Air Defence Command and Control System Modelling and Simulation for War-gaming

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***Abstract*—Command and Control (C2) is a crucial part of any military system. The article deals with modelling and simulation (M&S) of the C2 system in context with Surface Based Air Defence (SBAD) and fire control and target distribution. The main task was to design and simulate procedures of C2 systems which correspond with real C2 structures including target detection, identification and assignment to unallocated fire unit (FU). The model was designed as a generic C2 model, with variable time constant using uniform probability distribution. The queueing theory was also applied for a higher number of FUs and targets.**

Keywords— Command and Control, C2, Modelling and Simulation, M&S, War-gaming, air defence, SBAD

I. INTRODUCTION

Despite the fact, that the complex C2 system structures are very variable and usually customized to the specific tasks, in accordance with SBAD units, there are several roles (procedures) which are always included. The essential task is to detect an aerial object (potential target), by radar or a different type of sensor (visual, IR, etc.), next step is to identify the object, if it is friendly or hostile. This can be provided by Identification Friend or Foe (IFF) system of the radar or by other procedures (flight plan comparison, visual identification, etc.). In case of positive hostile identification and possible threat, the action has to be done. The target is assigned to the effectors (Fire units) and in case of possible engagement the FU, target is engaged. If the engagement is not possible, the target is passed to another FU, or to the queue and it is processed in accordance with queue theory.

A. State of Art

There is a number of different M&S tools on the market, which are used in security and military fields, e.g. tactical simulators, such as Virtual Battle Space (VBS) [1], PRESAGIS STAGE [2] or constructive war-gaming platform MASA SWORD [3]. All of them are world-wide popular, robust simulators used by many military and non-military institutions and companies. Even though, these platforms are very complex, the proper C2 structures, especially for Air Force/Air Defence are missing, or they have to be additionally created and implemented. The disadvantage of such commercial off-the-shelf (COTS) solutions is a high price and unknown inner structure which is often shipped as a black-box (companies are considering this core as their know-how). Those are the main reasons, why the own SBAD simulator is being developed. The final simulator will be Air Force and SBAD focused with open and easily modifiable structure, even for educational purposes.

B. Concept of the Simulator

Each step in the C2 process has designated time, which depends on a number of factors (e.g. type of the C2 system, level of automation, skills of the human crew, etc.) This time defines the essential criteria for the entire C2 system performance and in the simulator morphology in the uniform probability distribution form, where maximum and minimum time value is set.

The C2 simulation is being developed as an Event simulation [4],which is the main part of the hybrid simulator. The second part is designed as an Ordinary Differential Equation (ODE) solver for the simulation of the airplane and missile movement [5].

C. Modelling and Simulation Tools

The M&S of C2 System is a part of complex Air Defence Simulator which is currently under development at University of Defence in Brno. As a primary programming tool, we used the Python programming language, Jupyter notebook environment [6] in Google Colab [7] and Anaconda [8] programming platform. The Jupyter notebook environment offers number of benefits like language simplicity, robustness, world-wide usage and user support.

The Jupyter Notebook is an open-source application for interactive computing that allows the creation and sharing of interactive documents with live code, equations and visualisations [6] and the output is formatted as an interactive document for further educational applications.

II. COMMAND AND CONTROL SYSTEM

This chapter is focused on a general overview of the C2 system and its conventional structure, mainly in connection with the SBAD units. As it was mentioned in the introduction, there is no unified C2 system and it is usually modified for each task (mission).

A. Command and Control

For the purpose of the paper, a centralized type of C2 system with decentralized execution in a generic simple form was simulated. The entire C2 system consists of three entities, the Radar, the Command Post (CP) with Fire Direction Centre (FDC) and the Fire Unit (FU), see Fig. 1, where RADAR, CP/FDC and FU are represented by NATO Tactical Symbology [9]. Information of a more complex C2 system and data-link communication can be found in [10], [11].

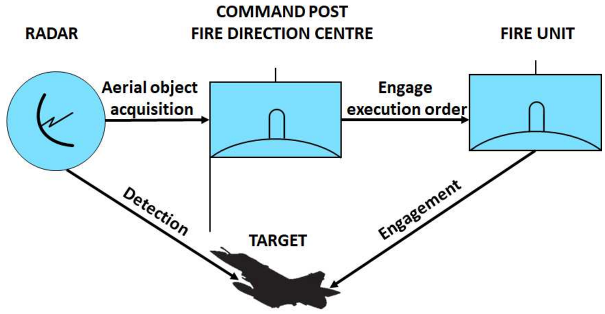

Fig. 1 Overall C2 System Simulation Structure

B. SBAD C2 Exexution

Definition of the real SBAD C2 system includes a large number of functionalities and roles, such as airspace surveillance, aerial objects identification, unit deployment, readiness state control, force protection, engage/cover order issue, etc. This is a very complex process which can be split within several levels of CP.

The presented structure represents a minimalistic version of the C2 system and covers the following essential functionalities (in parentheses, there is the entity which provides the task).

- Air surveillance (RADAR)
- Aerial object detection (RADAR)
- Aerial object ID Assignment (RADAR)
- Aerial object identification (CP/FDC)
- Target assignment to FU (CP/FDC)
- Target engagement order issue (CP/FDC)
- Target engagement execution (FU)
- Target elimination confirmation (FU)

The process is described in more detailed way in Fig. 2 and Fig. 3 and the radar model is based on the research [12].

III. SOLUTION

Each of the presented functionality (event) was modelled as an independent function by Python programming language with the following structure, see Code 1.

```
def FUNCIONALITY NAME
(addEvent, time, sim, targetId):
sim.AddLog(f'at {time} a target {targetId}T
EXT_OUTPUT, time=time, targetId=targetId)si
m.AddEvent(randomTime(time,MIN,MAX),
targetAssigned, sim=sim, targetId=targetId)
pass
```

Code 1 Python functionality step pseudocode

Each function has a unique name and following arguments,

- *addEvent* – add simulation state to the event list,
- *time* – assign simulation time to the event,
- *sim* – call simulation solver function,
- *targetId* – assign unique identification number of aerial object,

and conduct following actions,

- *sim.Addlog* – add the function data to the simulation log,
- *sim.AddEvent* – perform/add functionality time delay according to the uniform probability distribution with defined limit values (MIN and MAX).

A. Queueing Theory

In a case of multiple targets or fire units, the Queueing Theory (QT) was applied [13]. Generally, according to the Kendall's notation, the system is type ***M/M/n/r***. Where the first ***M*** represents the Poisson distribution of incoming targets (λ), second ***M*** stand for the Poisson distribution of service (μ), and ***n*** is a number of FU (parallel channels) and ***r*** defines the limits of a queue (number of targets or maximum waiting time).The value $\boldsymbol{p_k}(\boldsymbol{p_0})$ is a probability of a successful engagement, see (1).

$$p_{k+1} = \frac{\lambda}{\mu}\frac{p_k}{n} \Rightarrow p_k = p_0\left(\frac{\lambda}{\mu}\right)^k \frac{1}{n!n^{k-n}}; k = n+1, \dots, n+r \quad (1)$$

For the purpose of this paper, the ***D/U/n/∞*** type of QT system was used. The incoming targets are deterministically defined (***D***), the C2 system has the uniform distribution (***U***), there is the ***n*** FUs and an infinite queue (∞). In the case of no vacant FUs, the target is waiting in a queue and will be engaged immediately after the queue gets vacant. The simplification with an infinite queue is used only for the state model of QT system evaluation. In a real system, there is always the waiting time limit.

B. State Model

The State model consists of three main entities (blocks), the RADAR, the COMMAND POST and the FIRE UNITs, see Fig. 2 and Fig. 3. The State model illustrates functionalities of entities and their connection.

The state model of the FU (Fig. 3), shows the two channels system, which is solved by the queue theory. NO JOY represents the term for no or impossible activity.

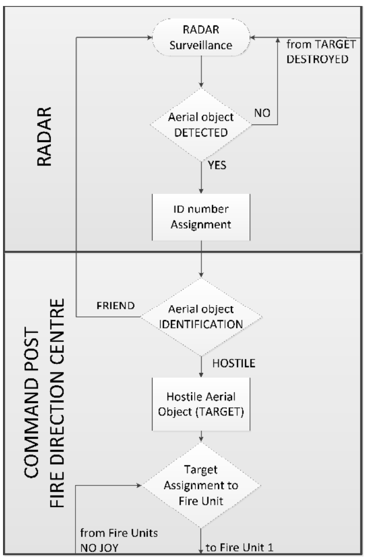

Fig. 2 State diagram of RADAR and COMMAND POST

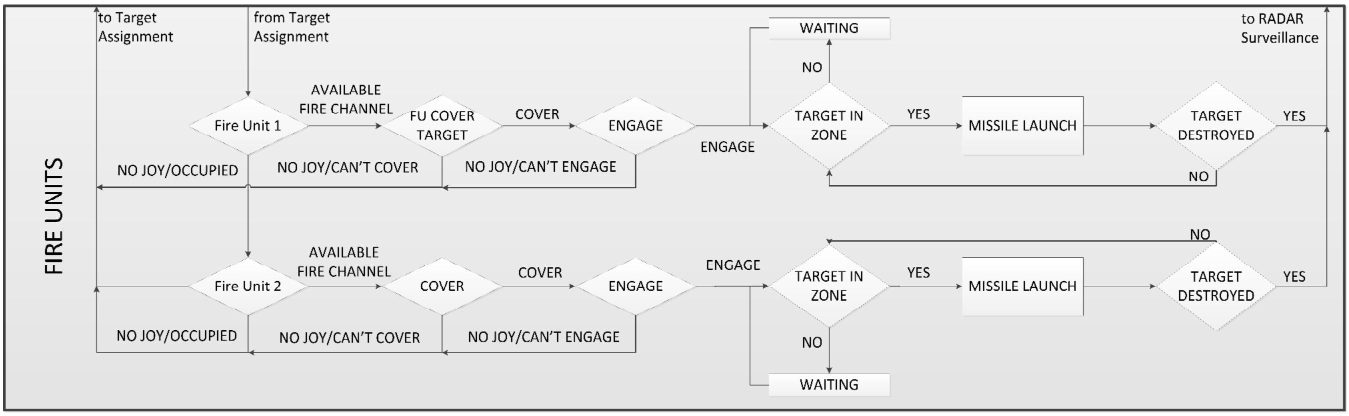

Fig. 3 State diagram of FIRE UNITs

IV. Simulation Evaluation and Verification

The presented solution was verified in the following scenarios.

A. Scenario one – C2 process evaluation

The first scenario consists of one aerial object (AO) and one FU, where the initial time is randomly generated using Python random library. This scenario serves for evaluation of the C2 process and the uniform probability distribution time setting of each step. See TABLE I.

TABLE I. C2 time settings and evaluation scenario one

C2 procedure name	Min time [s]	Max time [s]	Total sim. time [s]
1. AO detection[a]	3	5	0
2. AO info. transfer to C2	5	10	3.71
3. AO identification	3	5	12.52
4. Target assignment to FU	7	15	16.77
5. Target is covered by FU	3.5	5	28.19
6. Target is irradiated by FU	5	7	32.10
7. Target is aimed by FU	1	4	38.56
8. Missile is launched[a]	10	30	40.66
9. Target is destroyed[a]	3	5	59.17

a. These steps will be replaced with ODE times from ODE models.

The total simulation time starts from the moment, when an aerial object is detected. The procedures 1, 8 and 9 are for the purpose of this paper also defined by minimum and maximum time, however, in the following research they are going to be replaced with values of time from ODE part of the simulation [5], [14]. In the step one unique ID number is also assigned to the AO and it is used during the entire simulation.

The simulation log output of steps 4, 5 and 6 is in Code 2.

```
{'msg': 'at 16.774133751154 a target 1 was given
to 0 channel', 'time': 16.774133751154,
'targetId': 1, 'channelId': 0}
{'msg': 'at 28.19221362824 a target 1 is
followed on 0 channel', 'time': 28.19221362824,
'targetId': 1, 'channelId': 0}
{'msg': 'at 32.09943004293 a target 1 is
irradiated on 0 channel', 'time':
32.09943004293, 'targetId': 1, 'channelId': 0}
```

Code 2 Simulation log output

The log messages include the message time, target ID, FU ID and an information text (e.g. target is followed).

B. Scenario two – multiple FU and AO evaluation

This scenario represents the situation, where are two FUs and three AOs. According to the QT simulation settings (see chapter III.A) two out of three AO will be engaged by FU one and two. The last AO will wait until one of the FUs will be vacant. The C2 time settings is the same as in the scenario one.

TABLE II. Evaluation of scenario two

C2 procedure name	Sim. time AO 1 [s]	Sim. time AO 2 [s]	Sim. time AO 3 [s]
1. AO detection	0	0	0
2. AO info. transfer to C2	3.49	3.64	4.65
3. AO identification	10.78	12.55	13.46
4. Target assignment to FU	FU 1 15.76	FU 2 16.06	FU 2 58.19
5. Target is covered by FU	25.57	25.51	67.99
6. Target is irradiated by FU	30.01	29.61	72.09
7. Target is aimed by FU	36.42	36.11	77.23
8. Missile is launched	38.98	38.17	79.36
9. Target is destroyed	58.84	54.56	96.27

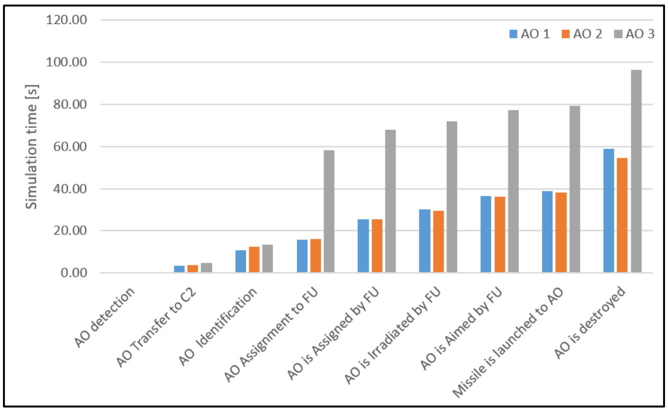

Fig. 4 Simulation of Scenario two - results

The scenario two simulation values apparently correspond with assumed results, see TABLE II. and Fig. 4, where all three AOs are detected, transferred and identified in *13.46 s*. Then the AO 1 is assigned to FU 1 and AO 2 to

FU 2. The FU 2 procedures were executed faster than FU 1 procedures, and the AO 2 was destroyed at time *54.56 s* (AO 1 at *58.84 s*). The FU 2 was vacant earlier, and therefore the AO 3 was assigned to the FU 2, and was engaged and destroyed at *96.27 s*.

V. Conclusion and Future Work

The paper and its results presents the implementation of the C2 system into the complex SBAD simulator, which is currently being under development at the University of Defence. Based on the results in the chapter IV, it can be stated, that the behaviour of the C2 structure model corresponds with the assumptions. The two generic scenarios have been designed. The first for the C2 process verification, where all C2 steps were defined by minimum and maximum time values with the uniform probability distribution. The second scenario was aimed for the multiple aerial objects and fire units, verification, using the queuing theory.

As stated in the introduction, the entire simulator is being developed for not only experimental tasks, but also for educational purposes. That is why, the Jupyter notebooks and Python language has been used and each part of the simulator has been developed as an independent Python library.

The paper is primarily focused on the C2 procedure and its modelling and simulation, where the C2 system structure is not always the same, and can be modified according to the specific tasks. Therefore, the simulation structure is designed in a generic form, where each step can be adapted to the given task.

The future work will be focused on the integration of the ODE simulator part (simulation of a target/missile aerial movement) with the event simulator part of the C2 and the RADAR. All of these parts will be implemented over the maps with terrain and enable providing the SBAD tactics evaluation and planning [15]. It will be also applicable for Fire Direction Operators effective training [16] in connection with improved ergonomic user interface [17].

Acknowledgement and Disclaimer

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All time values, command and control system structures, tactical and technical data of military systems are generic just for the purpose of the article and they are unclassified.

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