PROBLEMY MECHATRONIKI
UZBROJENIE, LOTNICTWO, INŻYNIERIA BEZPIECZEŃSTWA

ISSN 2081-5891 **10, 1 (35), 2019, 49--58**

PROBLEMS OF MECHATRONICS
ARMAMENT, AVIATION, SAFETY ENGINEERING

Mathematical Model of the Surveillance, Tracking and Fire Control System of the Short-Range ADGM System

Bogdan ZYGMUNT, Konrad SIENICKI, Damian WOJTYRA*

Military University of Technology, Faculty of Mechatronics and Aerospace,
2 gen. Witolda Urbanowicza Str., 00-908 Warsaw, Poland
**Corresponding author's e-mail address and ORCID*:
damian.wojtyra@wat.edu.pl; https://orcid.org/0000-0003-0396-6954

Received by the editorial staff on 8 April 2018
The reviewed and verified version was received on 28 February 2019

DOI 10.5604/01.3001.0013.0796

Abstract The paper presents the development and simulation of a mathematical model of an automatic tracking and fire control system. The authors focused on very short-range air defense (VSHORAD) gun/missile systems.
Keywords: automatics, mathematical model, anti-air system, automatic tracking

1. INTRODUCTION

Automated systems replacing human work are increasingly more common, both in civilian and military applications. Through the increasing availability of cutting-edge technologies, both air defense systems and means of air aggression are being developed.

This work has been compiled from the paper presented during the 22nd International Workshop on *CAD, CAM and CAE Systems*, Pisz, Poland, May 14-18, 2018.

The problem that automatic targeting systems face is the necessity of detecting and tracking objects located at distances ranging from several hundred metres to more than ten kilometres, both during the day and at night. The objects to be tracked are characterised by highly varied sizes, from UAVs to fighter aircraft. Additionally, the targets can achieve speeds of up to 300 m/s and are further characterised by high manoeuvrability. The required high dynamics of target and fire control systems translate to issues related to control systems, which must be characterised by high stability and as short an adjustment time as possible. Well-designed control systems must be complemented by the correct equipment, including an optoelectronic head, as well as other advanced elements of an Air Defense Gun/Missile System.

2. AIR DEFENSE GUN/MISSILE SYSTEM (ADGMS)

The mathematical model was prepared on the basis of the “Pilica” - Air Defense Gun/Missile System (Fig.1).

Fig. 1. General view of the Air Defense Gun/Missile System
(source: www.magnum-x.pl)

This system is a modification of the ZSU23-2 23 mm towed twin gun system, commonly used in the Polish Armed Forces. The system is armed with twin 23 mm cannons, with a theoretical rate of fire of 2000 rpm and an effective range of up to 2.5 km, and two GROM VSHORAD missiles with a range of 5.5 km and a ceiling of below 4 km. Each cannon is fed using a 50-round belt. Objects are observed and detected using an optoelectronic head integrated with the system. The head is equipped with a daylight camera, a thermal camera, and a laser rangefinder. Additionally, the camera feed is processed by a video tracker, enabling detection of objects in the feed. The Air Defense Gun/Missile System is also equipped with an on-board computer, which enables implementing control systems and automated target elimination algorithms.

The system also has other elements supporting automated operation, i.e. a yoke, an IFF device, a safety controller, gun drive controller, CP-1 controller, operator's panel displaying camera feeds and basic system status information. The Air Defense Gun/Missile System is used to provide anti-air point-defence to troops and important facilities.

3. MATHEMATICAL MODEL OF THE SURVEILLANCE, TRACKING AND FIRE CONTROL SYSTEM OF THE ADGMS

The surveillance, tracking and fire control system automates all target elimination processes, from target acquisition to directing fire on the target, taking into account deflection angles and ballistic corrections. Separation of all system functions was implemented through the ability to use three operation modes:

- manual mode
- semi-automatic mode
- automatic mode

The **manual mode** enables the operator to observe the situation in the air using the system's optoelectronic head and video tracker, which indicates objects in the feed which may be potential threats. Handling the yoke, the operator steers the gun drives, the algorithm minimises the discrepancy between the positions of the head and the gun axis, which enables the surveying operator to quickly react to threats without using automatic tracking. The manual mode enables target elimination without using all elements of the system; it can be used in the event the equipment is not fully operational.

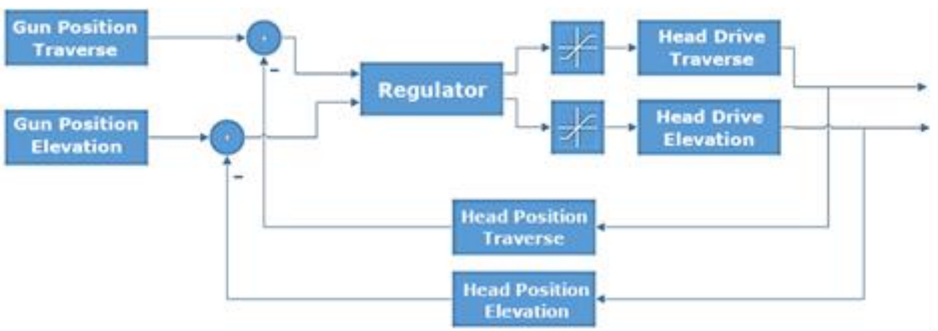

Fig. 1. Manual mode control system (source: author's own)

The **semi-automatic mode** performs both the air surveillance and automatic target tracking functions. In the first phase, as in the manual mode, the operator uses the yoke to steer the optoelectronic head. However, unlike the manual mode, the operator surveys the air situation using the optoelectronic head only.

If a threat is detected, the operator may move to phase two and activate automatic target tracking. When an object is selected using the video tracker, the head begins the automatic tracking of the object. The control algorithm, taking data from the video tracker, minimises the discrepancy between head and target positions.

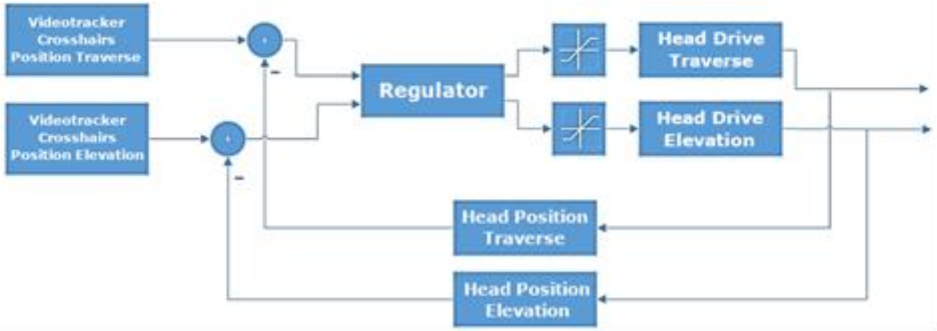

Fig. 2. Semi-automatic model control system (source: author's own)

The **automatic mode**, the system's primary mode of operation, enables automatic target tracking using the optoelectronic head and guns. After acquiring the target in the semi-automatic mode, the operator switches to the automatic mode. The control algorithm minimises the discrepancy between the optoelectronic head (which is tracking the target) and the gun axis. Additionally, if gun ammunition is used, the algorithm adds dynamically calculated deflection angles and a ballistic correction using information provided by the video tracker, optoelectronic head and ballistic charts. The automatic mode also includes cooperation with a command post. The algorithm aligns the gun axes to the transmitted target position data and begins tracking the acquired target.

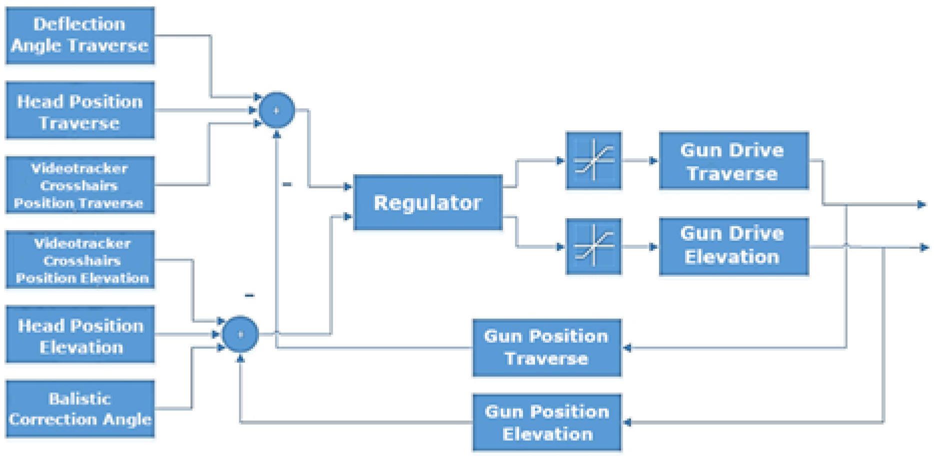

Fig. 3. Automatic mode control system (source: author's own)

Based on the above principles, a mathematical model representing all operation modes of the system was prepared. Using the actual response of the optoelectronic head systems and gun drives, the above objects were identified. The System Identification Toolbox from the Matlab software was used for system identification. The result of the identification are discrete transfer functions for the optoelectronic head's horizontal position and elevation, as well as gun drives. Due to the nature of the control systems, object input was specified as traverse and elevation speed, and the output as positions in the respective planes. Sampling time Ts = 0.1 [s] during identification.

Discrete transfer functions obtained in the identification process:

- Optoelectronic head transfer function – traverse

$$G(z) = \frac{0.069\ z^{-2}}{1 - 1.478\ z^{-1} + 0.478\ z^{-2}} \tag{1}$$

- Optoelectronic head transfer function – elevation

$$G(z) = \frac{0.169\ z^{-2}}{1 - 0.561\ z^{-1} - 0.437\ z^{-2}} \tag{2}$$

- Gun drive transfer function – traverse

$$G(z) = \frac{0.018\ z^{-2}}{1 - 1.876\ z^{-1} + 0.876\ z^{-2}} \tag{3}$$

- Gun drive transfer function – elevation

$$G(z) = \frac{0.041\ z^{-2}}{1 - 1.702\ z^{-1} + 0.702\ z^{-2}} \tag{4}$$

Two regulator types were applied in the mathematical model:

- Minimising function

$$U(n) = \frac{2}{1+e^{-\beta e(n)}} - 1 \tag{5}$$

$U(n)$ – control value, $e(n)$ – error value at a specific moment, β – regulator amplification factor value

- PI discrete regulator.

4. SIMULATION OF THE MODEL OF THE SURVEILLANCE, TRACKING AND FIRE CONTROL SYSTEM OF THE ADGMS

Matlab/Simulink software was used to simulate the developed model. Model simulation for the manual mode was conducted for varying speeds, the semi-automatic and automatic modes were tested for different speeds, distances and altitudes of the simulated targets.

Deflection angles and ballistic corrections were not taken into account in the model developed due to calculation complexity. However, adding the above elements will not change the system's dynamics, and consequently the simulation will remain reliable when the deflected point is taken into account. The results were compared when taking into account the PID regulator, as well as the minimising function. Below, simulation results for a target flying over at a speed of 100 m/s, at an initial distance of approx. 1 km and constant altitude of 700 m.

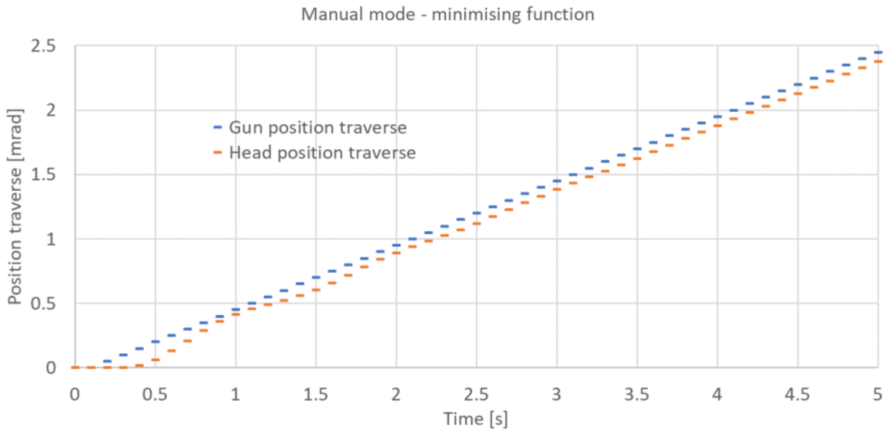

Fig. 4. Manual mode - head traverse control system (minimising function)

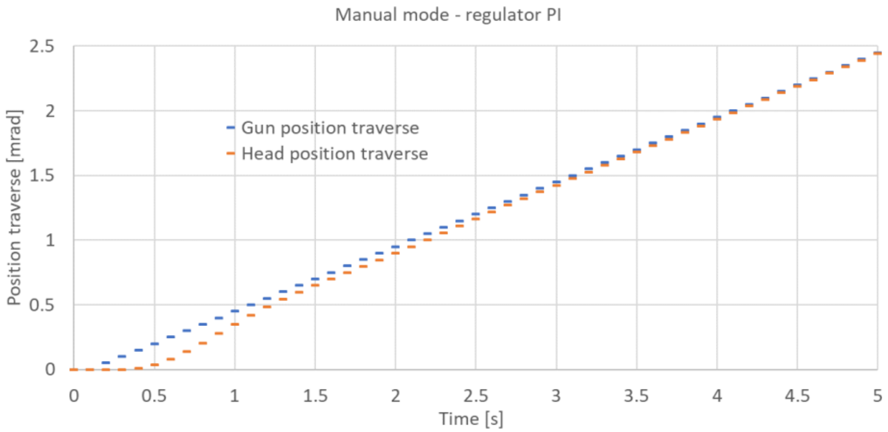

Fig. 5. Manual mode - head traverse control system (PI regulator)

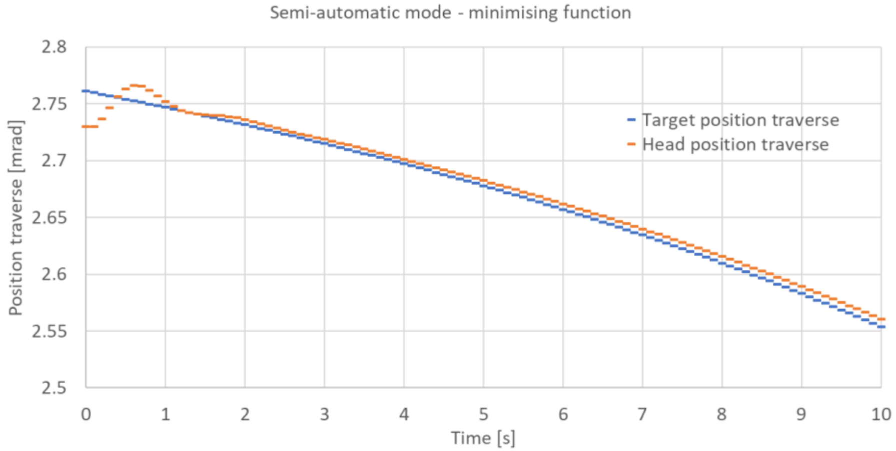

Fig. 6. Semi-automatic mode (tracking) - head traverse control system (minimising function)

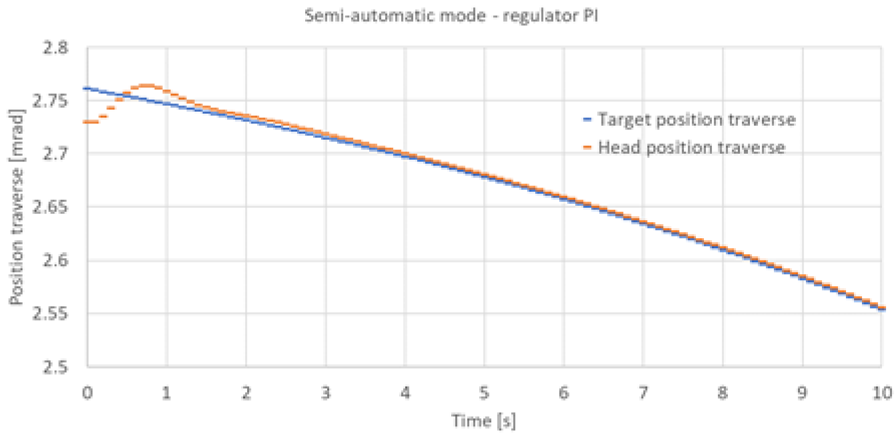

Fig. 7. Semi-automatic mode (tracking) - head traverse control system (PI regulator)

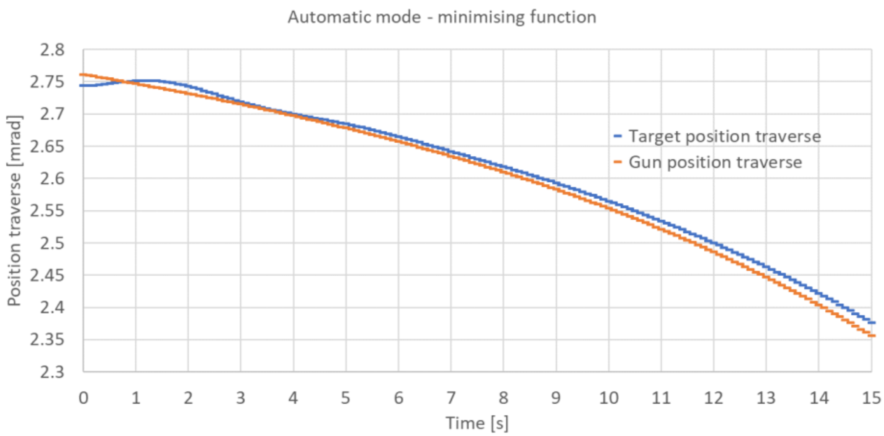

Fig. 8. Automatic mode - gun drive traverse control system (minimising function)

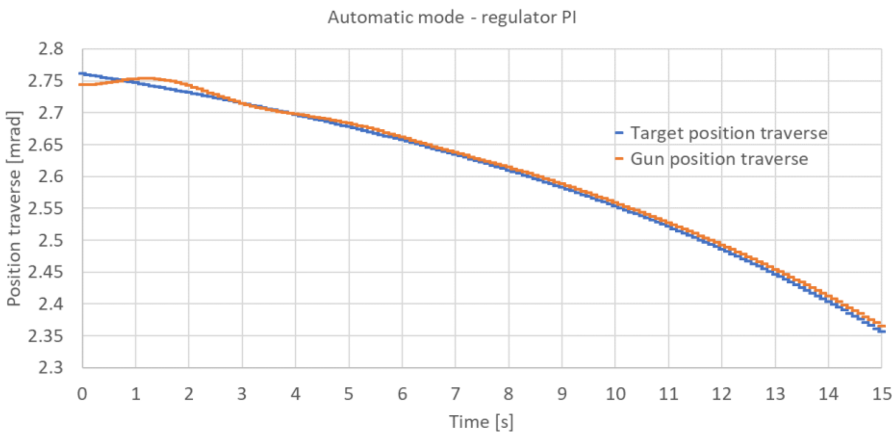

Fig. 9. Automatic mode - gun drive traverse control system (PI regulator)

In the above charts, the blue line shows the input value - target position (or a value forced by the yoke), while the red line - the value effected by the control system.

5. SUMMARY

The mathematical model developed enables determining the dynamics of the surveillance, tracking and fire control system. The minimising function reduces the system adjustment time, although due to the dynamics of the objects, the offset increases proportionally to simulation duration. The PI regulator is effective at reducing the offset emerging with time, which enables accurate tracking at longer fixing times. For slower targets, the PI regulator is more effective, while for higher target speeds, the adjustment time is too long. The mathematical model is part of a doctoral dissertation titled "Optimisation of the surveillance, tracking and fire control system of the short-range Air Defense Gun/Missile System". The correctness of this model will be verified at a later stage of the study by comparison with test range data.

REFERENCES

[1] Borowczyk Włodzimierz, Wojciech Kaczmarek. 2013. „Calculation of the selected parameters of the laboratory stand in study of the optoelectronic heads” (in Polish) . *Mechanik* 86(7) : 41-51 CD.

[2] Kaczmarek Wojciech, Jarosław Panasiuk, Włodzimierz Borowczyk, Krzysztof Dzięciołowski, Łukasz Zbrzeżny. 2014. „Selected aspects of laboratory tests of optoelectronic heads” (in Polish). *Mechanik* 87(7) : 273-283 CD.

[3] Kaczmarek Wojciech, Konrad Sienicki. 2010. „Mechatroniczne aspekty projektowania rozproszonych systemów obrony przeciwlotniczej”. *Mechanik* 83(7CD) : 501-508.

[4] Kaczmarek Wojciech, Jarosław Panasiuk, Konrad Sienicki, Waldemar Śmietański, Damian Wojtyra . 2016. „Research of ballistic calculator using optoelectronic head” (in Polish). *Mechanik* 89(7) : 714-715.

Model matematyczny systemu obserwacji, śledzenia i kierowania ogniem PZRA krótkiego zasięgu

Bogdan ZYGMUNT, Konrad SIENICKI, Damian WOJTYRA

Wojskowa Akademia Techniczna, Wydział Mechatroniki i Lotnictwa
ul. gen. Witolda Urbanowicza 2, 00-908 Warszawa 46

Streszczenie. W artykule przedstawiono opracowanie i symulację modelu matematycznego systemu automatycznego śledzenia i kierowania ogniem. Autorzy skupili się na przeciwlotniczych zestawach rakietowo-artyleryjskich krótkiego zasięgu.
Słowa kluczowe: automatyka, model matematyczny, zestaw przeciwlotniczy, automatyczne śledzenie.