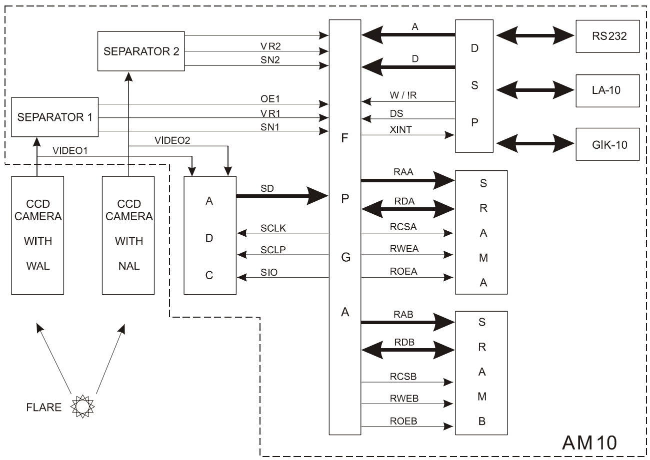


Figure 3. CLU computer structural scheme

The cameras selection is done by the command word (SiO) generated by DSP. The standardized composite video signals from CCD cameras (VIDEO 1 and VIDEO 2) are led to the synchronized impulses separation circuits (SEPARATOR 1 and SEPARATOR 2) and to the fast A/D converter input. From incoming video signal, impulses for vertical (VR) and horizontal (SN) synchronization are seperated and signal (OE) is generated, due to which is possible to recognize the odd from the even half-picture, Fig.4. The camera synchronization impulses determine the working rhythm of the entire system.

The video signal digitalization is done by the fast video A/D converter, which is controlled by automat in FPGA circuit (on the base of OE, VR and SN impulses), using the command signals SCLK, SCLP and SiO. The result of the A/D conversion is sent to the FPGA circuit using the SD bus.

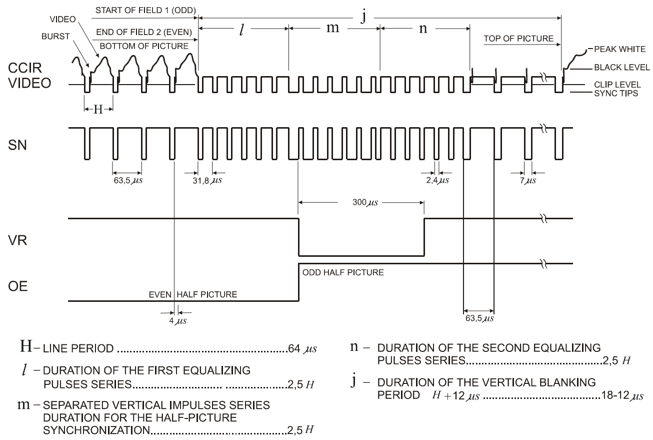


Figure 4. Video and control signals

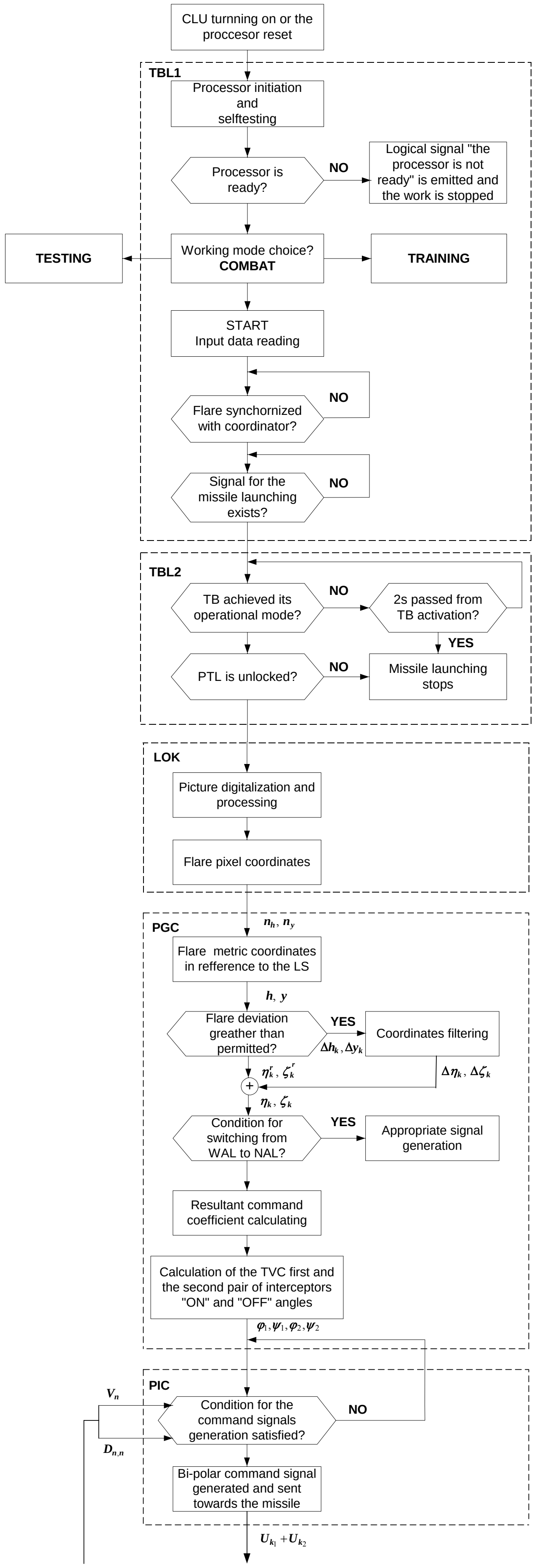
While the CCD camera cells integrate an odd half-picture, A/D converter makes the digitalization of the pixels from previous even half-picture memorized within the camera registers. As the result of A/D conversion, unsigned 8-bit numbers appear, which value is the digital equivalent of the corresponding pixel illumination. The second automat realized within FPGA circuit, takes all of the samples and sets them in SRAM-A, 512 KB memory chip. For the time of even half-picture duration, the flare is turned off. A/D converter than makes again the pixel digitalization of the previous odd half-picture which is memorized in camera registers. From every single incoming odd half-picture sample, with the flare on, the corresponding even half-picture sample, with the flare off, is subtracted from SRAM-A, and the difference between odd and even half-picture is placed into the SRAM-B. For the time of the odd half-pictures duration, DSP is reading the half-picture difference from SRAM-B and, utilizing a centroidal method, calculates the coordinates of the center of gravity of bright point (the flare), [1].

The information distribution between the DSP and FPGA circuits is made by 16-bit data bus and 16-bit adress bus of DSP and command signals W/R and DS. The FGPA is connected with memories SRAM-A and SRAM-B via 19-bit address buses RAA and RAB, 8-bit bus of the RDA and RDB subsystems and via standardized command signals for working with memories RCSA, RWEA, ROEA, RCSB, RWEB and ROEB.

On the basis of the guidance law adopted, the DSP calculates commands and in the form of command words sends them to the GIK-10 card, [6], [7], [8]. DSP also controls LA-10 card, which, in the other hand, controls the sequence of the missile launching, [4].

CLU software

A software shown in Fig.5, is supporting three CLU working modes: combat, testing, training, the first one being analyzed here in details.



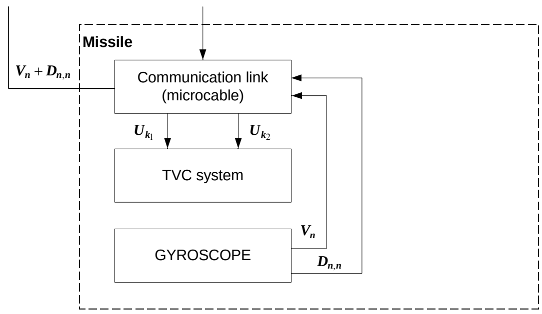


Figure 5. CLU software structural scheme

CLU software comprises the following parts:

1. START, a program for incoming data reading from data library, such as: constants and time delays in the guidance and control system, optical systems parameters, digital recursive filter coefficients, etc.
2. TBL, test before launching, consisting of two parts:

– TBL1 is the CLU functional test which prevents the missile launching sequence for the case when CLU is improper or the flare is not synchronized with the coordinator, $[4]$.

– TBL2 is the launching sequence control test, via LA-10 card, which prevents the BRM ignition if the rocket TB did not achieve it's working mode or PTL on the LT was not unlocked, $[4]$.

3. LOK, picture acquisition and processing program for the flare pixel coordinates determination, $[1]$.
4. PGC, program for guidance and control which has to obtain the following:

– the flare pixel coordinates transformation into the metric coordinates of the rocket position relative to the LS, Fig.6, according to the following expressions:

$$h = n_h \frac{x}{f} \tag{1}$$

$$y = n_y \frac{x}{f} \tag{2}$$

– to calculate the command coefficients in the vertical and horizontal planes, as the functions of the distance passed by the missile, $[9]$, $[10]$:

$$\eta = \begin{Bmatrix} \eta^r & , & x{<}x_{v\min} \\ \Delta\eta_k + \eta^r, & & x{>}x_{v\min} \end{Bmatrix} \tag{3}$$

$$\zeta = \begin{Bmatrix} \zeta^r & , & x{<}x_{v\min} \\ \Delta\zeta_k + \zeta^r, & & x{>}x_{v\min} \end{Bmatrix} \tag{4}$$

and the resultant command coefficient:

$$K = \sqrt{\eta^2 + \zeta^2} \tag{5}$$

where:

$$K=\begin{Bmatrix} 0, & K<0,5\,K_{\min} \\ K_{\min}, & 0,5\,K_{\min}\le K\le K_{\min} \\ K, & K_{\min}\le K\le K_{\max} \\ K_{\max}, & K>\mathrm{K}_{\max} \end{Bmatrix} \quad (6)$$

If the guidance error exceeds the permitted value, than the command coefficients increments $\Delta\eta_k$ and $\Delta\zeta_k$ is to be calculated due to the adopted law of guidance, in the form of digital recursive filter according to the following:

$$\Delta\eta_k = e_{h0}\Delta h_k + e_{h1}\Delta h_{k-1} + e_{h2}\Delta h_{k-2} - f_{h1}\Delta\eta_{k-1} - f_{h2}\eta_{k-2} \quad (7)$$

$$\Delta\zeta_k = e_{y0}\Delta y_k + e_{y1}\Delta y_{k-1} + e_{y2}\Delta y_{k-2} - f_{y1}\Delta\zeta_{k-1} - f_{y2}\zeta_{k-2} \quad (8)$$

where the linear guidance errors with respect to the SL are given by the expressions:

$$\Delta h_k = x\cdot\varepsilon_h - h_{ref} \quad (9)$$

$$\Delta y_k = x\cdot\varepsilon_y \quad (10)$$

and the angular guidance errors with respect to the picture center are:

$$\varepsilon_h = \left(0,5\,m_h - n_h\right)\delta_h \quad (11)$$

$$\varepsilon_y = \left(n_y - 0,5\,m_y\right)\delta_y \quad (12)$$

- to calculate the “ON” angles (φ_1,φ_2) and the “OFF” angles (ψ_1,ψ_2) for the both pairs of the TVC system interceptors in order to eliminate the guidance errors by implementation of the command coefficients calculated as shown above, $[6]$, $[9]$, $[10]$.

5. PIC, a program which generates impulsive command signals (U_{k1} and U_{k2}) by GIK-10 card and sends them to the TVC system (via communication channel) only when they could be executed, depending upon the missile angular position.

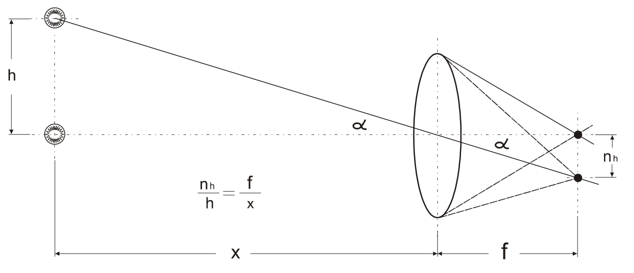


Figure 6. Flare and it image position on the CCD sensor in vertical plane

CLU characteristics

The main CLU characteristics which are identified by the calibration during testing mode of it operation are:

1. The CLU coordinator linear resolution is the minimal disposition of IR radiation source (flare) which causes the change in the flare image pixel coordinates value at the minimum distance between the emitter and CLU at which the pixel coordinates of the flare image, measured with WAL and NAL, have the same value (proper distance X_D). The resolution depends upon the number of CCD sensors pixels, number of points in the line and number of lines of digitalized TV picture. Also, depends upon the view angles of lenses in vertical and horizontal direction, the OS cross-chair width, the video amplifier band pass, the flare radiation intensivity and frequency, time of the CCD sensors exposition, the flare image blooming on the CCD sensor, the lens geometrical distortion and, finally, upon the visibility conditions in the IR communication channel between flare and the CLU.
For the coordinator linear resolution measurement, the target shown in Fig.7a is used and it is positioned at the proper distance $\left(X_D\right)$ from the CLU. This target is used for the resolution measurements both in vertical and horizontal directions and is the same as the graph for the standard TV picture resolution testing, when it is illuminated from the back side.
Moving the flare to the positions of known coordinates on target (Fig.7b), one is searching which is the minimum distance between two positions of the flare emitter in horizontal and vertical direction which can be recognized by CLU on the basis of the pixel coordinates of the flare image, for WAL and NAL.

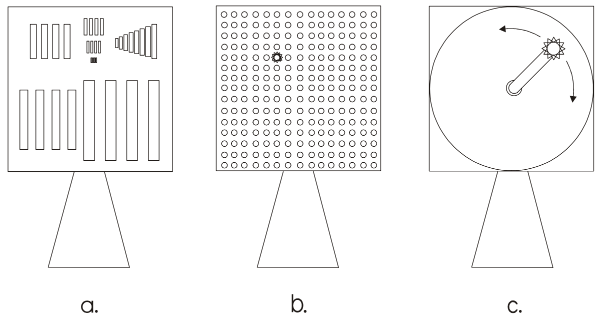


Figure 7. Targets for CLU characteristics testing
a) resolution; b) linearity; c) frequency response

2. The CLU coordinator linearity is the linear deviation of the flare image pixel coordinates with respect to the CCD sensor (picture) center, as the function of flare position in the view fields of WAL and NAL, at the proper distance from CLU. It is dependent on the same influential factors as the coordinator linear resolution is. For the coordinator linearity measurements, the target from Fig.7b is used, at the proper distance from the CLU. The OS cross-chair has to be positioned at the flare center, whose position is at the target center, and the flare image pixel coordinates, on the CCD sensor, have the zero values. Than, CLU must be fixed and WAL and NAL are measuring the image pixel coordinates, at the moments when the flare is turned on at the positions of the known coordinates on the target, for all of the four quadrants of the CLU coordinate system.
3. The CLU coordinator “zero” error is expressed as an error signal at the coordinator input even when the flare, simulating a target, is situated at the cross-chair center. This error is generated when the WAL, NAL and OS optical axes are not parallel, due to the CLU mechanical deformations during the long period of exploitation, displacement of the optical axes of lenses, lenses dilatation, nonverticallity of the lenses axes on to the appropriate CCD sensor plane, etc. This error is eliminated either in

"hardware" way by removing the mechanical deformations, or in "software" way by correction of the coordinates measured during the missile flight for the "zero" error value, which has to be memorized as a CLU input parameter.
The "zero" error is determined by measuring the flare image pixel coordinates deviation from zero position on the WAL and NAL CCD sensors, when the OS cross-chair is settled at the flare center on the target, at the proper distance from CLU.

4. The CLU coordinator sensitivity is defined as the flare minimal necessary radiation intensity which, in dependence on the missile maximum range, does not cause degradation in the CLU coordinator linearity and resolution, nor the change in the pulse width modulated command impulses. Sensibility depends upon the WAL and NAL pupil diameter and optical efficiency, the band pass and transitivity of IR filter in front of CCD sensors, time of exposure and the CCD sensors frequency response and sensitivity.
For the CLU coordinator sensitivity measurement, it is necessary to identify the minimum of the flare radiation power which does not cause the degradation of characteristics mentioned, at the maximum distance from the CLU to the target in Fig.7b.
5. The CLU coordinator spectral response or the CLU coordinator band pass is the spectral range of input radiation at the CLU lenses which is enough for CCD sensors to generate response signals greater than proposed signal/noise ratio, expressed in dB. The input radiation spectrum of the flare, near to the IR spectrum, has to be harmonized with the WAL and NAL CCD sensors spectral responses. For the CLU coordinator spectral response measurements, a collimator and the set of instruments and optical accessories are exploited, according to the rules and methods specially defined.
6. Sighting angles of the CLU lenses are the optical characteristics of WAL, NAL and OS and are defined as the sighting field of certain dimension in function of the distance from input aperture of corresponding lens. For the sighting angles measurement, the target shown in Fig. 7b could be used, located at the proper distance from the CLU. The sighting lens cross-chair has to be settled at the target center and the flare has to be moved to the positions of the sighting lens view limits, both in vertical and horizontal directions. The CLU lenses sighting angles are calculated according to the following expression:

$$\alpha = \tan^{-1}\frac{2a}{x_D} \tag{13}$$

$$\beta = \tan^{-1}\frac{2b}{x_D} \tag{14}$$

7. The CLU frequency response is defined as the maximum allowed rate of the flare angular position displacement (rad/s) at which amplitude and phase errors of the width modulated command impulses stay within missile closed loop guidance stability margin. Besides the other factors, it is dependant upon the CLU coordinator operation rate (T=20ms). For the CLU frequency response measurements, the target from the Fig.7c is used, placed at the proper distance from CLU, where the flare angular velocity of rotation can be changed on purpose.
8. The CLU minimal command threshold is the flare angular position minimum change, in reference to the LS, which causes the minimum intensity command signal (Kmin) at the CLU exit. The flare angular position minimum change is measured utilizing the target in Fig. 7c, placed at the proper distance from the CLU and is calculated in accordance with expressions (13) and (14). The OS cross-chair is positioned at the target center. Then, the flare minimal distance from LS has to be found in vertical and horizontal directions, at which, the minimal command signal is generated. The minimal command threshold is depending on the CLU coordinator resolution, the TVC system response rate and efficiency, the missile mass, the missile guidance "tunnel" diameter, etc.
9. The CLU exit characteristics are:
   - The TB and the gyroscope igniting impulse voltage and width, generated by the pressing of the CLU triggering button.
   - The PTL igniting impulse voltage and width, if CLU received the information that TB achieved it operational regime.
   - The BRM igniting impulse voltage and width, if CLU received the information that PTL is unlocked and the BRM ignition circuit switch is closed.
   - Impulses voltage, width and frequency, for the CCD camera synchronization with the flare.
   - Pulse modulated command impulses of constant voltage, with variable duration (from Kmin to Kmax) and the position depending upon the missile angular position during it every single rotation.
10. The CLU input characteristics are:
   - The CLU working voltage, obtained from the lithium battery by activation of the switch on the CLU trigger.
   - The flare radiation energy in IR spectrum, of certain frequency which, via WAL and NAL, is transmitted to the CCD sensors of corresponding spectral responses.

Conculusion

The CLU main functional parts are: optoelectronical coordinator, electronical block, OS, and trigger. The OS is of optoelectronical structure. The electronical block consists of few euro-formatted cards: LA-10, AM-10, GIK-10, DC-10 and mother board MB-10. The primary function of the computer based on AM-10 card is the CCD cameras signals processing in order to calculate the flare coordinates in real time, during the missile flight with the coordinator anti-jamming algorithm implementation.

The calculator is realized through the digital processor DSP TMS-320 F240. The video signals digitalization is achieved by the fast video A/D converter, controlled by the automat in the FPGA circuit.

The software supports three of the CLU operation modes: combat, testing and training. In the combat mode, the CLU software consists of the following programs: for the processor starting and self-testing, for the input data file (START) reading, for the launching sequence control (TPL), for the picture acquisition and processing (LOK), for the missile guidance and control (PGC), for the impulse command signals generation and sending them to the missile by the communication link (PIC).

The CLU basic characteristics are: the coordinator linear resolution, linearity, "zero" error, sensitivity, spectral response, as well as the lenses sighting angles, frequency response, the minimal command threshold, incoming and exit characteristics of the CLU.

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Izbor i analiza optimalnog rešenja uređaja za vođenje i lansiranje protivoklopne rakete

Prikazan je princip rada UVL protivoklopne vođene rakete koju strelac može da lansira sa ramena ili postolja. Opisane su osnovne funkcionalne celine i konstrukcija UVL, koji koristi CCD kamere kao senzore u koordinatoru. Izvršen je prikaz i analiza rada računara UVL i osnovne funkcije softvera koje se odnose na: kontrolu sekvence lansiranja rakete, akviziciju i obradu slike u cilju određivanja pikselskih koordinata trasera, vođenje i upravljanje raketom. Definisane su osnovne karakteristike UVL, metode za njihovu verifikaciju i faktori koji na njih utiču.

Ključne reči: **protivoklopna raketa, vođena raketa, vođenje rakete, koordinator, traser, CCD kamera, softer, blok šema**

Le choix et l'analyse de la solution optimale pour le guidage et le lancement d'un missile antichar

On a présenté le principe du fonctionnement de UVL d'un missile antichar guidé que le tireur peut lancer de son épaule où à partir d'un support. On a également décrit les foncti-ons principales de l'ensamble et la construction UVL qui utilise les caméras CCD comme senseurs dans le coordinateur. On a fait une analyse du fonctionnement de l'ordinateur UVL et des principales fonctions telles que: controle de séquence du lancement de missile, acquisition et traitement de l'image dans le but de déterminer les coordonées pixel de traceur, guidage et direction du missile. Les principales caractéristiques de UVL ont été définies ainsi que les méthodes de leur vérification et les facteurs y influents.

Mots clés: **missile antichar, missile guidé, guidage de missile, coordinateur, traceur,CCD caméra, logiciel, blocschéma, bloc-diagramme**

Выбор и анализ оптимального решения устройства для наведения и запуска противобронированной ракеты

В настоящей работе показан принцип работы пусковой установки противобронированной управляемой ракеты, которую стрелок может запускать со плеча или со кронштейна. Здесь описаны основные функциональные целостности и конструкция пусковой установки, которая пользуется CCD камера в роли чувствительного элемента в согласующем устройстве. Тоже сделаны демонстрация и анализ работы вычислителя пусковой установки и основные функции программного обеспечения, которые относятся к контролю последовательности запуска ракеты, к воспроизведению и обработке изображения с целью определения координат следящего устройства, и к наведению и управлению ракетой. Здесь уточнены основные характеристики пусковой установки, методы для их удостворения и факторы которые на них влияют.

Ключевые слова: противобронированная ракета, управляемая ракета, наведение ракеты, координатор, следящее устройство, CCD камера, программное обеспечение, блок-схема