A methodology to enhance Urban Reconnaissance UGV requirements through simulation

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Thesis submitted in fulfilment of the requirements
for the degree of Master of Philosophy

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October 2009

Declaration

I certify that this thesis is my own work, except where indicated. I have identified my resources. I also declare that this thesis has not been submitted, either in the same or different form to any other University.

Stanislas Gabrovsek, 2009

UNIVERSITY OF SUSSEX

MASTER OF PHILOSOPHY IN SYSTEM ENGINEERING

A METHODOLOGY TO ENHANCE URBAN RECONNAISSANCE UGV REQUIREMENTS THROUGH SIMULATION

SUMMARY

Abstract

Regarding to the increasing complexity of military systems, the development of initial system requirements matching with the user expectations, the architectural constraints and the technical standards is critical for the final performance and the global cost of the system. Computer simulation offers an efficient, fast and cheap way to evaluate, and even enhance, some of these user requirements at the earliest steps of the design process.

Based on the example of a Reconnaissance Unmanned Ground Vehicle concept issued from the UK MOD, this research proposes a methodology to enhance and validate military systems' requirements through a suite of appropriate simulation tools.

The modelling approach proposed consists of three successive phases, each phase providing new insights used to complete and refine the initial user requirements captured in a Requirements Management tool (Doors) database:

- The validation of the operational requirements, of which the aims are to simulate the specified capabilities of the UGV in a realistic scenario and to generate insights about new possible capabilities,
- The modelling of the UGV's environment in a standard architecture framework (DoDAF) in order to identify all the assets of the system of system and its functional breakdown,
- The behavioural modelling of the vetronics (Vehicle Electronics) architecture, leading to identify the most appropriate architectural and technological standards to support the UGV functionalities.

While existing tools and methodologies were identified to support the system's environment and the behavioural models, a Computer Aided War Gaming (CAWG) tool was developed to implement the modelling of the operational capabilities. The qualitative and quantitative results obtained on a reconnaissance scenario tool were used to improve the initial UGV requirements. The CAWG itself got positive feedbacks after a demonstration to the UK MOD.

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Acknowledgements

First, I would like to thank my supervisor Dr. Elias Stipidis for having offered me the opportunity to develop this project at the Vetronics Research Centre, and for his friendly support and useful advice throughout this year.

I would also like to thank the French Ministry of Defence for the funding of this MPhil, as well as the UK MOD/DSTL for having provided me some basic elements for my research.

Thanks to all the researchers in the Communications Research Group for their support and creating a pleasant working environment. My thanks especially go to my lab-mates, Ian, George and Tom, of whom I have learned a lot about research thinking and English and Greek cultures, including food, plumbing and sport cars.

Finally, thanks to my family, that has accepted to come with me in UK during my studies, and that has often endured my bad mood with a lot of patience …

1 Introduction

1.1 Thesis Objectives

Weapons systems are more and more complex, mainly because of the integration of multiple constituents and functionalities. In doing so, the decisions made during the initial phases of the project development have more and more impact on the final performances and Life Cycle Cost (LCC) of the system. Therefore, one of the main roles of a system architect in procurement agencies today is to make sure from the earliest stages of the development that the final system requirements will comply not only with the user expectations, but also with the engineer capabilities and the financial constraints.
For that, one can lean on his own skills and experience, and on a set of standard methodologies and software tools that have been developed during the last ten years to face to the growing complexity of systems. In that scope, simulation can efficiently help the system architect to make initial decisions, from the renunciation to certain nonessential user requirements to the introduction of additional standardisation constraints for example.

The main objective of this thesis is to present and describe how technical-operational simulation can be used to validate and improve the requirements for a new reconnaissance Unmanned Ground Vehicle (UGV) at the concept stage.

As a secondary objective, the exploitation of simulation in the whole design process will be discussed. Other useful modelling levels for a system architect are addressed, from the UGV System of System environment down to the system design and technology implementation. Standards and available tools are presented.

1.2 Thesis Structure

The rest of the thesis is organised as follows:

Chapter 2 presents the typical design process for military robotic systems. A modelling approach matching with this process is presented and recommendations about supporting tools and methodologies are made.

Chapter 3 introduces the Building Entry and Search (BES) UGV concept issued from the MOD (UK) and some other comparable projects abroad (France, US). Starting from existing documents, user requirements are captured, analysed and sorted in a standard Requirements Management environment (Doors).

Chapter 4 addresses the early validation of these requirements, showing the way a Computer Aided War Gaming (CAWG) tool can help the architect to illustrate the concept, define a representative using scenario and possibly identify unnecessary or additional user requirements.

The final chapter concludes the thesis by discussing the research work, achievements and potential future work.

2 Use of simulation in the design process of UGVs

"If you don't know where you are going, you are unlikely to end up there."

Forest Gump

2.1 Life-cycle, development and design process

UGVs, as all products and services, have certain life cycles. The life cycle refers to the period from the product's first launch into the market until its final withdrawal (Figure 2-2: Typical Life-Cycle diagram for UGVs (durations are indicative only)). The life cycle of any industrial products is generally split into 5 phases. Applied to military UGV products, they can be described as follows:

1. <u>Product development</u>

Product development phase begins when a company finds and develops a new product idea, on their own or as an answer to a new operational need expressed by the military technical services and formalised by the governmental procurement agency. A lot of money and time is spent during the development, while sales are zero and revenues are negative for the UGV manufacturer, except the Research & Technology funding. Usually, the development of a new UGV does not start from scratch, but takes advantage of similar previous products feedbacks as well as results from upstream studies.

At the end of the development, the UGV is tested against the initial user requirements. According to the results of the acceptance tests, the UGV system is declared ready to be deployed for operational usage, or a new cycle of development is launched to fill the weaknesses of the design (see Figure 2-1).

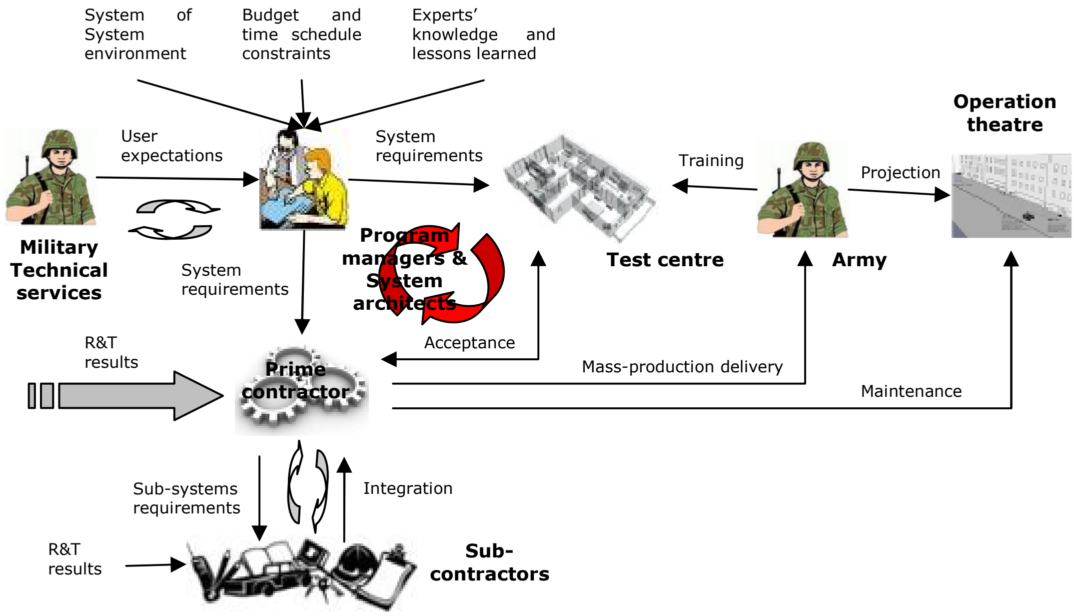


Figure 2-1: Main actors in the UGV Life-Cycle in DGA, FR

2. Introduction phase

The UGV introduction phase starts with the order and the production of a small amount of UGVs (pre mass-production). These UGVs are accepted or not by the concerned governmental service regarding to industry documents and then delivered to the military. Presentations and training sessions for future users are organised in an appropriate installation. Future users are trained to the using of the UGV in the planned types of mission as well to the maintenance of the UGV "on the field", possibly with dedicated tools. Then UGVs are sent to the conflict areas for deployment in the involved units. Because of the high public attention and scrutiny paid to robotics, the first missions conducted by a new UGV are very important to demonstrate its reliability. A failure during this introduction phase can have a very negative impact on the rest of the UGV life cycle (e.g. unexpected movements of as armed turret can postpone the further mass-production for 5 to 10 years because it demonstrates that the whole UGV architecture is not reliable enough: see the first trials of SWORDS UGV in Iraq).

3. Growth phase

The growth phase offers the satisfaction of seeing the product to take-off in the marketplace: the new UGV concept has shown its efficiency in operational context, and its design is starting to be copied and adapted by concurrent industries. For the manufacturer, this is the appropriate timing to focus on increasing the market share, for instance by opening the usage of the UGV to other missions through new types of payloads, or by declining the UGV design on a different range of UGVs (e.g. new payloads for the Packbot UGV and extension of the TALON mission range).

4. Maturity phase

For the user, this period is the time to develop efficiencies and improve product availability and service, for instance by defining standard usage and maintenance procedures, training courses and user manuals. The maintenance process is also optimised by organising periodic check-ups of the UGV. The design of the UGV has evolved and reached a level that can not be improved without reconsidering the whole architecture of the system.

Once the manufacturer has produced the amount of units that had to be delivered to the customer, the market is made of spare parts and replacement of units lost in action.

5. Decline phase

The withdrawal of a UGV out of the military is not an arbitrary decision, except in case of repeated failures. As the threat is evolving, the user needs change and the initial

UGV design is becoming less and less adapted but they still can be used for training purposes or sold as used to less wealthy organisations (e.g. Non Governmental Organisations).

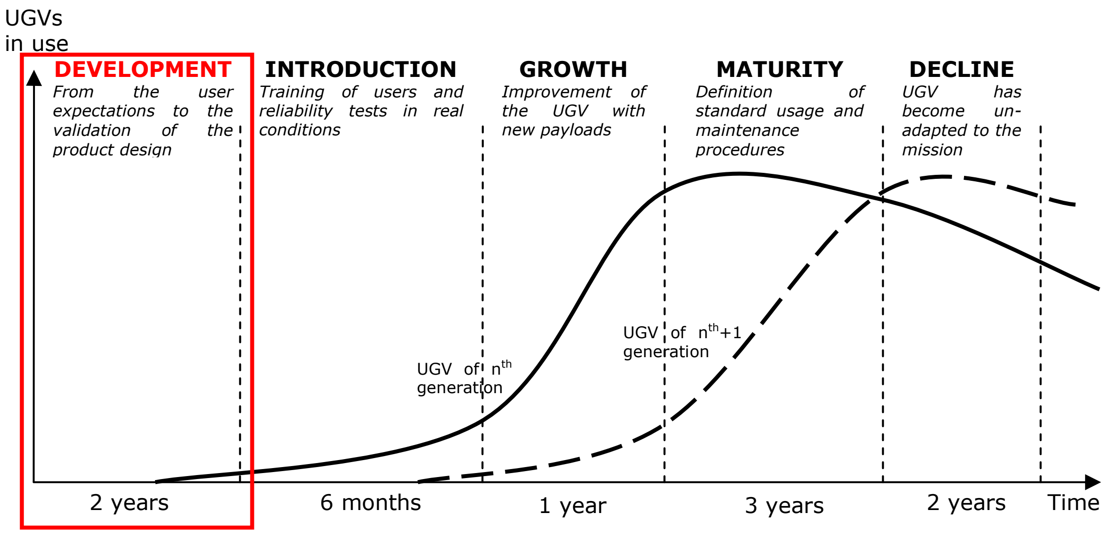


Figure 2-2: Typical Life-Cycle diagram for UGVs (durations are indicative only)

The development process is the set of methods and activities involved in the development phase of the product life-cycle, from the first emission of the user needs until the final validation of the product definition that will fulfil these needs. It is followed by the production phase that will allow introducing the product in the market.

In order to deal with the complexity of modern systems (see chapter 2.2), development methods and activities are often based on hierarchical design allowing the description of the system as a set of simpler, and easier to design sub-systems. These methods are applied in the typical development lifecycle called “V-process”. It allows building a system starting from an abstract description to an actual product which is validated by a step-by-step top-down and then bottom-up design flow.

Design is the set of activities involved in determining the requirements that constitute the basis for the making of every object or system. As a noun, "a design" is used for either designating the final (solution) plan (e.g. proposal, drawing, model, description) or the result of implementing that plan in the form of the final product of a design process [1]. In the rest of the document, the term “design process” is used to talk about the designing activities to avoid confusion.
Understanding user requirements is an integral part of systems design and is critical to the success of interactive systems as UGVs are. This chapter is showing how

simulation can be used to implement, illustrate then amend some of the initial user requirements.

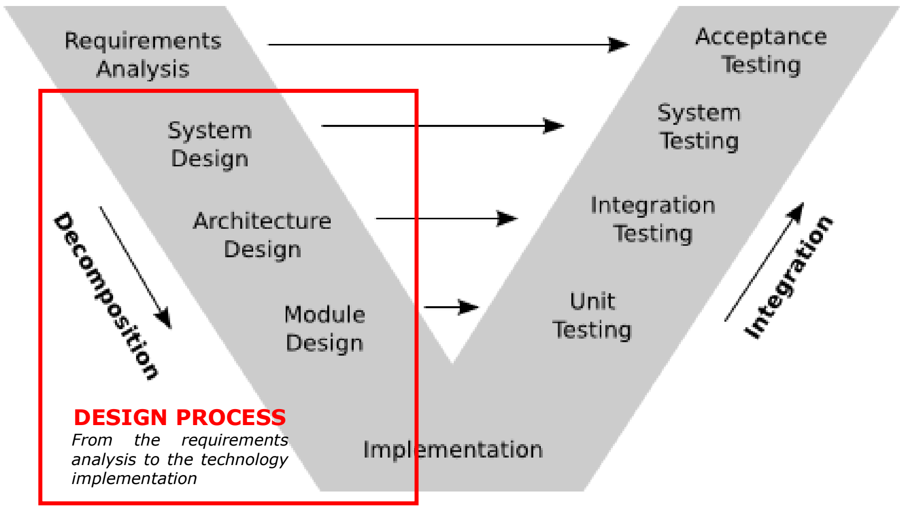


Figure 2-3: Development "V process" activities

2.2 Particularities of UGVs design

From the invention of the first robots until the late 90s, the design of UGVs was more a matter of researchers' ingenuity than a question of methodology, even for serious applications. The experimental side of the development process explains why the design process of UGVs has not been the object of specific works, except a very few open publications [2].

With the fast introduction of robotics in the military, acquisition policies are changing and UGVs design process has now to comply with standards and recommendations, like any other industrial systems do. It is out of the scope of this essay to detail the design process of industrial systems. Bibliography on this topic is massive, a good example of the implementation of such standards and recommendations for complex project design and management can be found in [3].

Chapter 3.1.2 proposes a typology of the different kinds of UGVs currently in use in the military; here, the particularities of UGV design, starting from the original definition of a UGV are explained.

First, a UGV is a <u>mobile system</u> that operates in an alleged <u>unknown environment</u>.

As a mobile system, its design will have to deal with most of vehicle architectures and technologies design issues: safety, reliability, engine type, energy storage, weight/power ratio … In addition, the need to operate in non-predetermined environments requires the robot architecture to be able to manage the presence of unexpected obstacles (for instance by the way of a reconfiguration of its mechanical architecture), and puts additional environmental constraints on the UGV mechanical design.

Second, a UGV is a complex distributed system mainly based on embedded information technologies.

A complex system can be defined as a system made of many sub-systems of which the design and the functioning involve different trades that could not manage the system as a whole [4]. No need to underline how much the robotics area particularly answers to this definition. The design process of a complex system requires methods and tools that will insure the conformity of the components, sub-systems and final system to the requirements, all along the realisation of the project: quality of service, ability to host new sub-systems … The number of the different factors involved in the process as well as the amount of components integrated make reliability and safety the weak links of complex systems design. In the case of UGVs, this difficulty is further increased by the fact that these components are distributed on distant sub-systems in wireless communications and the additional safety requirements attached (e.g. UGV recovery modes in case of communication breakdown).

The integration of embedded Information Technologies (IT) is also a key factor to take into consideration. As mentioned above, UGV architectures massively deal with sensors, computers and actuators technologies, as any modern vehicles architectures do. The problem of the integration of IT in vehicles (also named "vetronics") has become a major strategic challenge for the system designers, with important technical and financial impacts: while vetronics represents about 30% of the Life-Cycle Cost (LCC) of a medium range vehicle, reduction of hardware costs combined with the software implementation of new innovative functions are the main drivers of today's automotive electronics. Automotive and combat vehicles manufacturers are investing a lot of money to improve the design techniques of embedded electronic architecture and the reusability of hardware and software components (e.g. AUTomotive Open System ARchitecture [5]).

Third, a UGV is a military system.

Military systems differ from civilian systems on several points, which induce major consequences on their design process:

1. User driven requirements: Military systems are supposed to answer to an operational need previously expressed by the final military users, who are the only ones to know what needs the product has to answer to. Civilian products try to be in advance on the market and guess the customer's future expectations.

2. Variety of usage and flexibility of the requirements: Military products are very rarely used for their final purpose (making war), in the context they have been made for. The greatest part of their life is dedicated to storage, training and maintenance. In use, the military exploit the product at its limits and even a bit beyond, and expect it to continue to provide the same level of service.
3. Low mass-production: The will to stabilise the armament budget has compelled the military to significantly reduce the staff and new equipment expenses. Except for exceptional cases, military mass-production does not exceed a couple of hundred units.
4. Robustness and easy maintainability: For the same cost reduction reason, military products are required to be maintainable for 15 years and even more after refurbishment. In case of failure, military products have to be repairable "on the field" in order to not interrupt the mission.
5. Reactivity and ability to evolve: Modern conflicts are characterised by their asymmetry and the intensity of the engagements. That makes new types of threats appear very quickly (e.g. new type of Improvised Explosive Device) and to react efficiently, a product has to be designed or modified in a very short time.
6. Reliability, safety and security: Armament or active protection systems of military systems can represent a real danger for the surrounding people in case of malfunction. A particular attention has to be put on the reliability of the critical functions, and different recovery modes have to be introduced.

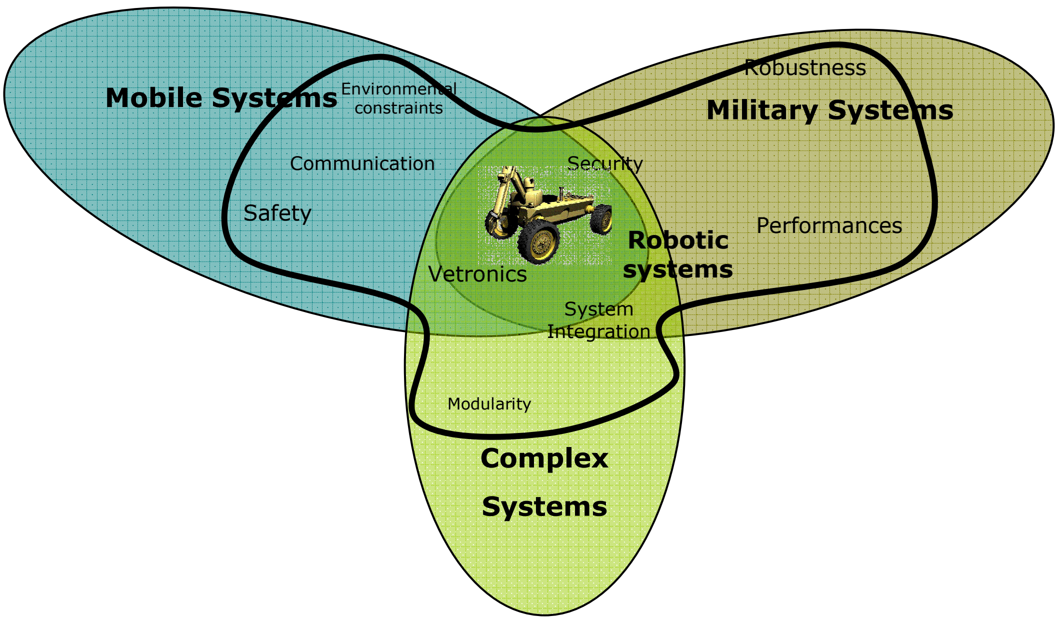


Figure 2-4: UGV design merges other domains' constraints

As illustrated in the Figure 2-4, UGVs are at the intersection of three major domains of engineering: mobile systems, complex systems and military systems. Consequently, they put together the difficulties of such systems' design.

The majority of the problems that happen during the system life-cycle results from misunderstandings or omissions in the initial system requirements (a good example of that is analysed in [6]).

Regarding to the operational (human beings' lives are in play) and financial consequences that design mistakes in military systems can have, it is of first importance to validate these requirements at the earliest stages of the design.

2.3 Benefits expectable from modelling and simulation

Modelling is the representation of the system according to different angles of interest (costs, functions, mechanical design …). A model is "a set of entities and relations created as a result of an abstraction process" (International Council On System Engineering definition). Behavioural models can represent the modification of the state of the system over time and/or variations of the inputs, leading to the simulation of the system's behaviour (behavioural simulation).

The benefits that can be expected from modelling at the different stages of the development are of three types.

Operational benefits

- Conceptualization: Graphical tools to illustrate a concept (e.g. 3D representation of the mechanical design) allow a better common understanding of the user needs
- Fast feedback cycles: Through an iterative process of short virtual designs of the system, the system architect and the user can converge faster towards optimised user requirements
- Faster system's delivery to the Forces: thanks to the shortening of the concept's validation phase.

Technical benefits

- Approach driven by the models : reusability of HW and SW modules
- Better management of the interfaces between the sub-systems
- Easier validation of the sub-systems performances before the system integration

Financial benefits

- limitation of the number of expensive prototypes
- reduction of the duration of the development

2.4 Overall modelling approach and recommended tools

The tool that would allow to support the whole design process presented in chapter 2.1 does not still exist in the market. Even though recent tools and methodologies are quite close to achieve this goal (e.g. Rhapsody/UML), they are not well adapted to projects that are still at the stage of the concept and that have not reached a certain level of maturity.

On the basis of this assessment, it was decided to propose an original approach of the BES UGV modelling, based on a 4 phases sequence:

- phase 1: capture of the initial requirements, issued from the existing documents
- phase 2: modelling and validation of the operational requirements
- phase 3: modelling of the system environment
- phase 4: behavioural modelling of the system

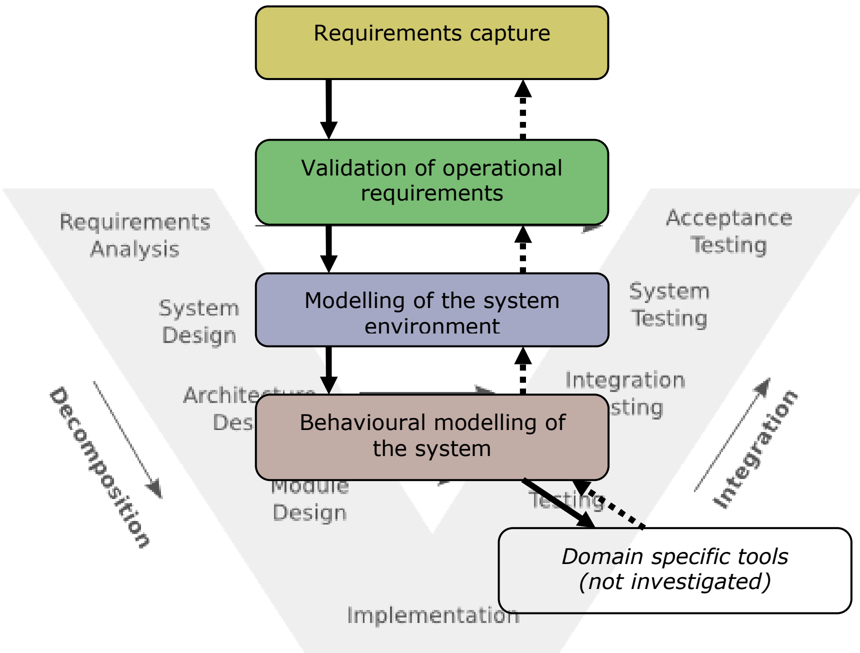


Figure 2-5: Modelling approach initially proposed

This approach was based on the assumption that the product of each phase would be directly exploitable by the following phase, as shown on the Figure 2-6.

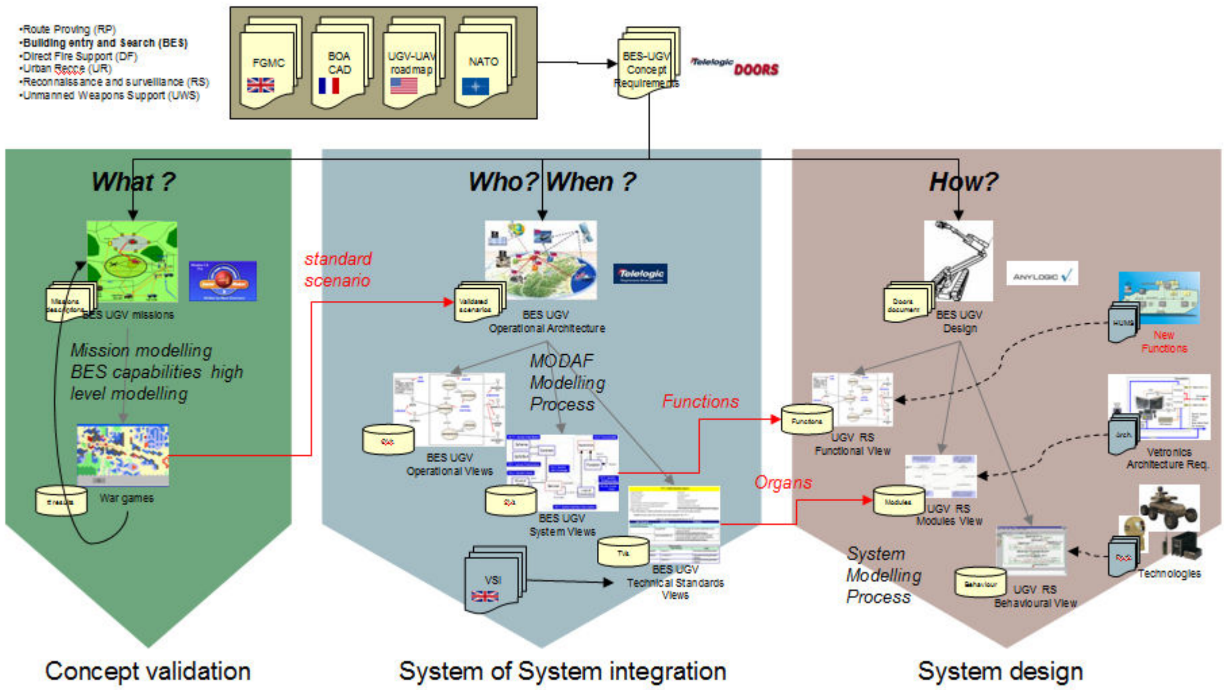


Figure 2-6: Original modelling process showing the interfaces between the different modelling phases

The modelling process illustrated by the Figure 2-5 and Figure 2-6 was slightly adapted to use the requirements management tool as a gateway between the different tools, as shown by Figure 2-7. But direct gateways between the tools are also possible, and further investigations on this topic are proposed in the conclusion of this thesis.

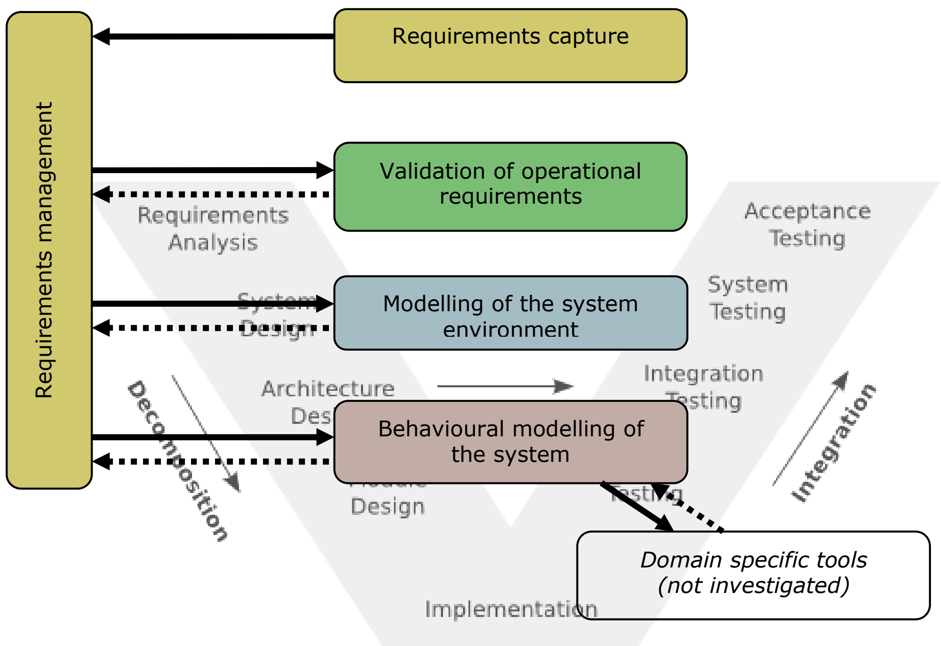


Figure 2-7: Modelling approach finally adopted

2.4.1 Capture and management of the requirements

2.4.1.1 Objectives

Requirements management is the process that captures, traces and manages stakeholder needs and the changes that occur during the project's lifecycle. Efficient requirements management has to provide two main capabilities:

- Structuring, in order to make the requirements more manageable in terms of omissions or duplicate information,
- Communication, in order to ensure that requirements are communicated correctly to the rest of the project team.

2.4.1.2 Inputs

The inputs of the requirements capture phase are the initial existing documents in a Word format issued from studies in relation with the BES UGV concept considered here: FGMC (UK) [7], FCS (USA) [8], MINIROC (FR) [9], URBAN OP 2020 (NATO) [10]. Due to a lack of time, only the outputs from the FGMC and MINIROC studies have been considered here.

2.4.1.3 Outputs

The outputs of the requirements capture and management phase are a BES UGV requirements relational database made of different modules:

- FGMC requirements
- MINIROC requirements
- BES UGV requirements

These three modules are connected together by the way of links to represent the relationships between these requirements.

2.4.1.4 Recommended tool

<u>Doors (IBM)</u>

Doors is a leading requirements management tool used by thousands of engineers around the world. It was developed and marketed by Telelogic, now IBM. It is out of the scope of this project to give a detailed presentation of Doors (for that, refer to [11] chapter 9).

In this project, Doors has been used to capture the initial BES UGV requirements, to ensure the traceability between the different sources and to record the additional requirements issued from the other modelling phases. The structure of the BES-UGV requirements database is shown on Figure 2-8.

An extract of the export of the database in a word format is joined in annex 3 (Chapter 7.2).

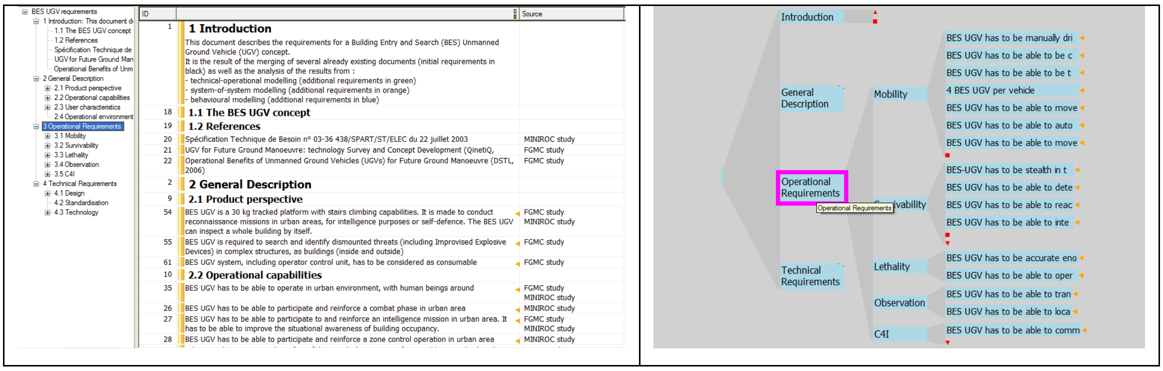


Figure 2-8: Structure of the BES UGV requirements' Doors database

2.4.1.5 Conclusion

Many books have been written on the topic and there is plenty of tools available on the market to support the requirements management process. However, as reminded in [11], "requirements engineering is common sense, but it is perceived to be difficult and is not well understood". Even though it is out of the scope of this thesis to detail "good" practices to capture and manage requirements, the following principles have to be kept in mind:

- Always define first an outline hierarchical structure, that considers all the aspects of the design: operational, technical, environmental … This is probably the most difficult task.
- Write down requirements as soon as possible, in a simple and comprehensive language.
- Only write testable requirements.
- Do not try to achieve perfect requirements at the first attempt, but improve them iteratively.
- A regular presentation of the current requirements' status to the final users is often better than a final review by requirements management "experts".

2.4.2 Modelling of the operational capabilities

2.4.2.1 Objectives

The main goal of this phase is to model and assess the capabilities expected from the UGV by the final user, into a simulated operational scenario.

2.4.2.2 Inputs

The inputs of this phase are:

- the operational requirements at the capability level, issued from the requirements capture phase in Doors,

- some rough ideas about the UGV concept, issued from a survey of the already existing systems,
- a good knowledge of the operational context (organisation, tempo, environment), issued from operation feedbacks (Retex) or military advisors for instance.

2.4.2.3 Outputs

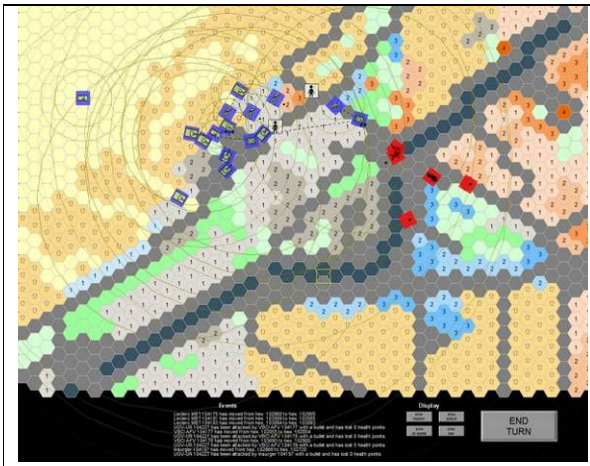
Outputs expected from the operational capabilities modelling phase are the validation of a realistic and representative operational scenario for the BES UGV, and some insights about the BES UGV concept itself, as modelled in the different game sessions played. These insights are then converted (manually) in additional requirements and added to the Doors database.

2.4.2.4 Recommended tool

MOD military experts use high-level (or technical-operational) simulation to get insights about new organisational concepts, very rarely underneath the company level. But such tools are not suitable for modelling a single unit's capabilities.

Engineers can use general purpose modelling tools (e.g. Matlab-Simulink) to get a first idea about the behaviour of a system design, in a well-defined and deterministic scenario. But such tools are not adapted either for getting general insights about a concept in different using conditions.

A short survey has led to the conclusion that a product allowing a system architect to model and simulate a UGV concept at the very beginning of the development process was not available on the market.




```
//definition of the capabilities of each asset
name:="UGV-BES";//this is the name of the unit that will be drawn once it gets selected.
//mobility capabilities
move_range:=2;//maximal distance (in hex) the unit can progress in one turn
mounted:=false;//unit's status : mounted or dismounted
//stealth capabilities
max_visibility:=0.3;//defines the visibility level of the unit (0:invisible 1:always
visible)
size:=0.2;//defines the relative size of the unit (0:micro UGV 1:MBT)
//fire capabilities
LOS_range:=5;//maximal distance (in hex) a target can be engaged
LOS_power:=1;//fire power of LOS armament
illuminator:=true;//able to designate a target
NLOS_number:=0;//number of NLOS ammunitions
NLOS_range:=0;//range of NLOS
NLOS_power:=0;////fire power of NLOS armament
//protection capabilities
DAS_protect:=false;//DAS capability or not
armour_protect:=1;//level of protection
max_hp:=10;//number of initial health points of the unit (in points)
//observation_capabilities
height:=0;//elevation of sensors
detect_range:=3;//maximal range of detection (in hex) = there is something
reconn_range:=2;//maximal range of reconnaissance (in hex) = RED, BLUE or WHITE
identi_range:=1;//maximal range of identification (in hex) = BMP3, CH2 ...
//communication_capabilities
C2_range:=5;//maximal range of communication with other units (in hex), not use except
for the UGV
C2_ID:=0;//C2 identification for communication and carrying
//other capabilities
BES_inside:=0;//index number of the BES
IED_sensor:=true;//able to detect and defuse IED
UGS_inside:=2;//number of Unmanned Ground Sensors the BES is able to carry.
//the general variables of the units are defined in obj_blue_units object
event_inherited();//this calls the create event of the parent object
```

Figure 2-9: CAWG screen and example of model attributes file

2.4.2.5 Conclusions

On the basis of this assumption, it was decided to develop a software tool dedicated to this task, starting from the principles of Manual War Games played at MOD/DSTL. The chapter 4 of this thesis describes the development of a Computer Aided War Gaming Tool (CAWG) in detail and the results achieved.

2.4.3 Modelling of the system (and system of system) environment

2.4.3.1 Objectives

As explained in section 2.2, a UGV is a complex system in interaction with many other assets, involved in today's battle space capabilities and supposed to move towards integrated network-centric warfare (Weapon System of Systems).

By doing so, system compatibility and interoperability are the most problematic issues, as they have to take into account time constraints and different lifecycles of the many technologies and systems involved.

Furthermore, the development of such systems of systems also involves many partners from defence agencies and industries, who need to cooperate and exchange information about the design process of these systems in a consistent way. This is exactly the purpose of architecture frameworks.

Several architecture frameworks exist. In recent years, four standards have emerged to support the systems engineering process:

<u>ADP233:</u>

AP233 is a part of the STandard for the Exchange of Product information (STEP) International Organisation for Standardisation standard (ISO 10303) made for exchanging systems engineering data. The scope of AP233 is quite wide, covering everything from requirements, functional modelling … down to product structure. It considers the whole system engineering lifecycle and provides the necessary links into domains of the design process (requirements analysis, detailed design, manufacture …).[12]

<u>SysML:</u>

The Systems Modelling Language (SysML) is a graphical general-purpose systems modelling language that supports specification, structure, analysis, design, verification and validation of complex systems. It was an initiative of the Object Management Group to reduce the Unified Modelling Language's (UML) software-centric restrictions and make it more adapted to systems modelling.

<u>DoDAF:</u>

The purpose of the Department of Defence Architecture Framework (DoDAF) developed by the US in 2004 is to provide guidance, rules, views and product specifications for describing architectures for military operations. It is an extension of the former C4ISR architecture framework developed in the 90s as a response to the will of the federal government to improve the way to acquire, use and dispose information technology.[13]

Basically, DoDAF provides four related views of architecture:

- "All Viewpoint" (AV) describes the overall scope and objectives of the system,
- "Operational Viewpoint" (OV) describes the required tasks and activities,
- "Systems Viewpoint" (SV) deals with systems functionality,
- "Technical Viewpoint" (TV) provides rules and guidelines for the system architecture.

The strength of DoDAF implementation tools (like System Architect) is to offer different ways (graphical, tabular, textual …) to fill in the views and to provide automatic mechanisms to manage the consistency of the data elements and the relationships between each view.

DoDAF has been adopted or customised by a number of other defence ministries around the world (MoDAF in UK, AGATE in FR).

<u>MoDAF:</u>

Roughly, Ministry of Defence Architecture Framework (MoDAF) can be described as an extension of DoDAF providing two additional views in order to better cover the acquisition process constraints:

- Strategic Viewpoint deals with capability management,
- Acquisition Viewpoint supports programme management.

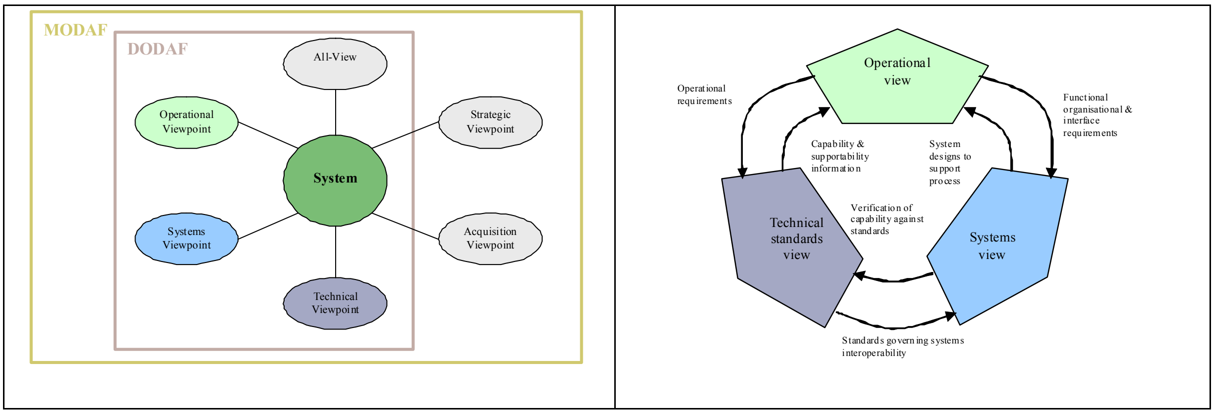


Figure 2-10: DoDAF/MoDAF views and their interactions

It is very important to notice that neither DoDAF nor MoDAF provide the method to analyse the system and describe it in the different views. For that, the user has to rely on standardised methodologies like the Activity Based Management (ABM) method.

2.4.3.2 Inputs

The inputs used to start up the modelling of the BES UGV concept in DoDAF were:

- The representative scenario issued from the modelling of the operational capabilities in CAWG,
- The operational requirements at the capability level (updated with the results of the CAWG phase),
- A basic knowledge of the system of system operational environment (interoperability standards, interfaces).

2.4.3.3 Outputs

The outputs of the DoDAF modelling process are all or a part of the views and diagrams presented above. DODAF views allow to clarify the BES UGV operational environment and usage. They allow to clearly identify the different assets in communication too. Even though this project was not focused on this modelling phase, some requirements resulting of this analysis have been added to the Doors database.

A deeper description of the system through the System View would have allowed to clearly identify all the functionalities of the BES UGV, as well as the relationships between these functions (System View SV-04).

For the rest of the modelling process, the assumption is made that this functional description is available.

2.4.3.4 Recommended tool

<u>System Architect (Telelogic/IBM)</u>

System Architect is the leading application in the industry world for visualizing, analyzing and communicating organization's enterprise architecture. It is designed to support many different business processes, structured data and object modelling techniques, like DoDAF, through specific add-ons.

Many other tools are available (Rhapsody, Artisan …). Some of them offer the ability to generate code for embedded applications, through a UML description of the software parts of the system. That makes these tools very powerful for the industry, but also probably less adapted to a procurement agencies’ usage than System Architect.

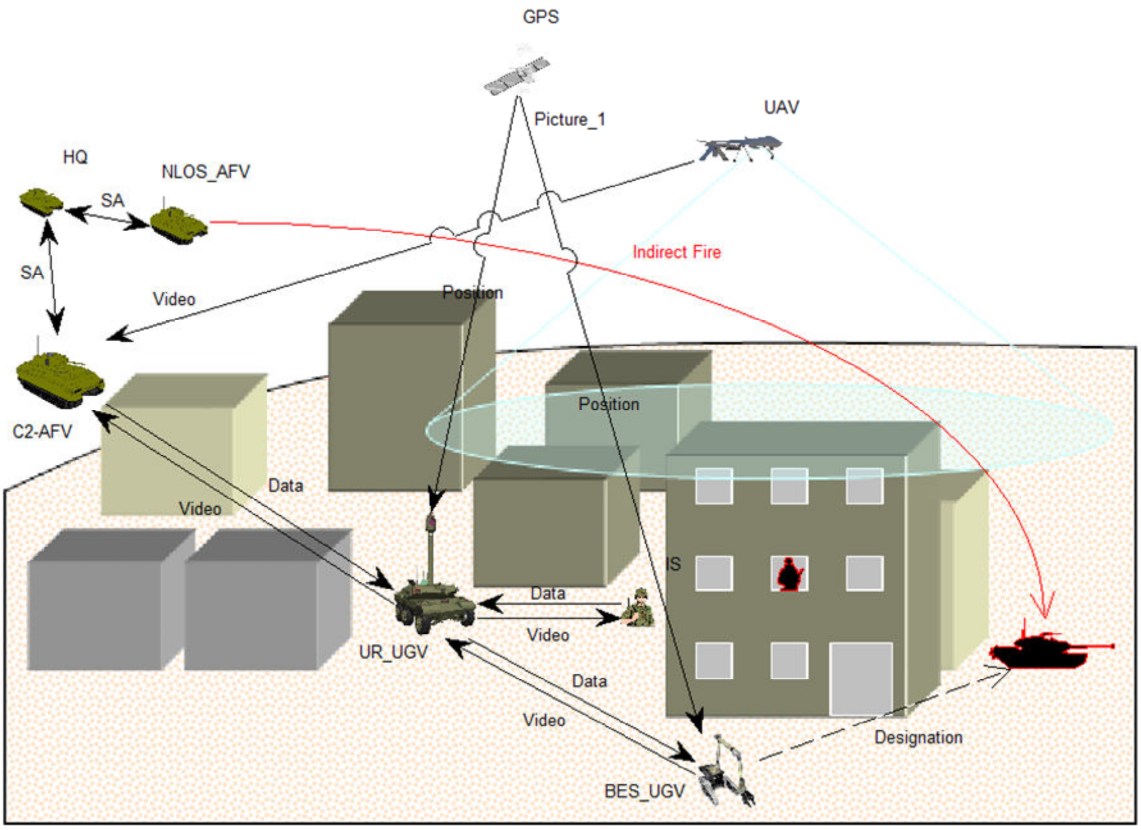


Figure 2-11: DODAF Overall View (OV-01) of the BES-UGV concept

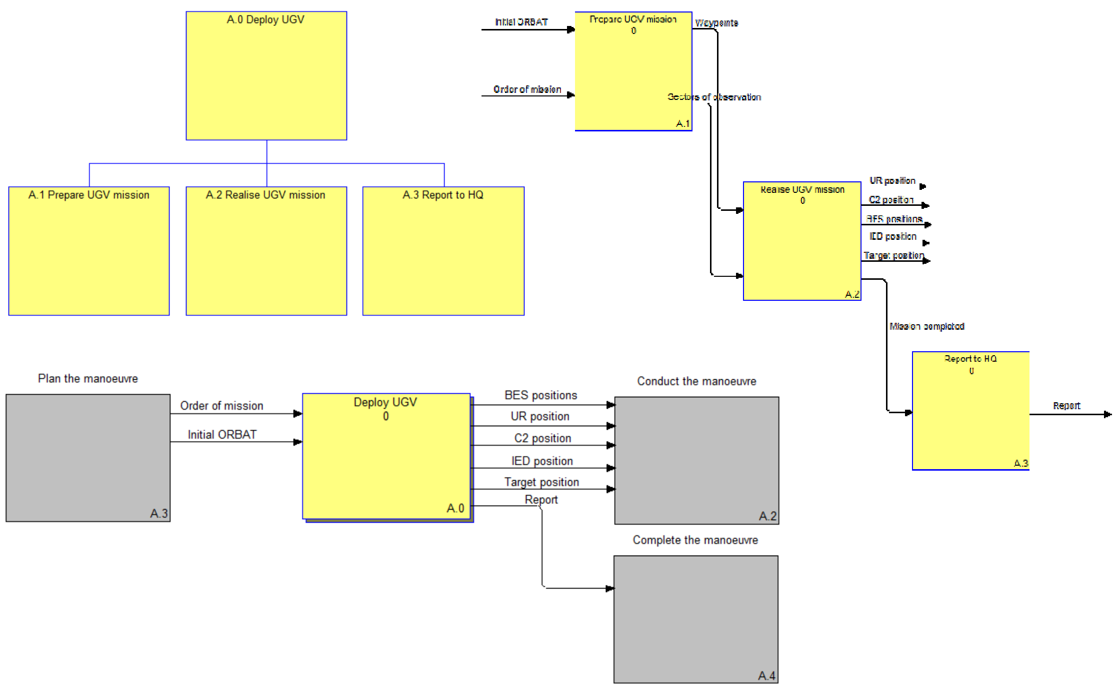


Figure 2-12: DODAF OV-05 Activity model and node tree of the UGV deployment function

The Figure 2-11 presents a way to describe the overall BES UGV concept in an OV-01 DODAF diagram. Figure 2-12 shows the functional description of the UR UGV deployment activity in an OV-05 (Operational Activity Model) DODAF diagram.

2.4.3.5 Conclusion

The purpose of an architecture framework is not to give a solution to a problem. It is a tool that can help the system architects to arrive at the solution by capturing, structuring, and giving access to the information required by different stakeholders, in a standard set of viewpoints.

Until now, the use of such architecture frameworks in the defence industry was limited to large-scale projects, with a lot of systems in interaction. In the next years, the development of Network Enabled Capabilities should favour the usage of DODAF (and its variants) even for more minor projects, as they will have to comply with standard Systems of Systems' interfaces.

Most of the tools that implement standard architectural frameworks (including System Architect) offer the possibility to import requirements from a Doors's database and to link these requirements with DODAF views' attributes. This feature contributes to implement a seamless modelling process, from the requirements' capture down to the behavioural modelling, which is described now.

2.4.4 Behavioural modelling of the system

2.4.4.1 Objectives

The objective of this last phase of the modelling process is to help the system architect to make the best architectural and technological choices to implement the functionalities expected from the BES-UGV on SW and HW devices, as parts of the UGV vetronics architecture. A model of UGV vetronics (Vehicle Electronics) architecture that implements the different functions issued from the functional analysis can help the system architect to:

- clarify the partitioning of the system architecture
- clearly identify the interfaces of the functions
- implement technological solutions on functions
- implement standards on functions

There are many different ways to model a vetronic architecture, according to the expected accuracy of the simulation results and the deepness of the architectural breakdown. Roughly, two types of modelling approaches for electronic architectures can be distinguished:

The physical approach is based on the physical modelling (mathematical equations, VHDL description) of each individual components of the architecture. As the inputs and outputs of the models often match with the real components pins, the model of the architecture is more or less a copy of the architecture schematic. Many modelling environments and libraries of electronic components are available on the market.
A good example of such a physical modelling is provided in [14]: A model of electronic component has been developed in the pSpice environment on the basis of experimental data and specifications from the component data sheet.
This type of modelling can be well adapted when accurate results about performances are required (e.g. is the RDY message arrived in less than 7 ms?), and when the design of the vetronic architecture is imposed. Nevertheless it requires investing a lot of time in modelling, and simulation times can be significant even for observing transient phenomena.

The behavioural approach is based on a macroscopic description of the behaviour of the different functions or components of the architecture. It is the choice of the modeller to model a function down to the component level (hierarchical breakdown or "white box" approach), or to describe the behaviour of the function without going deeper inside ("black box" approach). Obviously, the results of simulation are directly linked to the quality of the models. As a consequence, it is possible to run long scenarios (e.g. complete UGV mission) with low-detailed models as well as short phases (e.g. transition between two functioning modes) with accurate models. In [15], the behavioural model of a standard automotive protocol available in the OPNET library is used to simulate and analyse the network performance for a city-bus information integrated control system and validate the system requirements. The nodes are described by the way of functional and state diagrams, which do not match necessarily with their physical structure. A mixed approach is possible when the modeller needs to get the benefits of the physical approach (e.g. analog signal accurate analysis) and those of the behavioural approach (e.g. complex operating modes) at the same time. For instance, in [16], a model of a communication bus transceiver is developed in VHDL with low (physical) and high (behavioural) abstraction level basic blocks.

Behavioural modelling can be considered according three points of view:

- functional point of view,

- behavioural point of view,
- object point of view.

The functional point of view consists of analysing the system first and breaking it down into high level functions that can be represented as boxes linked together by relationships. Then, each of these functions can be broken down into sub-functions and so-on. A function, or "activity", is characterized by:

- its input data (e.g. throttle orders, speed),
- its output data (e.g. engine torque),
- possible constraints (e.g. engine started),
- the treatment that is realised to produce the output data from the input data (e.g. torque table, mathematic model)

The treatment (or transfer function) implemented by a function is described through a new functional analysis down to a refinement level that enables the outputs to be easily expressed against the inputs (e.g. y=f(x) or a simple algorithm).

Therefore, the functional approach is essentially made of progressive refinements. That is why it has been the foundation of a lot of system analysis and software development methodologies (SA, SADT). Depending on methods, additional concepts have been introduced, that do not change the approach fundamentally. Two usual extensions are the "data-store" concept and the identification of "data-control" that manage the execution of the activities.[17]

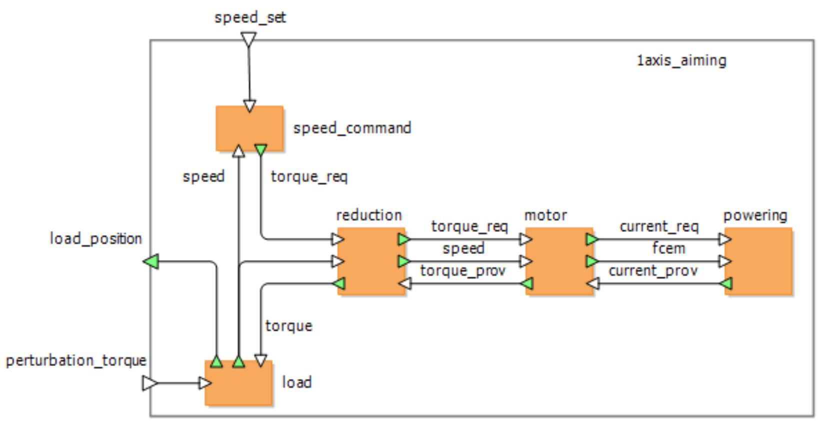


Figure 2-13: Functional view of the UR UGV turret command (1 axis)

As an example, the Figure 2-13 shows the upper level of functional decomposition of a turret behavioural model developed out of the scope of this project.

While the functional point of view is focused on the working principles of the system, the behavioural point of view puts the emphasis on the dynamical response of the system to stimuli. This response is expressed in terms of:

- Different states of the system,
- Transitions between states,
- Events from the environment to the system, completed or not with conditions (also called guards),
- Responses from the system to its environment. These responses can be associated to the transitions (Mealy diagrams) or to the states (Moore diagrams).

Models issued from a behavioural approach are based on "Finite State Machines" (states-transitions diagrams) or on one of their numerous variants (Petri graphs, Harel statecharts). [17]

The Figure 2-14 shows the way a turret's functioning modes controller has been modelled out of the scope of this thesis, using statecharts in the Anylogic environment.

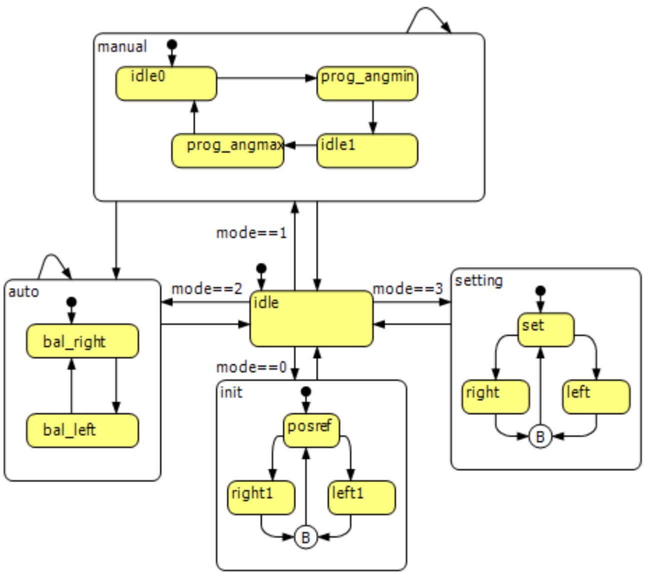


Figure 2-14: Behavioural view of the UR UGV turret's functioning modes controller

Although the functional and behavioural points of view are opposed in the theory, they are often jointly implemented in modelling tools. For instance, ASA (Verilog), that supports the SADT formalism, allows the user to describe the systems functions' behaviour by state machines. From the behavioural point of view, the system is seen as a set of machines in communication, which can be simulated.

Similarly, Statemate (IBM), that natively supports a SA-like modelling approach, implements some "control activities" represented by statecharts to manage the

conditions of the activation of the daughter functions of the current activity. A complete script language allows programming the actions associated to the states and transitions of statecharts, as well as the behaviour of the activities when they are activated, that makes the global model able to be simulated.
Finally, it is very rare to manipulate purely functional or behavioural simulations: every complex system has both a functional (processing of the inputs data to produce outputs data) and a behavioural (reaction to environment's stimuli) dimension.

Finally, the object point of view is based on an incremental process of abstraction of the objects of the "real world". There is a duality with the functional approach. Indeed, the object approach aims to identify the manipulated objects and their relationships first, then the treatments, encapsulated in the objects as "methods"; while the functional approach first identifies the functions, then the data flows that link them together.
The concept of "class" allows factorising all the objects that have common properties (attributes and methods) and the "heritage", to specialize daughter classes regarding to their specific properties, while reusing attributes and methods of the mother class (polymorphism). Lastly, "aggregation" allows defining a class whose objects are made of other objects.
Libraries of objects' classes can then easily built.
In practice, in object methods like OMT (Object Modelling Technique), functional and behavioural points of view are also considered.
For instance, OMT proposes 3 types of diagrams:

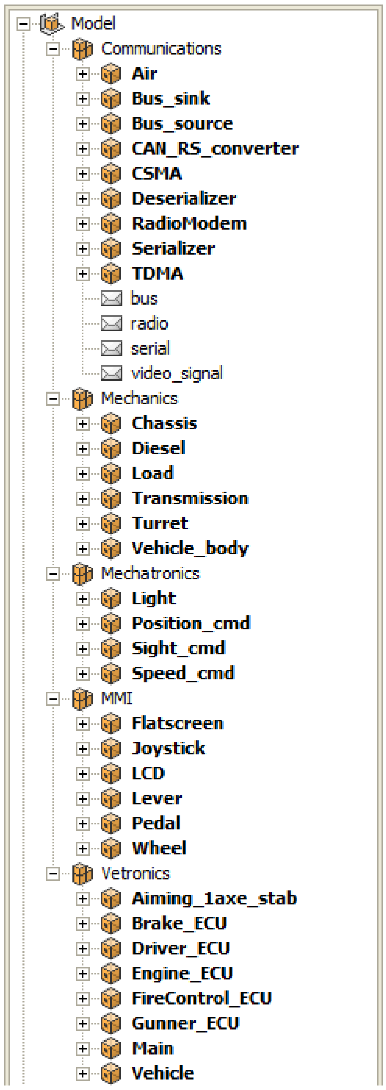


Figure 2-15: Content of the Vetronics objects library V1.0

- Class diagrams (or Static Structure Diagrams) represent the classes (with attributes and methods) and their relationships (heritage, aggregation, association),
- State-Transition diagrams (or Dynamic Diagrams) use the state diagrams formalism to specify the evolution of the state of objects of the same class and the interactions between objects of different classes,

- Data flows diagrams (or Functional Diagrams) use a SA type formalism to describe the data flows between the methods.

The **Error! Reference source not found.** presents the current content of a vetronic components library developed out of the scope of this thesis. This library was used to model some of the functions of the robot presented in the next chapter.

2.4.4.2 Inputs

The inputs of this phase are:

- The description of each BES-UGV functionality issued from the system modelling phase,
- Any recommendations guideline or standards related to the architectural design and technological choices (e.g. Vehicle System Integration)
- Behavioural models of basic vetronic components
- A good background of the user in the domains concerned, including the knowledge of similar projects' architectures.

2.4.4.3 Outputs

The outputs of this phase are:

- Structural drawings of possible solutions for HW and SW implementation of unitary functions, at different levels if needed,
- Quantitative results of simulation (e.g. communication range according the power of the date emitter/receiver, the height of the mast …)
- Qualitative results and insights during the interactive using of some behavioural models (e.g. design of the Man Machine Interface)

2.4.4.4 Recommended tools

<u>Statemate</u>

"*Statemate provides a direct and formal link between user requirements and software implementation by allowing the user to create a complete, executable specification*" [18]. Indeed, using a combination of traditional graphical design notations combined with some of the Unified Modelling Language (UML) diagrams, Statemate allows the user to create a visual specification that represents the functions and behaviour of the system. This specification may then be executed (graphically simulated) so the system engineer can explore different scenarios to determine if the behaviour and the interactions between system elements are correct. This executable specification is also used to communicate with the customers to confirm that the specification meets their requirements. Additionally, Statemate can automatically generate production quality C applications from the graphical specification, specifically tuned for automotive ECUs.

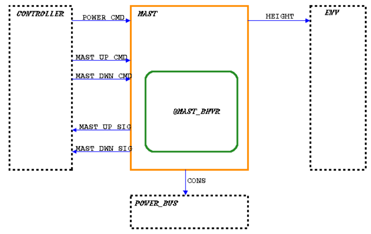
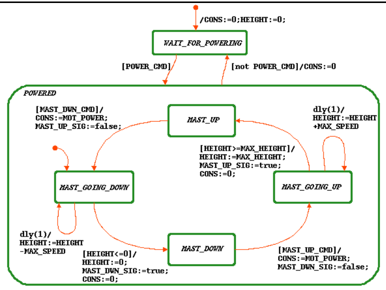
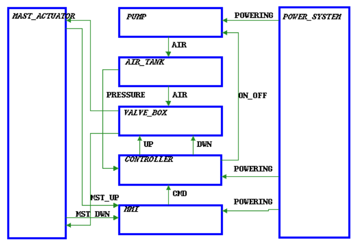
 Functional view	 Behavioural view	 Module View

Table 2-1: The three main system views in Statemate

Anylogic

AnyLogic is a general-purpose modelling and simulation tool for discrete, continuous and hybrid systems. As an extension of UML-Real Time language, AnyLogic modelling language allows multiple modelling approaches (Figure 2-16):

- UML-based Object Oriented modelling
- Block-based flowchart modelling
- Statecharts – regular (event-driven) and hybrid (continuous)
- Differential and algebraic equations
- Explicit modelling in Java

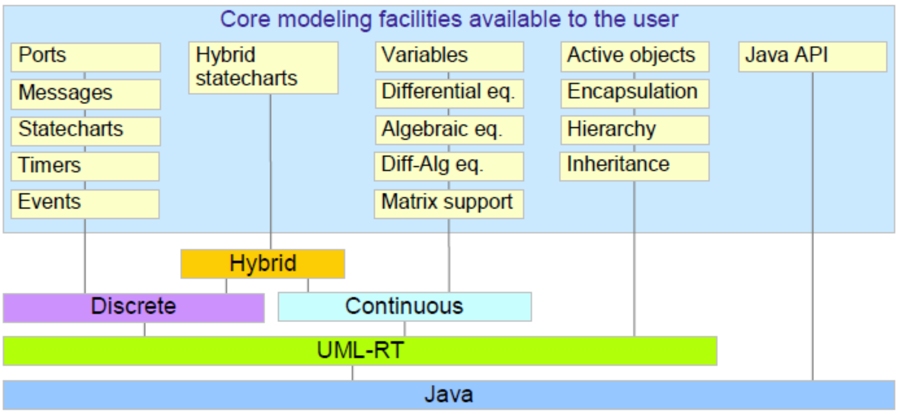


Figure 2-16: Anylogic modelling framework [19]

2.4.4.5 Conclusions

Functional modelling allows to simply and intuitively identify the different functions that have to be implemented on the UGV to complete the expected roles, as well as the information exchanged between them. But without dynamical aspects, it is only a sequence of treatments with no possibility to synchronise them together or with the rest of the environment.

Object modelling provides the reusability and the modularity that is necessary to design a library of basic vetronics components or functions. But without dynamical aspect, an object modelling is only a static description of the abstractions identified and their relationships.

As a simulation can be seen as a dynamical exploitation of a modelling, it is obvious that the behavioural point of view is essential to take into account the temporal dimension of any reactive system, as vetronics architectures are in particular.

Statemate and Anylogic are both able to support behavioural modelling. But Anylogic object approach is more developed while Statemate is more focused towards the functional description.

2.5 Discussion and conclusions

In this chapter, a generic system design process was described as well as the specificities of the UGV one that make modelling and simulation even more profitable for such complex systems.

A sequential modelling process consisting of three phases was presented, from the early validation of the capability requirements down to the system behavioural modelling.

Each phase of the process was described and analysed, and supporting tools usable by system architects were recommended. In the proposed modelling approach, the different outputs of these models are used to enhance and complete the system requirements managed in a Doors database.

A lack in the area of the validation of the operational capability requirements was identified, and it was decided to develop a specific tool to fill this gap. The next chapters of this thesis are dedicated to the development of this tool, starting by the description of the BES UGV concept, which has been used as an application case for the tool.

3 The BES UGV concept

"A robot may not injure a human being, or through inaction, allow a human being to come to harm."

1st law of robotics, Isaac Asimov

This chapter details the creation of the BES UGV concept.

3.1 Exploitation of robots in land forces

Unmanned Ground Vehicles (UGVs) are widely used by land forces today, for many different applications. Their current design obviously results of the normal technology progress but also of more radical turnarounds, consequence of the evolution of military users' needs, which is presented now.

3.1.1 UGV historical background

A UGV is a ground robot designed for military applications. That refers us to the definition of a robot. Encyclopaedias agree to consider a robot as "a mechanical device that automatically accomplishes tasks that are considered as dangerous, hard, repetitive or impossible for human beings or with the goal of better efficiency" [20, 21].

The first unmanned ground vehicle with a military purpose was the "land torpedo", a remote controlled tractor designed in 1917 by the Caterpillar company to drive up to enemy trenches and explode.

This idea was taken up in 1940 by the German "Goliath". Soldiers could drive the electric-drive "Goliath" and its 75 to 100 kg of explosives by wire remote control up to enemy tanks and bunkers. It was mainly used on the Eastern front (8000 Goliaths have been built) to balance the German troops outnumbering. At the same time, the Russian made the "Teletank", the first wireless remote-controlled tank.

Figure 3-1: The Goliath UGV (Wikipedia)

During the cold war, the work on military unmanned vehicles stagnated and it had to wait the progress of computer sciences in the 70s to see appear the first autonomous mobile robot in the labs (Shakey from Stanford Research Institute).

Some military UGV projects in the 80s have been reported but none of them has overstepped the experimental stage. They were far behind the UAVs in term of development. Except for training purposes (e.g. remote control tanks for missiles fire training), they were judged of no utility by the military [22].

The first Persian Gulf War (1991) marked the introduction of UGVs in the US army, for mine-clearing applications. M-60 tanks and bulldozers were equipped with mine-clearing and remote-control equipment to open breaches in mined areas. They were used with success and a lot of countries started to develop similar systems.

Figure 3-2: The French AMX30B2-DT mine-clearance RC tank (DGA)

Encouraged by the success of the mine-clearance applications for UGVs, the military financed a lot of studies and demonstrators in the 90s in order to find other possible operational interests for UGVs (reconnaissance, medical assistance …) and to develop basic technologies (sensors, image computing, autonomous navigation …). But even though some high performance UGVs were developed, none of them was robust and reliable enough to be put in the military hands, furthermore very recalcitrant to trust the complex missions considered by the engineers to these machines.

Figure 3-3: The French SYRANO demonstrator (DGA)

The Iraq and Afghanistan conflicts (2003-) signalled the return to more pragmatic uses of UGVs. These conflicts are characterised by their:

- Asymmetry: the enemy compensates the lack of military technology by a guerrilla tactic and the use of homemade bombs and traps called Improvised Explosive Devices (IED)
- Urban area environment: the population is concentrated in cities and suburbs, where the enemy can hide more easily and organize attacks of convoys and patrols

These two aspects combined with the ultimate fear of casualties made naturally emerging a new application for small, robust and slow but agile UGVs: IED detection and disposal (coalition forces in Iraq have neutralized over 11,100 IEDs since 2003 [8]).

Figure 3-4: "Packbot" (US) in IED detection operation (iRobot)

Since, these UGVs have demonstrated their interest and by the end of 2008, about 12,000 UGVs were projected in Iraq [23].
It was the beginning of a new era for UGVs. The industry, attracted by the UGV market prospects, decided to invest a lot of money to develop more and more, not only efficient but also reliable UGVs. And in May 2007, the US army deployed the first armed UGVs "Special Weapons Observation Reconnaissance Detection Systems" (SWORDS) in Baghdad.

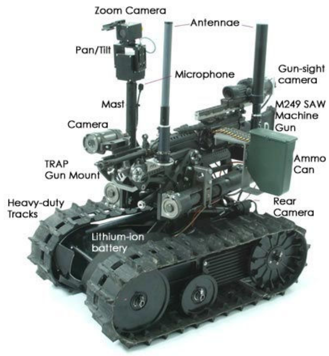


Figure 3-5: "SWORDS" armed robot (Foster-Miller)

In the future, one of the Pentagon's objective is to "aggressively develop and field" robotic systems, to have one-third of the ground combat vehicles unmanned within 15 years.

3.1.2 Classification of military robots

On the basis of the known UGVs in the major nations of NATO, existing and in-development UGVs can be sorted in three categories, regarding to their weight range.

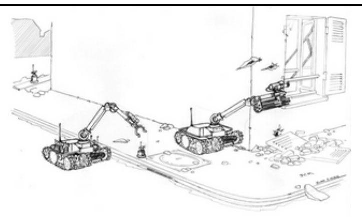
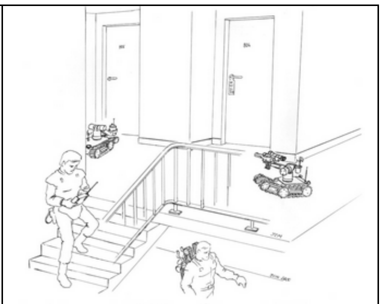
Illustration (issued from a GIAT Industries study reported in [24])			
Weight range	Heavy (5-40 tons)	Medium (100 kg-10 tons)	Light (5-80 kg)
User	Engineering	Light Cavalry Infantry	Engineering Infantry Special forces
Purpose	Mine detection Mine clearing	Reconnaissance Burden carrier	IED disposal Building inspection
Environment	Open area	Semi-urban and urban area	Urban area
Main features	Wireless of optical fibre link (<2 km) Video operation Slow (<10 km/h) Manually driven up to the operation area Can operate in convoy Embedded RC crew station	Wireless link (<8 km) Video operation Fast (> 50 km/h) Suite of sensors Range of mission modules (observation, target designation, armament) Automatic follower mode up to the operation area Semi-autonomous mode Embedded RC crew station	Wireless link (500 m) Video operation Slow (<10 km/h) Manipulator arm Suite of sensors Portable MMI
Existing products (examples)	M1 Panther (US)	SYRANO (FR)	Talon (UK)

Table 3-1: Typology of military robots

The Building Entry and Search (BES) UGV system studied in this document is a new concept of light UGV made for reconnaissance and building inspection in urban areas, which is now going to be described in details.

3.2 Description of the FGMC BES UGV concept

3.2.1 Future Ground Manoeuvre Capability background

The Future Ground Manoeuvre Capability (FGMC) is a research programme initiated in 2003 by the Defence Equipment Capability – Ground Manoeuvre (DEC-GM), the service of the UK MOD in charge of the land equipment acquisition requirements definition.

The objective of FGMC is to conduct long term research for DEC-GM, looking out to the 2030 timeframe to understand the future capabilities required when Challenger 2 (CR2) and Warrior (WR) will have reached their Out of Service Date (OSD). The battlefield capabilities considered include mounted, dismounted and engineer capabilities within the future force scaling equivalent to a today's battle group, named Unit of Tactical Execution (UTE).

The major contributors to FGMC are the Defence Science and Technology Laboratory (DSTL) and Qinetiq, under contract with the DSTL. Their activities in FGMC consist to scope the capability required by a UTE, provide technology guidance and study novel systems concepts [25].

Considering the growing place of robotic systems in the military, one of the first studies was to evaluate the potential utility of unmanned systems to the FGMC UTE and their contribution to the UTE's operational effectiveness.

A first background research and concept development of UGVs was carried out in 2006 by DSTL [26]. A bibliographic search was conducted to identify UGV requirements, potential roles and application areas, and key technologies applicable to UGVs. Then a variety of military personnel in DEC-GM and DSTL were consulted to prioritise the roles in which UGVs could offer the greatest potential capability enhancement. This method led to identify 6 applications of greatest importance:

- Reconnaissance (Recce) vehicle
- Urban reconnaissance for fighting in urban areas
- IED and mine detection, disruption, neutralisation or clearance
- Target designation
- Nuclear, Biological and Chemical (NBC) detection and decontamination
- Unmanned weapons platform

In a second step, the experts of DSTL developed and refined 5 UGV concepts likely to support these applications:

- Reconnaissance and Surveillance UGV (RS) UGV
- Urban Recce UGV (UR) UGV
- Building Entry and Search (BES) UGV
- Unmanned Weapons Platform (UWP) UGV
- Route Clearer/Countermine UGV (RP) UGV

The main characteristics of these concepts are reminded in annex 1 (chapter 7.1).

A more detailed technology survey and development study of these UGV concepts was then contracted to Qinetiq [27]. The Qinetiq's study considered on-going equivalent programmes abroad, paying particular attention to the US Future Combat System (FCS). Potential enabling technologies (fuel cells, high resolution cameras …) were reviewed and quoted according to their Technology Readiness Level (TRL) at the considered future and that in the different fields of applications: platform technology, command-control and autonomy, communications, sensors, survivability, and lethality.

The Qinetiq's study report recommends to develop several system demonstrators and especially the BES concept, mainly because it raises robotic specific questions: semi-autonomous functions for stair climbing, stereo vision, manipulator arm …. The next chapter (3.2.2) describes this concept in detail.

Qinetiq's report put also the emphasis on a major difficulty for future UGVs development, which is the lack of definition of concepts of use and qualification of the military benefit from the use of unmanned systems. The manual wargaming sessions ran by the DSTL were a first step toward a better understanding of the concepts of use for future UGVs. The manual war gaming approach, as it was exploited by the DSTL is presented in the chapter 4.2.

3.2.2 The FGMC BES UGV concept in detail

3.2.2.1 Operational need

The operational need was expressed by the military as followed:

"Searching of building environments is an extremely hazardous task for infantry personnel. Increased situational awareness of building occupancy is a high priority for urban war fighting" [7].

On this basis, the refinement made by DSTL lead to these primary user requirements for the BES UGV concepts:

"Access and search buildings, search complex structures, identify dismounted threats

and the presence of explosives" [7].

3.2.2.2 Key requirements

Information contained in the documents [7, 26, 27] have been analysed, classified and synthesised in a DOORS document for further uses. DOORS (IBM) is a requirements management tool designed to capture, link, trace, analyse and manage a wide range of information to ensure the project complies with specified requirements and standards. Basically, DOORS stores all the requirements and attached information in a central database using folders, projects and modules. This representation of formal requirements and additional data (performances, comments …) provides the requirements structuring that is essential to complex projects [11].

The full set of user requirements for the BES-UGV with some additional comments is attached in User Requirements for the BES-UGV (extract of DOORS database). Information in red have not to be considered at this stage, as they precisely result from the later validation process described in chapter 4.

3.2.2.3 Proposed concepts

Four concepts have been proposed by the Qinetiq study team. They are summed up here by decreasing order of weight. All the vehicles below are supposed to be remote-controlled from the outside of the building to be inspected.

The first concept is a large vehicle (>300kg), fast but with limited in-building mobility. It would park next to the building and use tentacles for entry and search.

The second concept is a small vehicle (20 to 300 kg), slow but able to manoeuvre inside buildings and equipped with a manipulator arm for door opening and payload positioning.

The third concept is a very small vehicle (4 to 20 kg), man portable and able to manoeuvre in very confined spaces, with a payload manipulation capability.

The last concept is a micro UGV (< 4kg) that can be thrown through a window in the room by a soldier. It can move very slowly and has no manipulation capability.

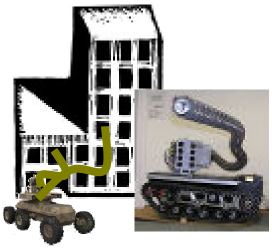
 Tentacled UGV concept (here the snake-arm from OCRobotics)	 Small UGV concept (here the TALON-Qinetiq)	 Portable UGV concept (here the Packbot-iRobot)	 Throw-able UGV concept (here the Spy ball – WowWee)

Table 3-2: Illustration of the BES UGV concepts proposed by Qinetiq

The first concept was judged too complex and vulnerable by Qinetiq, as well as the third concept was eliminated because its small size could not provide good access capability (e.g. for moving obstructions).

Finally, the only solutions retained by Qinetiq were the small and the micro UGV concepts.

3.2.3 Comparable projects abroad

3.2.3.1 In France

The French military procurement agency (DGA) has launched a research program in 2003 in order to define evaluate the possible contributions of robotics to urban combat called "Mini-Robot de Choc" (MINIROC). The study, aiming to the conclusion that the user needs could not be fulfilled by one only robot, has proposed a range of 3 robots with specific requirements for each:

- a throw-able robot, called MRS (Micro Specialised Robot), operable at the combat group level,
- a reconnaissance robot, called PRM (Small Modular Robot), operable at the infantry group level,
- a fire support robot, called REC (Reconnaissance Robot), operable at the company level.

A set of 15 different mission payloads (Table 3-4: MINIROC mission modules) was defined too, in order to cover the different types of mission trusted to the PRM and REC robots.

The design of these robots was completed in 2005-2006 and the prototypes were assessed by the DGA and operational users in 2007.

Among all the conclusions of the evaluation report [9], the military insist on the fact that *"the use of robots is limited by the rhythm required by certain manoeuvres".* The architectures and technologies used were found *"not efficient enough to provide good short situation awareness"* (vision sensors) and the *"communication losses even in short range were a major handicap of the systems".*

The other conclusions and remarks issued from the MINIROC robots evaluation have been used to complete the BES UGV initial requirements DOORS document.

  MRS	 PRM	 REC
Light, portable : 2,1 kg B/W and colour cameras Throw-able in a package Speed : 0,5 m/s Battery range : ½ h Dimensions (L x W x h) : 24 x 16 x 10 cm	Portable : 26 kg Reversal, fall, stair climbing management Speed : 2 m/s Battery life : 2,5 h Dimensions (L x W x h) : 67 x 50 x 19 cm B/W and colour cameras Microphone and loudspeaker Ultra sonic telemeters Mechanical and electrical interfaces for 2 additional mission payloads	Transportable by 4 men : 160 kg Payload : 100 kg Speed : 3,5 m/s Battery life: 1 to 5 h Dimensions (L x W x h) : 150 x 80 x 48 cm Can embed 6 mission payloads B/W and colour cameras Microphone and loudspeaker Ultra sonic telemeters Mechanical and electrical interfaces for 2 additional mission payloads

Table 3-3: The MINIROC robots family (DGA)

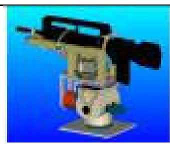
 Localisation/ Navigation module	 Obstacles detection module	 Intruding detection module	 Smoke grenade launcher	 Manipulator arm	 Anti-personel armament

Table 3-4: MINIROC mission modules (DGA)

As the MINIROC UGVs are not currently in mass production, the French army has recently purchased around ten modified US Packbot UGVs (see 3.2.3.3) for IED detection and disposal purposes in Afghanistan.

3.2.3.2 In Germany

The BWB (German Procurement Agency) is one of the main sponsors of the Military-ELROB contest that stands in Germany every 2 years, and of which the overall goal is to present a comprehensive overview about current developments and possibilities for the use of robotic capabilities in the context of military operations in open and urban areas.

It is a showcase for most of the major European industries and the designs of the UGVs presented there are quite representative of the level of maturity of the technology in the different domains of robotics.

Some of the trials in 2006 were specifically dedicated to the tactical awareness in urban environment and the detection and removal of IED in urban terrain [28].

None of the deployed UGVs was able to complete the planned mission, despite the preliminary knowledge of the type of obstacles that would be encountered on the way. The main difficulties were found to lie in:

- Ergonomics of the human-machine interface
- Communication in urban and non-urban domain under difficult conditions
- Mobility in non-urban terrain
- Agility in narrow urban structures
- Navigation and manoeuvring under difficult conditions
- Stair-climbing capability
- Use of elevator-able manipulators
- Movement and interaction inside buildings
- Recognition and circumnavigation of obstacles
- Moving on pathless terrain
- Manoeuvring at high inclination angles
- Communication and navigation without sight

				
Robowatch	Rheinmetall Defence Electronics	Telerob Gesellschaft	Diehl	University of Wuerzburg

Table 3-5: Some of the German BES UGV concepts presented at ELROB 2006 (Elrob)

3.2.3.3 In the United-States

The US Department of Defense has prioritised the capability requirements for UGVs, according to the different units of operation (company, brigade of division) [8]. It makes clearly appear the priority need for reconnaissance (recce) UGVs.

Mission Area	Company	BCTs	Division
Reconnaissance	1	1	1
Mine Detection/Countermeasures	2	2	2
Precision Target Location and Designation	3	3	5
CBRNE Reconnaissance	6	4	3
Weaponization/Strike	4	6	6
Battle Management	8	5	4
Communications/Data Relay	5	7	7
Signals Intelligence	7	8	8
Covert Sensor Insertion	9	9	10
Littoral Warfare	13	10	9
Counter CCD	10	11	11

Table 3-6: Ranking (from 1 to 10) of capability requirements, regarding to different units of operation (from US DoD report [8])

The research in the BES UGV area in the US is pulled by the current needs of the interventions in Iraq and Afghanistan and pushed by the budget invested in the Future Combat System (FCS), in which robotics holds an important position.

It is almost impossible to list all the urban robotic projects developed in the US, as the robotics constitutes now a very attractive market for many companies and laboratories.

The robots currently employed by the US army in Iraq that could present an interest for the BES-UGV design are the Packbot (iRobot Corp.), the Multi-function Agile Remote Control (MARCbot) and the Talon (Foster-Miller, bought by Qinetiq). The Packbot is by far the most deployed UGV, with more than 12 000 units deployed in 2008 [23]. The Swords and the Maars, which are armed versions of the Talon, are still under evaluation, as well as the Matilda (Mesa Robotics) and the BigDog (Boston Dynamics).

 Packbot	 MARCbot	 Talon/Swords /Maars	 Matilda	 BigDog
Dimensions (LxWxh): 47x45x37 Weight: 18 kg Speed: 9.3 km/h Dual track articulations Vertical Obstacles: 30.5 cm Stair Climbing (20.3 cm)	Dimensions (LxWxh): 60x48x34 Weight: 11.3 kg Low cost (< 10000$)	Dimensions (LxWxh): 86x57x42 Weight:52 to 71 kg Payload capacity : 45 kg Speed: 8.3 km/h Able to climb slopes and stairs up to 45 deg.	Dimensions (LxWxh): 76x53x30 Weight: 28 kg 3 configurations : sensor/camera, disrupter and manipulator units Speed: 3.6 km/h	Dimensions (LxWxh): 100x40x75 Weight: 100 kg Petrol engine 4 legs hydraulically actuated Speed: 6.5 km/h Slopes up to 35 degrees

Table 3-7: Some of the numerous BES UGVs designed in US

3.2.3.4 Other interesting designs

The Dragon Runner (Qinetiq North America) is reported to be *"the first fully modular ground robot system capable of both quick reconnaissance and improvised explosive device (IED) disarmament in urban, mountainous or rural environments"* [29]. Even though this affirmation is a bit over-confident, the modular design of the mechanical part allows switching from wheels to tracks, and adding whatever combination of flippers, cameras, sensors and/or arms very easily to increase the range of mission.

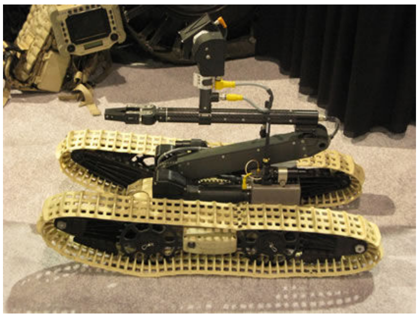


Figure 3-6: The Dragon Runner UGV (Qinetiq NA)

Another interesting design is the "robot snake" developed by the Israel Defence Forces (IDF). This UGV is about two meters long. It mimics the movements and appearance of real snakes, slithering around through caves, tunnels, cracks and buildings, while at the same time sending images and sound back to a soldier who controls the device through a laptop computer [30]. No further information is given about the mobility capabilities of this UGV in urban area (notably its ability to climb stairs).

Figure 3-7: The "robot snake" (IDF)

3.3 Discussion and conclusions

In this chapter, the global area of military robotics has been introduced as well as the specific BES UGV operational capabilities expressed by the UK MOD.
Considering the number of different existing applications and designs, it was out of the scope of this project to give an exhaustive overview of the existing and in-development BES-UGV concepts. Some representative concepts issued from a preliminary Qinetiq study have been presented, as well as comparable BES UGV projects in France, Germany, and US. It would have been interesting to extend this survey to other types of UGVs (Urban Reconnaissance, Explosive Ordnance Disposal systems …) and even to some UAVs (e.g. helicopters) as there is no strict border between the different kinds of application.
These concepts have been examined mainly from their external shape and design point of view, without considering any technology implementation issues (standards, HW and SW architectures, communications …).

The lessons learned from this survey deal with several aspects.

First, all the examined BES-UGV concepts are fully remote-controlled, with a very poor level of autonomy (e.g automatic return on path in case of data loss). A reason for that could be the lack of robustness of the existing sensors architectures and algorithms in operational conditions. As a consequence, **the operator is fully focused on the robot manoeuvre and he can not pay more attention to the local situation awareness**. It appears that the availability of a reliable **navigation-by-waypoints functionality** would highly increase the attention level of the operator as well as the survivability of the robot.

Second, even though the technology allows the design of very small and stealth UGVs, the size and the geometry of the obstacles to cross away (stairs, steps) as well as the size of the objects to move (doors, object, IED) requires **minimal dimensions and weight for the UGV**. Waiting for new locomotion ways to be validated in real conditions ("snake robot" or "BigDog"), the "Packbot" dimensions and mobility architecture (tracks and flippers) seems to be a good compromise, as it allows carrying and manipulating the necessary mission payload, crossing obstacles, while keeping it portable by a man.

Third, the **decoupling of the UGV chassis and payload architectures** (as manned AFV do) seems to be the best way to facilitate the integration of different mission modules, while reducing maintenance costs. Standard electrical and mechanical interfaces allow making both sub-systems evolve independently. But if the modularity of the chassis itself is quite appealing idea in a first approach, it has to be studied in terms of cost versus the benefits expected for a small UGV that will always stay very vulnerable. Furthermore, a **dedicated chassis to a mission** will always provide a better service than a generic purpose one.

Fourth, none of the designs reviewed perfectly matches with the BES-UGV user requirements. The Qinetiq concepts have been quoted regarding to the DOORS user requirements. It appears that the concepts proposed by Qinetiq do not comply with major user requirements in the following areas:

- Transportability: The small BES-UGV concept is too slow and not powered enough to be remote-controlled up to the operation area. Furthermore, the transport by a man can not be considered as a normal situation, regarding to the current burden to the soldier.
- Data range: The small BES-UGV size and technical constraints of operating inside a building do not allow to integrate a long-range wireless communication system. On the other hand, the operation range required by the user does not allow using a wire of optical fibre link because of the length of wire to embed and the risks of breakage.
- Survivability: During the building approach, the small BES-UGV is very vulnerable to any types of threats (e.g. sniper), as it can not detect and react to such threats.
- Mobility: The tempo of the manoeuvre is significantly slowed down by the maximal speed of the robot between two exploration phases.

It is now proposed to study particularly how the **merging of the UR and BES-UGV concepts** could help to find answers to the drawbacks mentioned above.

The key idea is to take benefit of the speed and the level of protection offered by the UR UGV to transport the BES UGV up to the operation area, meaning the entry of the building to explore.

During the building exploration, the UR UGV is used as a communication relay (up and down data streams) between the BES, the C2 station and the infantry group, significantly increasing by this way the operation range of the BES UGV. Considering the short distance between the BES and the UR UGV, a wire or wireless link can be used. If necessary, the UR UGV can provide an efficient fire support to the BES operation thanks to its powerful armament. The BES exploration can be fully remote-controlled by the C2 station or computer-assisted through a semi-autonomous mode (waypoints definition).

After the exploration, the BES UGV is embedded again in the UR. Two BES UGV can be transported simultaneously in a UR.

It has to be mentioned that the **UGV marsupial transportation mode is not a new idea** and that some nations (US, Germany) have already made some partial demonstrators. Recent advancements in robot technology have produced mobile robot teams. For instance, General Dynamics in US has developed a system made of the Mobile Detection Assessment and Response System (MDARS) and the Man-Portable Robotic System (MPRS) to complete military patrol tasks. The MDARS travels long distances over rocky ground transporting the MPRS. When the MDARS reaches an area that is too small for it to explore, it releases the MPRS to finish the assignment.[22]

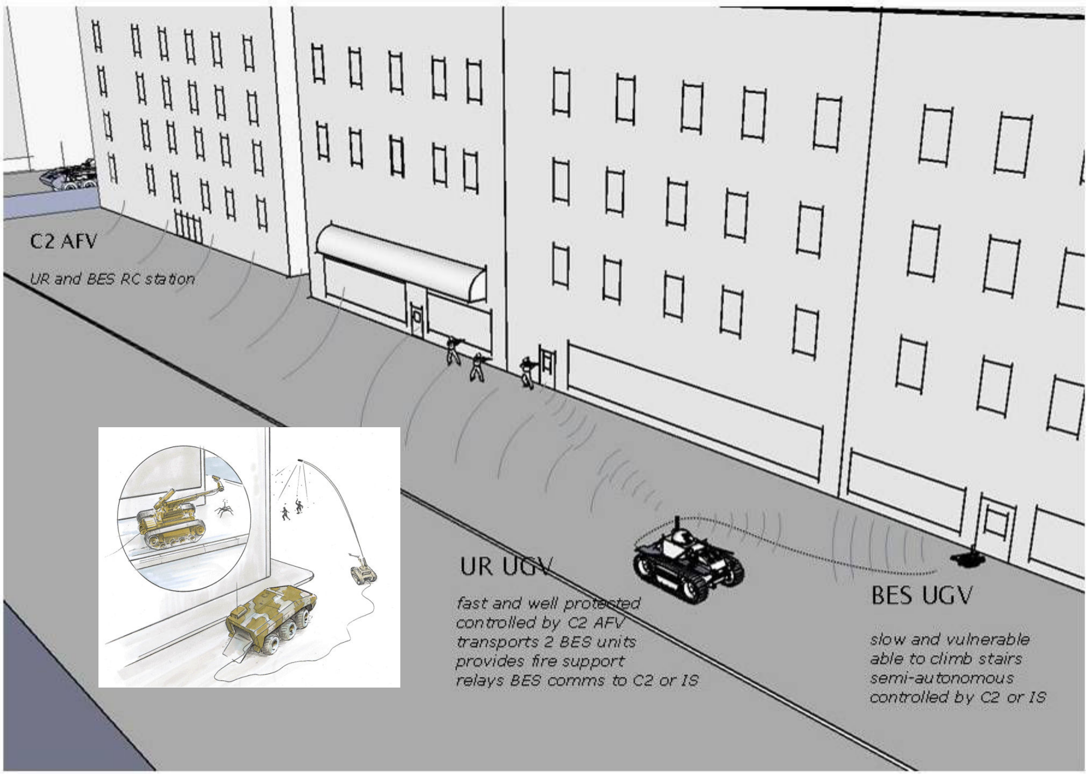


Figure 3-8: An illustration of the mixed UR-BES UGV concept. In vignette, the same type of concept issued from a NATO study [10]

Within this thesis, the mixed UR-BES UGV concept is evaluated in a simulated operational scenario in order to get insights about the employ of such a system in operational conditions.

4 Validation of the BES UGV operational capabilities

"You have to learn the rules of the game. And then you have to play better than anyone else."

Albert Einstein

There are many different ways to validate a concept before developing it: sketches, scaled model, prototyping …. Modelling and simulation is often the fastest, cheapest and most efficient ways to get first feedback from the user.

This chapter is starting by presenting and discussing the Manual War Gaming (MWG) methodology used by the DSTL Land Battle Space Department (LBSD) to simulate UGV operations. Then, the principles of another approach based on Computer Aided War Gaming (CAWG) are explained, implemented and assessed, in order to try to fill in the MWG weaknesses.

4.1 Background on war games

Originally designed to train apprentice commanders to battlefield operations, chess developed in the 18th and 19th centuries into more complex wargames.

Modern wargaming originated with the military need to study warfare and to replay old battles for instructional purposes (Prussian "Kriegspiel" in 1811). During World War II, the German army regularly gamed operations on manual wargames very similar to current manual games. [31]

Figure 4-1 : "World in Flames" WG session at Allied HQ in 1944 [31]

After World War II, the development of computers for operational research led the military strategy experts to conclude that simulation of war could provide more precise and unambiguous answers than manual war gaming. At the same time, the introduction of nuclear weapons and strategic bombers probably made the tactical aspects less crucial for the army, and manual war games were temporarily neglected. But during Vietnam war, the over-confidence in computer simulation results led the US headquarter to make wrong decisions, leading the military to reject the computer simulation to the benefit of more pragmatic war games. [32]

In the late 70s, the chaos theory asserted that the behavior of dynamic systems with a lot of degrees of freedom (such as military structures) was hugely sensitive to initial conditions and environment. That gave a scientific reason to the military to finally admit that fast and cheap manual wargames, even though inaccurate, could give results as right as long and expensive computer simulations, when all the operational elements of the plan (logistics, communications, tactics, C4I …) have been considered [31, 33].

Today, war gaming is massively used at different levels of the military organisations for a wide range of applications, from the classical infantry commander training to the teaching of strategy and diplomacy at the highest levels of commandment (only in the US MOD, more than 600 different types of wargames are in use). Military war gamers have their own structure within the military, which is often considered as the most sensitive from the security aspects. War gaming is also used efficiently for commercial purposes, to simulate a set of business conditions and train decision-makers to design successful strategies depending on different objectives and market reactions [34].

Finally, thanks to IT technologies, modern war games can today involve many participants at any given time from many different locations, which make war games more and more representative of the real world [35].

4.2 Manual war gaming at DSTL

4.2.1 Principles

As mentioned in the introduction of this chapter, the aim of the war gaming sessions conducted by DSTL was to assess the operational benefits of future UGV concepts. As each UGV concept developed in the work reported in chapter 3.2.2 was designed to carry out a different role in the battle space, all concepts were individually modelled in the manual wargaming, in two different modified commercial manual war gaming platforms: Fire Team (West End Games) for the urban scenario and Assault (Game Designers Workshop) for the open area scenario. Then, the concept performance of each UGV was translated and modelled in the format required by each game to represent the key characteristics.

For each of the games, RED and BLUE forces were deployed onto the separate identical maps, situated on either side of a dividing screen in a "Battleships" configuration, as shown in Figure 4-2.

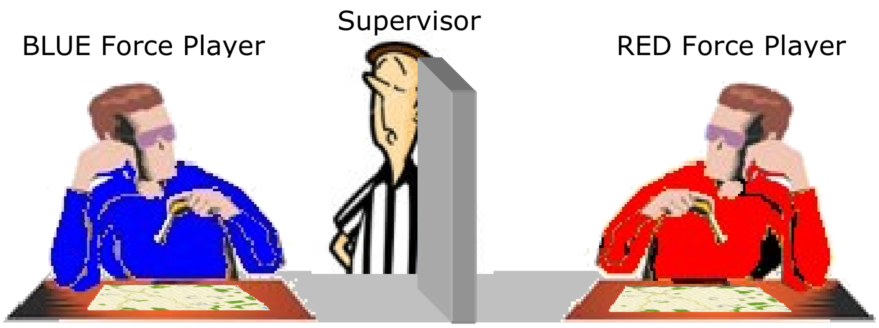


Figure 4-2: DSTL manual war gaming configuration

The role of the game controller is to assign objectives and means to each player, to supervise the sequence of events, to control the application of the gaming rules, to act as an independent observer for some phases (e.g. simulation of an UAV reconnaissance) and to collect the players' insights during and after the game, by the way of a questionnaire.

War gaming is a "turn based" game, meaning that each participant plays on his turn. A typical turn sequence of events is described in chapter 4.2.2. The game ends with the completion of one of the players' mission, or by decision of the supervisor.

Once a game is played, the players and the controller can decide to:

- refine the UGV concept itself, e.g. new observation capability,
- change the modelling of the UGV capabilities to make it more realistic, e.g. maximum mobility range by each turn,
- assess the same UGV concept in a different mission scenario or order of battle (ORBAT), e.g. offensive or defensive scenario,
- stop the UGV concept assessment, e.g. because they have enough insights about this concept.

That makes the war gaming approach not a single step but an iterative process (Figure 4-3: War gaming incremental process).

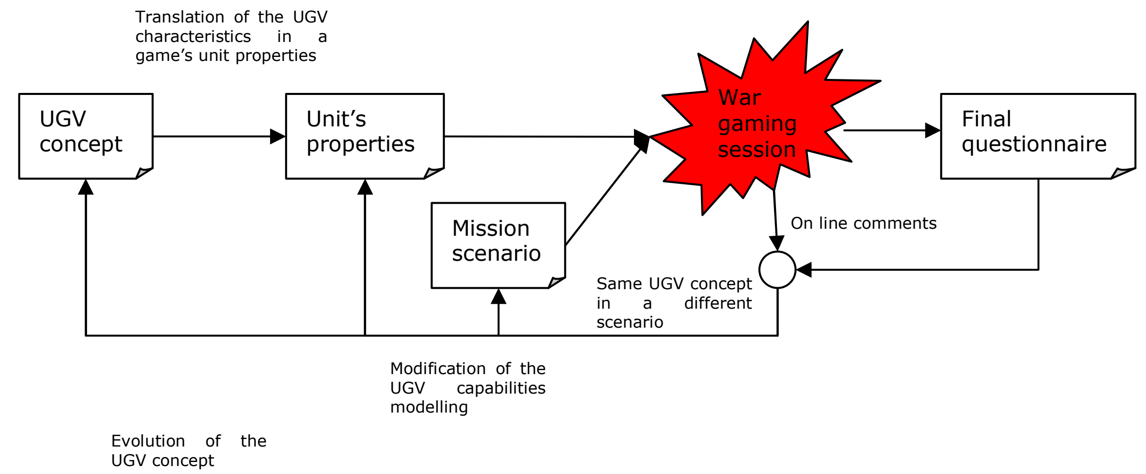


Figure 4-3: War gaming incremental process

4.2.2 Typical sequence of events in a turn

Each player takes place in front of his own 2D map representing the environment of the mission. The environment consists of an urban area made of buildings and religious structures. The map for the game was created by DSTL from real satellite imagery, with different building types represented by different coloured hexagons (or "hexes") on the map, and different floor heights by the numbers in each hex. Each hex represents an area of 25m × 25m.

The game starts by an initialisation phase, which consists of:

- a public presentation of the overall context of the operation by the supervisor (political context, environment, weather conditions …)
- the private communication of objectives and military means to each player
- the private definition of each player's ORBAT, meaning the initial positioning of the player's units on his own map

Then, as already mentioned, the game consists of a series of turns, each representing approximately 10 minutes of "real time". Each turn is divided into a series of actions, with BLUE and RED force players having alternating actions. Players use their actions to move and fire units. The judgement of the players and supervisor limits the BLUE or RED players' activities in each action, reflecting the Command and Control (C2) issues associated with the environment and short timescales.
The possible actions in each turn are, by chronological order:

4.2.2.1 Intelligence, Surveillance, Target Acquisition, and Reconnaissance (ISTAR)

Detectability of each asset is computed on the basis of signature characteristics and localisation on the map (e.g. no ISTAR by satellites possible in buildings), then a random draw is performed to check if the asset has been detected, recognised or identified. Battalion ISTAR assets is modelled at the beginning of each game turn, to reflect intelligence information gathered from a wide variety of sources. A dice is thrown for each BLUE and RED unit on the game map, giving each player the opportunity to detect, recognise or identify opposition forces.

4.2.2.2 Moving

The unit to be moved is selected by the player. The player defines the path of the unit, hex by hex up to the maximal displacement allowed by a turn, depending on the unit's characteristics. The unit moves along the path. At each point, the visibility with the enemy is checked by the supervisor and the other player is warned. If the asset has been detected, the other player can decide to fire on it or not. In that case, a fire sequence is started.

4.2.2.3 Attack

The attacker can only decide to engage a target he knows the direction of. In that case, the attacker and the defender throw their dice. The difference between the die, the attacker's firepower level and the defender's survivability level give the inputs of combat data tables managed by the supervisor. According to the output of the data tables, the attacked unit is declared to be destroyed or not. Data tables for firepower and survivability of all the units (including UGVs) were created by DSTL military advisors for use in the game.

The Figure 4-4 sums up the data exchanged between the participants, and the operations realised by each player, as it was noticed during the observation of War Gaming sessions played at DSTL.

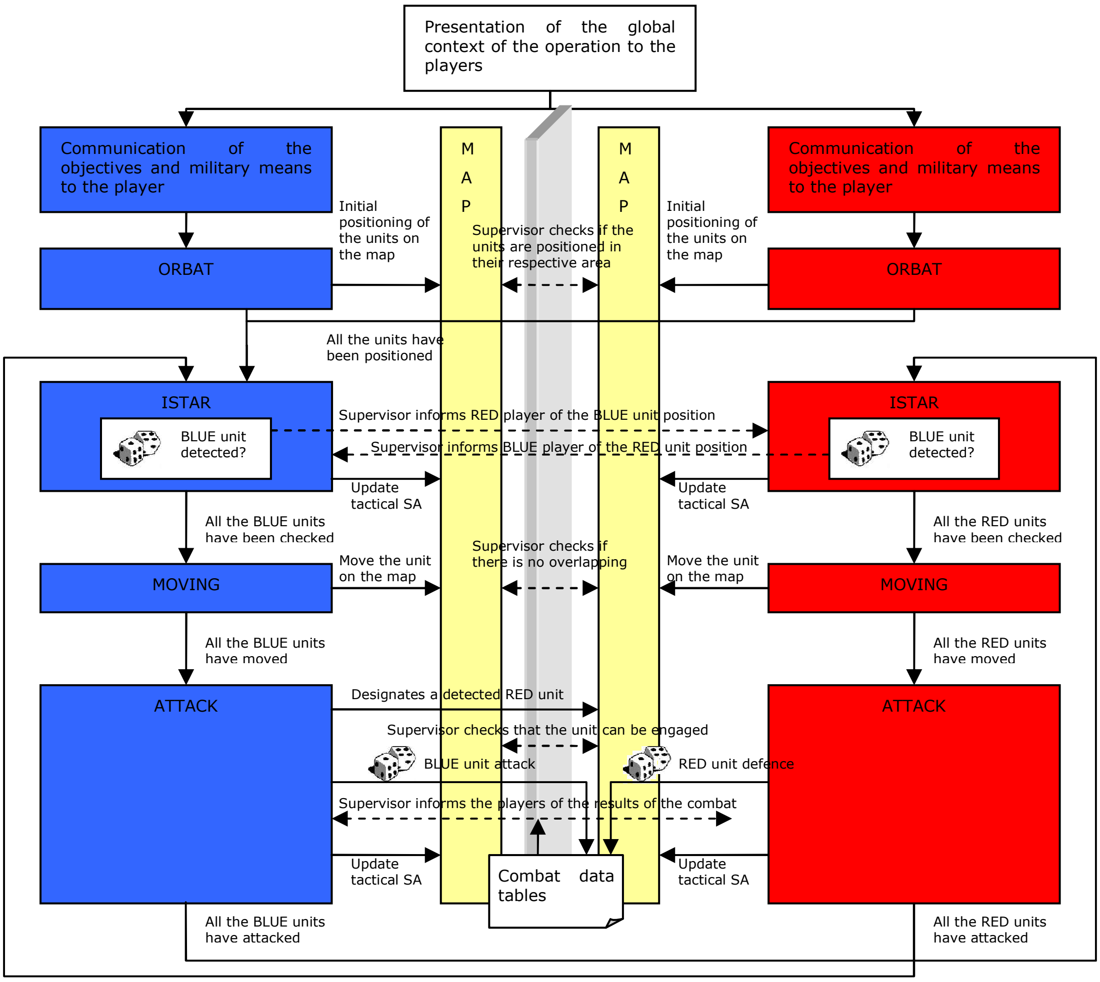


Figure 4-4: Sequence of events in a MWG turn (for a better clarity, only the BLUE attack process has been represented)

4.2.3 Analysis and conclusions on MWG sessions

4.2.3.1 About the UGV concepts

As the conclusions on the UGV concept itself have been the subject of a classified report by DSTL [36], only the general insights are considered here, while the emphasis is put on the MWG process analysis.

Roughly, the conclusions of the war gaming sessions ran by DTSL were that the "*UGVs capabilities had a positive impact on the operational tempo*" [36].

Considering the Situational Awareness (SA), the BES UGV's ability to identify enemy positions in buildings was found very useful, as it "*allowed the BLUE Commander to apply his resources in the appropriate place prior to the assault*" [36]. The UGV capabilities in general "*made a very significant contribution to BLUE SA, and in particular the BES provided valuable ISTAR information*" [36]. From the survivability point of view, it was stated that "*all the UGV concepts had a positive impact on the survivability of the battle group in performing a variety of tasks, reducing the risk to manned assets*" [36]. The lethality of the Blue force was significantly enhanced by "*the networked capability of the UR UGV concept to direct precision on-demand direct fire*" [36].

In essence, the report has concluded that UGV capabilities integrated into the battle group could significantly increase the ground manoeuvre operational effectiveness.

Some weaknesses of the UR and BES concepts, as modelled in the game, have also been reported:

- The information from the BES UGV was occasionally found to be incomplete, because of the difficulty of identifying humans in buildings in an urban environment, requiring the BLUE player "*to send a manned asset to clarify the information*" [36].
- BES UGV was found "*easy to decoy*" [36] (e.g. use of paint or blankets to disable sensors). So all concepts should be equipped with an immediate self defence capability to avoid enemy forces and civilians from approaching. The limited field of view of the sensors was also found very penalizing for the close situation awareness.
- The absence of a tactical Unmanned Aerial Vehicle (UAV) had a major negative impact on the overall capability of the battle group, mainly because of "*the inability of BLUE to identify enemy movements in depth*" [36].
- Unmanned Ground Sensors (UGS) could have been used in coordination with UGVs, in order to "*provide BLUE force with information of any movement on possible routes of advance*" [36], without requiring a UGV.

4.2.3.2 About the MWG process

The MWG method itself was judged by the players an "*effective way of gaining insights into the complex issues surrounding the operation of a unit the size of a battle group*" [36].

The time required by the checking of the Line Of Sight (LOS) between units and the calculation of the engagement results was found a major drawback of the MWG. During the gaming sessions, DSTL experts have developed an Excel application that allows checking the LOS between hexes semi-automatically and to access the combat

data tables more easily, and this was found very useful by the players and the supervisor.
But this calculation constraint still limits the accuracy of the modelling. For instance, no potential communications issues were explored for simplicity of gaming, even though players were conscious that significant issues exist (particularly considering UGVs operations), with regards to communications links in the urban environment and overall bandwidth limits in the battle-space.

Finally, it was found that the high levels of concentration required by the players and supervisor, combined with the time required to play a scenario phase "*makes it unsuitable as a tool for assessing multiple variations in capability or the quantification of effectiveness*" [36].

On the basis of these conclusions, it was proposed to DSTL to make a survey of the possible extra simulation tools that could address the MWG drawbacks mentioned above, while complying with the following user expectations, collected at the occasion of a meeting with the FGMC/LBSD war gaming experts (Feb. 24th 2009 at DSTL).

<u>Ease of use</u>

The players insisted on the fact that the tool had to be very easy to configure and use by non IT-skilled people. Indeed, FGMC/WG players are chosen for their particular skills in military tactic, without any regards to their IT competencies.

<u>Modularity</u>

As FGMC is a long-term study of which the aim is precisely to get insights about future robots concepts capabilities, the makeup of the tactical units, the definition of the units, their capability and their performances have to be perfectly identifiable and very easily modifiable.

<u>Opening and ability to evolve</u>

The tool is supposed to be opened to further modifications and involvements, on the basis of the players' feedbacks.

<u>Level of realism</u>

In order to provide the maximum of insights about the using of the system in real operating conditions, the CAWG tool has to be the most close to the reality as possible.
As the expected level of realism was difficult to quantify by the players, the assumption was made that the tool has to be at least as realistic as the manual war game currently used at DSTL.
Realism level is closely linked to the deepness of the modelling, which also conditions the development time and the game speed during the use.

4.3 Computer Aided War Gaming Tool

A survey of existing CAWG led to the conclusions that no commercial tool was complying with the user expectations. Then, the development from scratch of a computer tool dedicated to the simulation of a BES UGV deployment and engagement scenarios was considered with good chances of success, taking into account the background acquired during the attendance to DSTL manual war games sessions.

4.3.1 Aimed improvements considering MWG

Considering the drawbacks of manual war gaming reported in chapter 4.2.3.2, the expected benefits from the design of a CAWG tool are:

- the ability to develop scenarios with a faster tempo,
- the ability to better match with the reality,
- the ability to get qualitative insights but also quantitative results,
- the ability to easily configure the units' parameters,

all these requirements leading to a better time investment and global efficiency.

4.3.1.1 Increased gaming tempo

Considering the MWG drawbacks reported by the players, the first objective of CAWG development was to increase the gaming tempo by implementing automatic computation of:

- Moving (what is the maximum distance a unit can be moved?)
- Lines of sight between the units (which units are visible, and by who?)
- Results of engagements (what is the result of the attack?)

4.3.1.2 Better level of realism

It was assumed that the CAWG to develop had not only to increase the speed of the gaming by automatic computation, but also to allow taking into account more UGV characteristics and environmental parameters that were supposed to have a significant influence on the UGV utilisation.

The Table 4-1 lists the attributes that have been retained after the MWG sessions analysis.

Topic	**Domain**	**Effect**	**Manual WG**	**Computer Aided WG**
Environment	Weather	All	No	no
	Terrain	Type	Yes	yes
		Elevation	No	yes
		Traficability	No	yes
		Masking	No	yes
	Time passing	Mission duration	Yes	yes

	Morale	All	No	no
Communications	Tactical	Audio communication	No	no
	C4I	All	No	no
	Remote Control	Range	No	yes
Units	Move	Speed	No	yes
		Range	Yes	yes
	Protection	DAS	Yes	yes
		Armour	Yes	yes
	Observation	Detection range	Yes	yes
		Reconnaissance range	Yes	yes
		Identification range	Yes	yes
		Sensitivity to mask	No	yes
		Line of sight	Yes	yes
	Direct fire	Range	Yes	yes
		Power	Yes	yes
		Ammunitions	No	yes
		Probability of hit	Yes	yes
		Line of sight	Yes	yes
	Indirect fire	Range	Yes	yes
		Power	Yes	yes
		Ammunitions	Yes	yes
		Designation	No	yes
		Probability of hit	Yes	yes
C4I	Satellite	Tactical SA (Battalion level)	Yes	yes
	UAV	Tactical SA (Regiment level)	No	yes

Table 4-1 : Attributes modelled in MWG and CAWG

4.3.1.3 More accurate analysis of results

As concluded in chapter 4.2.3.2, the tool has not only to generate the same kind of qualitative insights from the players as the manual wargames do, but also to provide quantitative outputs that could help to determine the best configuration of UTE and BES UGV capabilities regarding to different kinds of mission.

Expected results are:

- Qualitative: Ability to record and to replay all the actions (moves and attacks) conducted during a game for after action review

- Quantitative: Ability to observe and compare the effects of a performance modification on the scenario achievement. This particular objective, which gets the best of computer simulation capabilities, can only be achieved if the enemy reacts to the blue force actions in the same way. Otherwise, results could be distorted by the second player's reactions and difficult to interpret.

4.3.1.4 Simpler environment required for gaming

MWG requires mobilising three skilled people during three days (the average duration of a MWG session), of which approximately one third is really productive from the insights point of view, considering the time spent to manage the gaming. Indeed, a large part of the time is spent in installing the game, distributing the counters, explaining and checking the rules …

The ability to implement the map and the gaming rules in a software tool would allow:

- to play directly on office computers, possibly in a distance,
- to use a "player vs computer" mode, in case of unavailability of the second player,
- to repeat scenarios with the same expected enemy reactions.

4.3.2 Architecture of the global model

The overall architecture of the model results from the analysis of the attributes to take into account in the simulation (Figure 4-5).

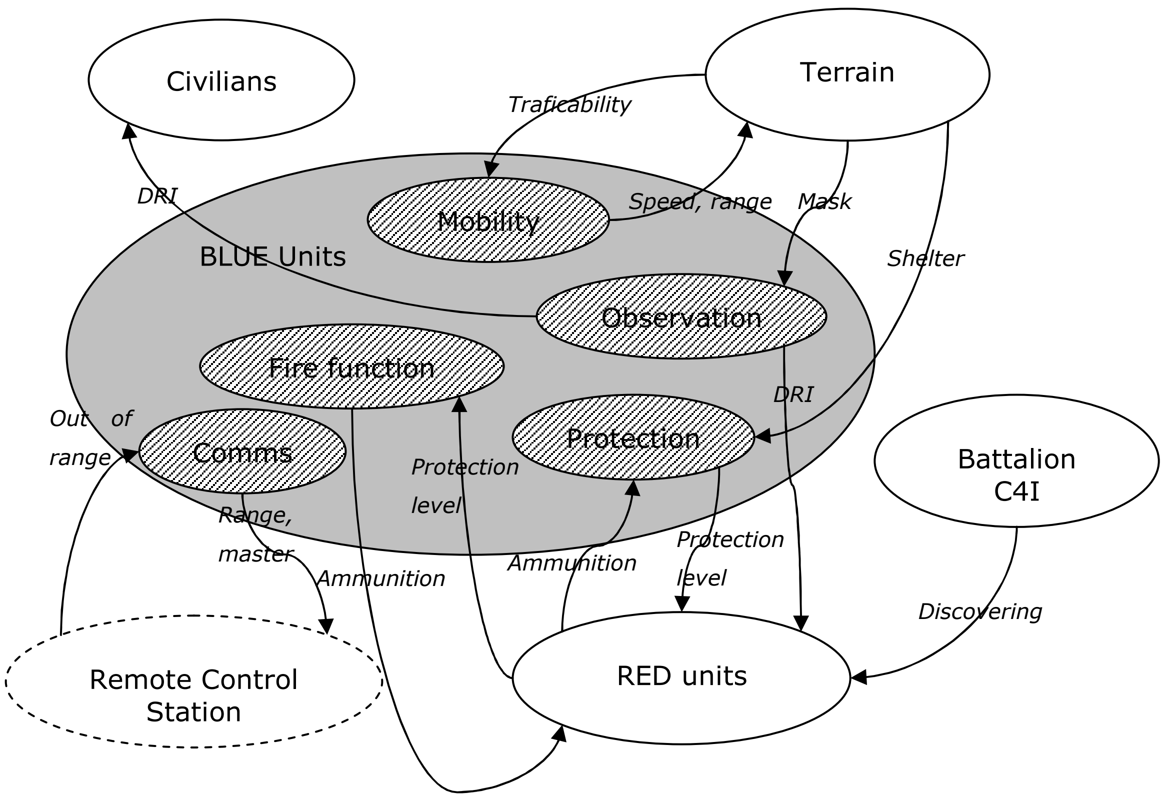


Figure 4-5: Interactions within the entities of the modelling

4.3.3 Terrain modelling

4.3.3.1 Urban Operations Area

The operation area has been chosen in order to get insights about the whole BES UGV using process, from the initial UTE deployment to the final recovery. An aerial picture of a suburb of Kabul fulfils all the necessary conditions: open and urban area, different types of buildings, and preferential paths between obstacles (Figure 4-6).

Typical Urban Environment for BES-UGV intervention (Kabul suburb)

The matching aerial view (Google map)

Figure 4-6: Typical example of intervention terrain

4.3.3.2 Dimensions

The dimensions of the operation area have been set to 2km x 2km approximately. It is a good compromise between the accuracy required to make buildings inspected by UGVs and the distance needed to allow managing different types of engagement between AFVs.

No zooming capabilities have been implemented, so the whole map is displayed permanently.

The map has been split in hexagons of 50m diameter approximately. Hexagons (hexes) are preferred to squares because they better fit with the obstacles in the real world, and they allow more natural moves of the units. The size of the hexes is a compromise between the accuracy and the readability of the map. It also refers to the terrain area a unit is able to manage by itself.

The Figure 4-7 shows the way the aerial picture of the urban area was segmented to obtain the map used in this project.

This way of modelling the terrain allows to consider large scale maps, as the one which was used in the considered scenario, as well as very detailed maps, in order to simulate a single room inspection for instance. In that case, hexes' dimension can be set to 1 m, in order to simulate walls, furniture and room entries.

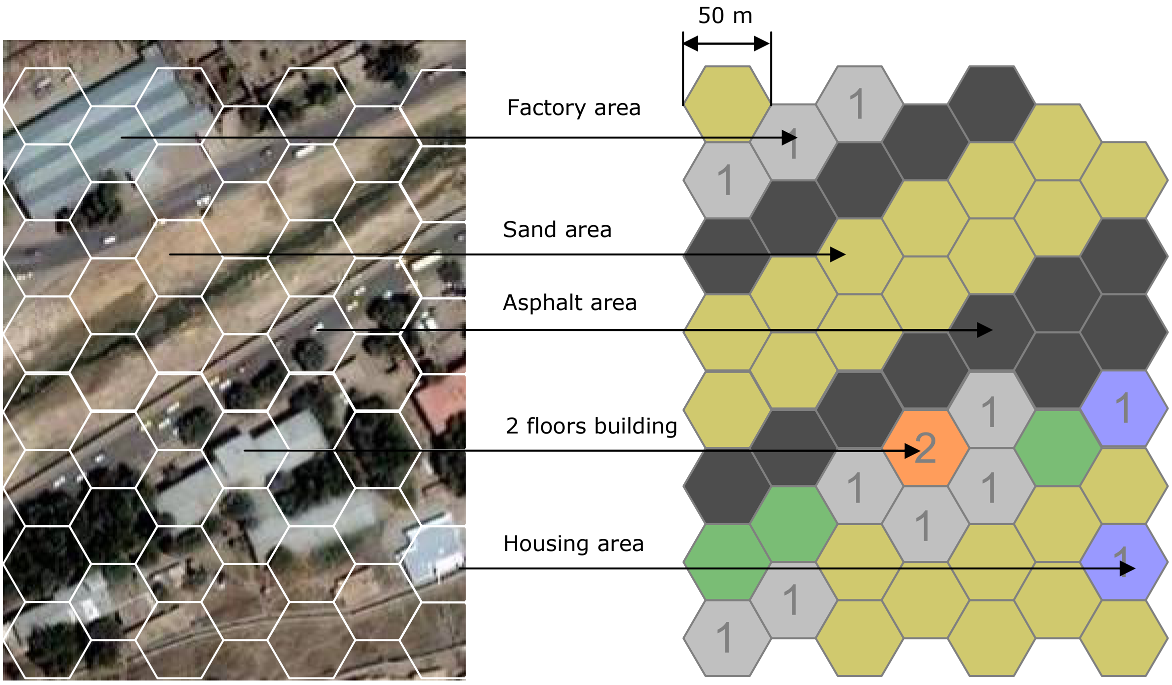


Figure 4-7: Segmentation of the aerial picture into elementary hexes

4.3.3.3 Terrain

As every military people know it, the nature of the terrain has major impacts on the ability of a unit to move, to detect, engage and destroy a target but also on the tactical decisions and the way to conduct the mission, by taking advantage of natural and artificial obstacles to keep hidden and protected.

The nature of the terrain is particularly important in the case of the BES UGV because of its small dimensions that make critical the choice of the right path to reach its objective at the right time. It is also a determining factor in the BES UGV requirements definition, while the mission can not be completed without endowing it with specific capabilities: e.g. ability to climb stairs to reach upper floors, ability to deploy a mast to observe over a wall.

As presented in 0, the whole operations area is divided in elementary terrain areas called hexes. So, each hex defines the characteristics of the type of terrain which is present by a majority in the considered parcel (see Figure 4-7: Segmentation of the aerial picture into elementary hexes).

In order to describe the reality in the best way without uselessly complicating the simulation, the following parameters have been retained:

- the elevation of the terrain, meaning the elevation of the floor of the considered area (e.g. 4th floor of a building),
- the height of the terrain, meaning the maximal height of the obstacles present on the considered area (e.g. a 10m height forest),

- the impact on the mobility, meaning how the mobility of a unit present on the considered area is affected by the terrain (e.g. sand),
- the impact on the observation, meaning how the Detection, Recognition and Identification performances of the unit are affected by the terrain (e.g. dense forest),
- the impact on the protection, meaning how the protection of the unit can be increased by the obstacles present on the considered area (e.g. walls in a housing structures area)

It has to be noticed that a distinction has been made between administrative, housing and manufacturing buildings. This is to manage the higher probability of finding civilian people in the housing areas during the White units' initial positioning phase by the computer.

A number is then affected to each parameter. These numbers are used in different ways, depending on whether they are used to affect the mobility and observation capabilities or the fire and survivability ones.

For the mobility and observation capabilities, these numbers multiply (or divide) the nominal mobility and observation characteristics. For instance, a MBT with an intrinsic mobility performance of 8 on asphalt will have a mobility performance of 8 x 0.8 = 6 in the sand and 8 x 0.2 = 1.6 in dense urban areas.

For the fire and survivability capabilities, this number will be added (considering the possibility of negative numbers) to the intrinsic capability of the unit during a combat phase. For instance, an RPG equipped soldier with a fire power of 4 in open area will have a fire power of 3 when it is used in forest (difficulty to aim the target) and a fire power of 6 when the grenade is launched from the second floor of a building (because it offers a higher chance to damage an AFV by the top, where it is less protected).

These parameters have been set regarding to geometric factors (e.g. floor level, height) but also according the following empiric considerations:

- Mobility is nominal on asphalt tracks. For instance, it is a bit more difficult to move in sand and in bush areas (x 0.8) and much more difficult to move in wooden areas (x 0.5 to 0.3).
- Observation capability is highly impacted (x 0.5 to 0.3) by the possible presence of branches and leaves interfering with the sensors' field of view.
- Wooden areas also reduce the probability to hit a target (-1) as leaves and branches can interfere with the gunner line of sight. On the opposite, a high elevation position provides a higher chance (+2) to damage an enemy AFV by the top, where it is less protected.

- The level of protection capability is increased when the unit operates in a dense forest or in a building (+2), because of the additional protection offered by the surrounding walls.

Whatever the numbers given to the parameters are, it has to be reminded that the CAWG tool has been designed to make comparative analysis with different UGV capabilities' levels. In so doing, it is more important to keep the terrain's parameters constant than to set them accurately.

obj_	sand	asphalt	water	houses	bush	woodland	forest	Private _1_flr	Private _2_flr	Private _3_flr	Working _1_flr	Working _2_flr	Public _1flr	Public _2flr	Public _3flr	Public _4flr
mob_impact	0.8	1	0	0.2	0.8	0.5	0.3	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
obs_impact	1	1	0	0.5	0.8	0.5	0.3	1	1	1	1	1	1	1	1	1
fire_impact	0	0	0	-1	0	-1	-1	1	2	2	1	2	1	2	2	3
prot_impact	-2	-2	0	2	0	1	2	2	2	2	2	2	2	2	2	2
floor_level	0	0	0	0	0	0	0	1	2	3	1	2	1	2	3	4
height	0	0	0	3	3	3	3	3	6	9	3	6	3	6	9	12

Table 4-2: Terrain's model parameters

4.3.3.4 Line Of Sight

Line Of Sight (LOS) testing between units is a key factor for observation and direct fire purposes. In order to determine if two units are in LOS in the terrain model, the following algorithm has been implemented: if there is a hex between the units that is higher or equal to the hex the units are placed on, then there is no LOS.

The elevation of the sensors is taken into account by adding the height of the units' sensors to the height of the hex the unit is placed on.

This algorithm is a good compromise between the speed of simulation and the level of accuracy required to estimate LOS. The Figure 4-8 and Table 4-3 present different cases of units' situations and the related LOS test results after the application of the simple algorithm mentioned above.

After having checked the LOS between two units, the observation capabilities (Detection, Reconnaissance and Identification attributes) of the Blue unit are considered. The stealth (or detectability) of the target is taken into account by increasing the probability of the target to be spotted according to its size.

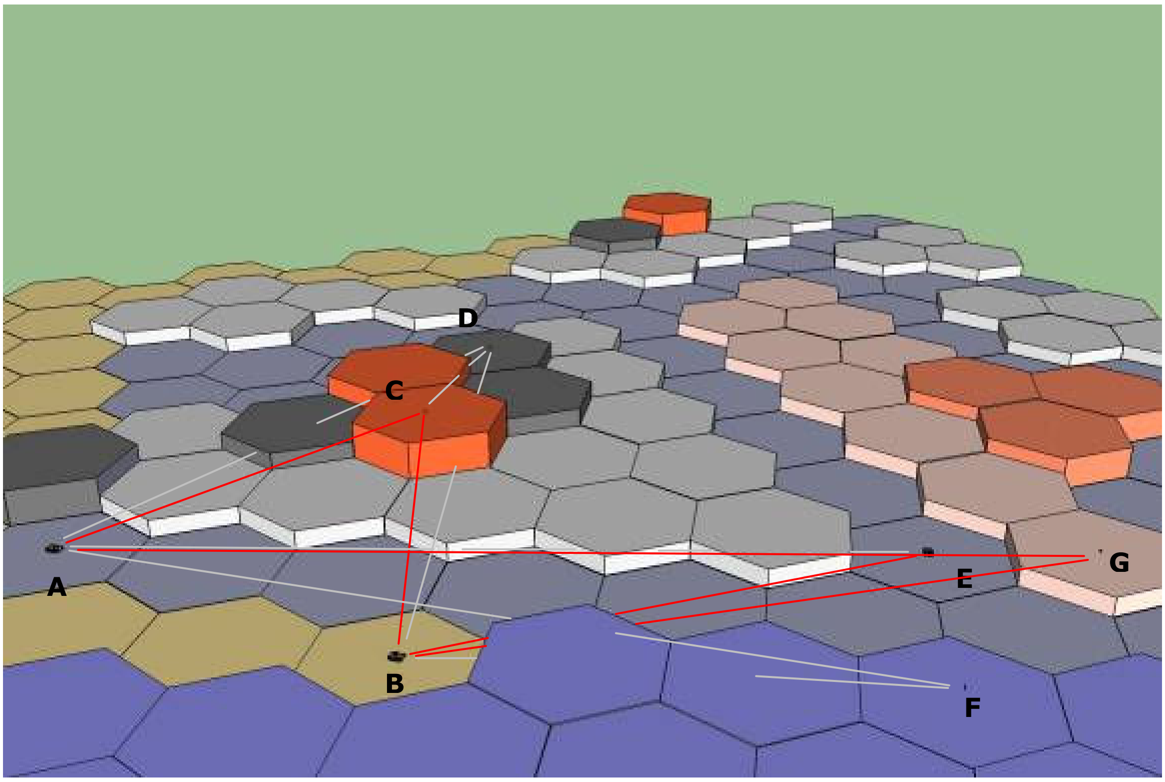


Figure 4-8: Example of LOS (red) and NLOS (gray) units' situations

In LOS Of	C Red RPG	D Red RPG	E Red AFV	F Red Sniper	G Red RPG
A Blue AFV	yes	no (higher obstacles between)	no (behind the road corner)	no (not close enough to the building side)	yes
B Blue AFV	yes	no (higher obstacles between)	yes	no (not close enough to the building side)	yes

Table 4-3: Results of the LOS algorithm

The Figure 4-9 shows the inheritance of the terrain's properties in the Obstacle model class. All the types of terrain inherit from the Obstacle class and its properties (height, mob_impact …). With such a structure, additional properties can possibly be added to each type of terrain (e.g. density of the forest) or groups of terrain if needed.

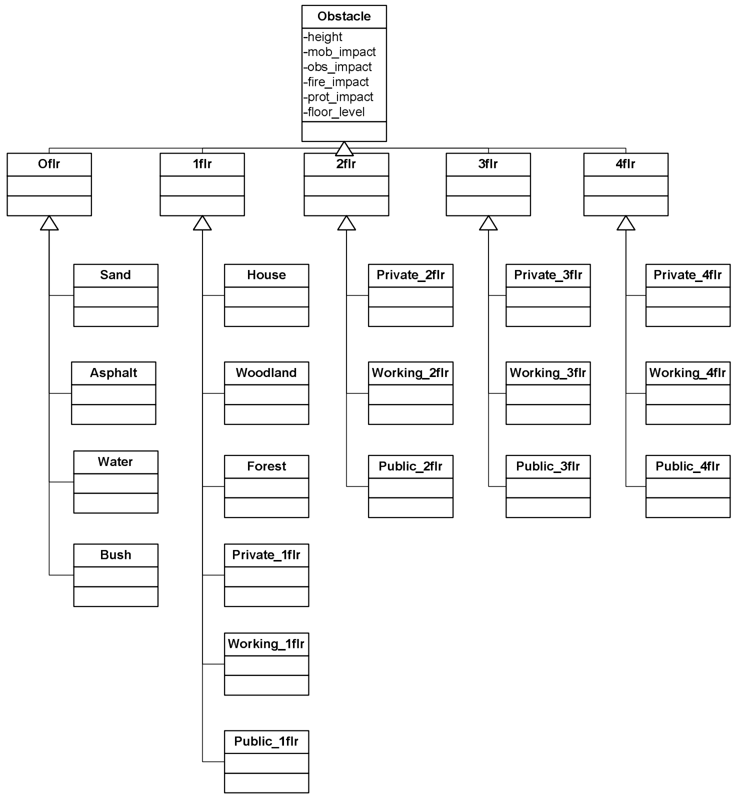


Figure 4-9: Terrain model class

4.3.4 Communications modelling

Only the command and control communication range between the BES UGV, the UR UGV and their C2 station have been modelled. This is to take into account the loss of control that could happen when the distance between the UGV and its remote control unit is greater than the communication range.

C2 station is warned it is about to lose the communication with the UGV.

The rest of the Blue Force's tactical communications is not modelled as it is assumed to be operational in all conditions (full coverage of data communications).

4.3.5 Units modelling

Three groups of units are involved in the mission. The Blue Force is made of all the units managed by the player. The Red Force is played by the other player (not implemented yet) or the computer, as well as the White Force, made of the passive population.

All the units have common (e.g. operational status, level of protection, fire power …) and specific capabilities (e.g. marsupial transportation, ability to climb stairs, DAS equipment …) that make the object approach very well adapted to this type of models.

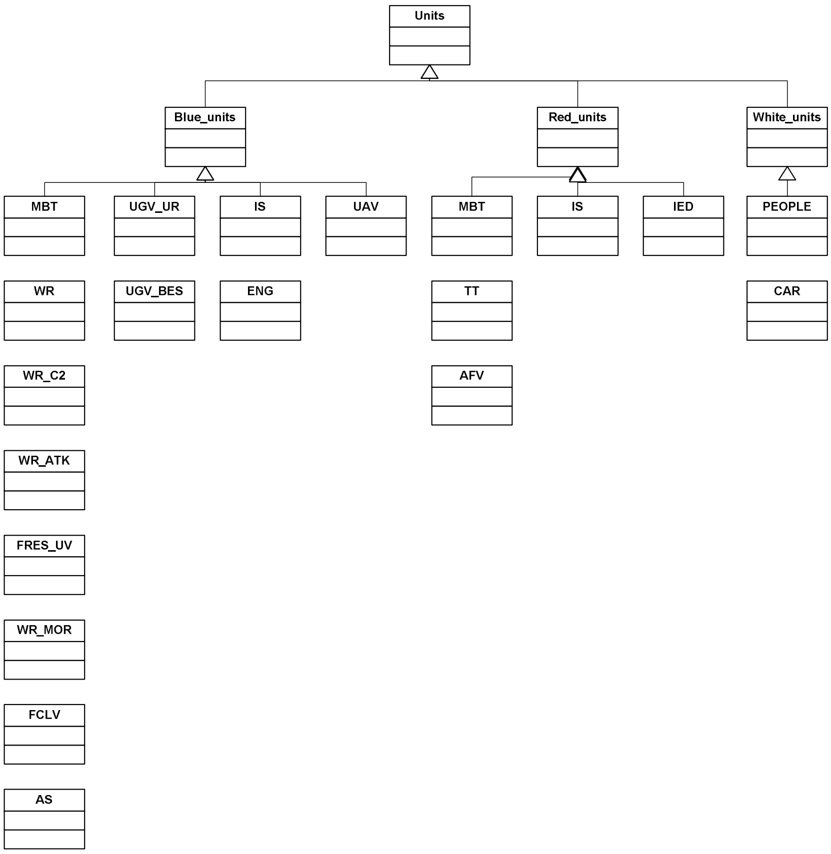


Figure 4-10: Units model class inheritance diagram

The Figure 4-10 shows the inheritance of the units' properties in the Units model class. All the types of units inherit from the Units class and its properties (indirect fure capability, mobility range …). The Units class is split in three classes grouping together the particular behaviours of the Blue, Red and White units. By this way, additional properties can possibly be added to each type of group of units, or individual units (e.g. ability to embed BES UGV for URs UGVs) if needed.

4.3.5.1 Blue Force

The Blue Force is the set of all the allied units. To simulate the different solutions of deployment for the BES-UGV and to get insights about the interactions between the BES-UGV and the rest of the UTE, it is necessary to model a representative set of the different types of units that could participate to such a mission, and to give the player the ability to select, organise and deploy the UTE ORBAT according to the mission scenario to simulate.

obj_blue_	MBT	WR	IS	ENG	WR _C2	WR _ATK	FRES _UV	WR _MOR	UGV _BES	UGV _UR	FCLV	AS	UAV	
Type	AFV	AFV	Soldier	Soldier	AFV	AFV	AFV	AFV	UGV	UGV	AFV	AFV	UAV	
move_range	4	3	1	1	3	3	4	3	2	3	4	2	4	in hex / turn
LOS_range	20	15	10	10	12	15	15	12	5	0	12	0	0	in hex
LOS_power	10	8	1	1	5	8	8	5	1	0	5	0	0	0-10
illuminator	TRUE	TRUE	FALSE	FALSE	TRUE	TRUE	TRUE	FALSE	TRUE	TRUE	TRUE	FALSE	FALSE	true or false
NLOS_number	0	2	1	0	2	2	2	20	0	2	0	10	0	number of missiles
NLOS_range	0	50	3	0	50	50	50	20	0	10	0	50	0	in hex
NLOS_power	0	10	6	0	10	10	10	2	0	6	0	10	0	0-10
DAS_protect	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	true or false
armour_protect	5	3	0	0	3	3	4	3	1	2	2	4	0	0-10 (0:no protection 10:undestroyable)
max_hp	10	10	10	10	10	10	10	10	10	10	10	10	10	number of initial health points
height	2	2	2	2	2	2	2	2	1	4	2	2	100	height of the sensors
size	1	0.8	0.2	0.2	0.8	0.8	0.8	0.8	0.2	0.5	0.5	1	0.2	0 (micro-robot) to 1 (MBT)
detect_range	50	25	5	5	25	25	30	10	3	15	5	5	10	in hex
reconn_range	30	15	3	3	15	15	20	6	2	10	3	3	5	in hex
identi_range	25	10	2	2	10	10	10	4	1	8	2	2	3	in hex
C2_range	_	_	_	_	_	_	_	_	5	10	_	_	_	in hex
IED_sensor	FALSE	FALSE	FALSE	TRUE	FALSE	FALSE	FALSE	FALSE	TRUE	FALSE	FALSE	FALSE	FALSE	true or false

Table 4-4: Blue Force units' model attributes

The Blue Force units' attributes have been selected in coherence with the expected level of realism reported in Table 4-1. Then, the value of each attribute has been defined on the basis of the typical level of performance usually achieved for the equipment considered. For instance, typical DRI ranges for MBTs are 1500, 1000 and 800m, leading to set the detection, reconnaissance and identification attributes to 50, 30 and 25 (in hexes). Some of the units' attributes are binary (e.g. illuminator), meaning that the capability is implemented or not on the unit.

4.3.5.2 Red Force

The Red Force is the set of units that act to prevent the Blue Force completing its mission. It is made of vehicles, infantry soldiers and Improvised Explosive Devices (IED), as this is one of the major threats in the current conflicts.

The Red Force is played by the computer, which moves the units and attacks the Blue Force units according to pre-programmed rules (very simple in the current tool).

IEDs are static traps that can only be discovered by Engineers or BES-UGV.

As shown on Table 4-5, only a subset of the Blue Units' attributes is considered for the Red Units. This is to make the simulation faster, but it would be very easy to involve other Red Units' characteristics in the simulation. Again, the attributes' values are set regarding to real typical performances for each type of unit.

obj_red_	TT	MBT	AFV	IS	IED	
Type	AFV	AFV	AFV	Soldier	IED	
move_range	2	4	3	1	0	in hex / turn
fire_range	12	20	50	3	0	in hex (e.g. 20 = 1000m)
fire_power	5	10	10	6	8	0-10
armour_protect	2	5	3	0	0	0-10 (0:no protection 10:undestroyable)
max_hp	10	10	10	10	1	number of initial health points
size	0.5	1	0.8	0.2	0.1	relative size of the unit (0:microUGV 1:MBT)
height	2	2	2	2	0	height of the sensors

Table 4-5: Red Force units' model parameters

4.3.5.3 "White" Force

The White Force is the set of people and vehicles that do not take part to the combat, but that can deeply modify the decisions of the Blue Force, since collateral damages avoidance is considered as a major objective of the mission. It could be also represent a United Nation (UN) force, as long as they do not react to a threat.

4.3.5.4 Mobility

The mobility capability of a unit is defined by the maximal number of hexs it can move at each turn. It includes the time required to do the navigation and give the moving orders to the driver. It depends mainly on the characteristics of the unit itself (e.g. wheeled or tracked vehicle) but it is affected by the nature of the terrain the unit is currently placed on.

e.g. FRES_UV has an intrinsic mobility of 4 hexs (~200m) by a turn, when moving on asphalt. When it moves in a high density housing area (narrow streets), its mobility range decreases to: move_range (=4) x mob_impact (=0.2) ~ 1 hex by a turn.

4.3.5.5 Observation

The observation capability of a unit is defined by its Detection, Recognition and Identification ranges, which depend on the type and performances of the sensors.

These DRI performances are affected by the nature of the terrain.

e.g. MBT has intrinsic DRI capabilities of 30,20 and 10 hexs respectively (~1500, 1000 and 500m). When it observes from a woodland area, its detection range decreases to: detection_range (=30) x obs_impact (=0.5) = 15 hex.

At each turn, the updated DRI performances of Blue Force units are combined with the LOS algorithm to determine the Red Force units that are visible. In the example of Figure 4-8: Example of LOS (red) and NLOS (gray) units' situations , units C and G in unit B LOS are out of the unit B DRI range, which finally makes the unit E the only one detected by B.

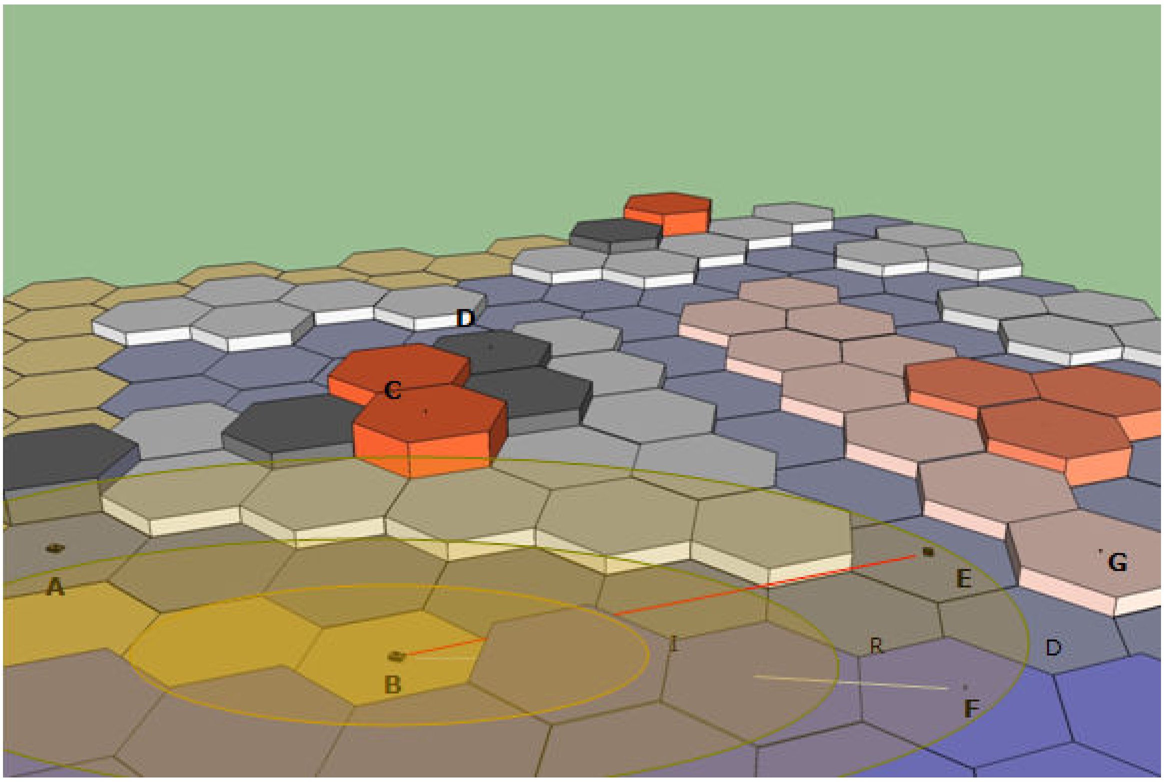


Figure 4-11 : Combination of LOS and DRI computation to determine visible units

4.3.5.6 Protection

The protection capability of a unit is defined by its ability to detect and destroy incoming ammunitions (optional active protection) and to resist to an aggression (armour). This is to match the best with the "integrated survivability" concept. No collaborative protection mechanism has been implemented.

4.3.5.7 Fire Function

Blue Force units can be equipped with direct fire armament (primary and secondary armament) and/or indirect fire armament. Only Laser Guided Missiles are modelled in order to take into account the designation constraint. The number of ammunitions is limited.

4.3.5.8 Improvised Explosive Devices (IEDs)

IEDs are modelled as static camouflaged traps that can be located anywhere in built areas (IED) or on roads (mines). They can only be discovered by UGVs or Engineers specially equipped for that (refer to Table 4-4: Blue Force units'). When an IED has been discovered, it is marked and it remains visible by the other units during the rest of the game.

When a unit (AFV or soldier) moves to a hex where an IED has been planted, it is destroyed at the next Red Force turn.

4.3.5.9 BES UGV

The BES UGV is modelled as a remote controlled UGV transported by the UR-UGV up to the operation area. This marsupial capability allows it to take benefit of the UR-UGV moving speed and protection while its using is not required. It also increases the remote control range, by making the UR-UGV as a communication relay for the BES.
In addition to the other units features, the BES-UGV is able to climb stairs in order to explore buildings and detect IEDs.

All the units' attributes are defined in the constructor script file attached to each class of unit or group of units. The Figure 4-12 shows an example of such a definition file, for the UR-UGV unit.

```
//definition of the capabilities of each asset

name:="UGV-UR";//this is the name of the unit that will be drawn once it gets selected.

//mobility capabilities
move_range:=4;//maximal distance (in hex) the unit can progress in one turn
mounted:=false;//unit is not transported

//stealth capabilities
max_visibility:=0.7;//defines the visibility level of the unit (0:invisible 1:always
visible)
size:=0.5;//defines the relative size of the unit (0:micro UGV 1:MBT)

//fire capabilities
LOS_range:=0;//maximal distance (in hex) a target can be engaged
LOS_power:=0;//fire power of LOS armament
illuminator:=true;//able to designate a target
NLOS_number:=2;//number of NLOS ammunitions
NLOS_range:=10;//range of NLOS
NLOS_power:=6;////fire power of NLOS armament

//protection capabilities
DAS_protect:=false;//DAS capability or not
armour_protect:=4;//level of protection
max_hp:=10;//number of initial health points of the unit (in points)

//other capabilities
IED_sensor:=false;//unable to detect and defuse IED

//observation_capabilities
height:=0;//elevation of sensors
detect_range:=15;//maximal range of detection (in hex) = there is something
reconn_range:=10;//maximal range of reconnaissance (in hex) = RED, BLUE or WHITE
identi_range:=8;//maximal range of identification (in hex) = BMP3, CH2 ...

//communication_capabilities
C2_range:=10;//maximal range of communication with other units (in hex), not use except
for the UGV
C2_ID:=0;//C2 identification

//slave_units_ID
BES_inside:=4;
BES_ID[0]:=0;

//the general variables of the units are defined in obj_blue_units object
event_inherited();//this calls the create event of the parent object
```

Figure 4-12: Definition file of the UR-UGV's capabilities

4.3.6 Combat modelling

When it has not attacked at his turn already, a unit A can decide to engage a unit B when the following conditions are met:

- Unit A has a direct fire capability AND it has remaining ammunitions AND unit B is in Line Of Sight AND unit B is in direct fire range,

OR

- Unit A has an indirect fire capability (missiles) AND is has remaining ammunitions AND unit B is spotted by a LASER designator AND unit B is in indirect fire range.

Engagement is modelled in the same way as in manual wargames. It is based on the units' fire power and protection capabilities (possibly modified by the type of terrain) and on a part of random, to simulate the probability of hitting or not the target.

4.3.6.1 Capabilities adjustment

First, the units' fire power and protection level are adjusted according to the type of terrain.

fire_power = Theattacker.fire_power – Theattackerhex.fire_impact

e.g. direct fire_power of a Blue Force MBT in woodland = 10 – 1 = 9. This is to simulate a possible slight loss of accuracy of the fire loop in this type of environment (moves, masks …)

protection_level = Thedefender.armour_protect + Thedefenderhex.prot_impact

e.g. protection level of a Red Force AFV in housing zone = 3 +2 = 5. This is to simulate the extra protection offered to the spotted unit by masks (walls).

4.3.6.2 Combat solver

Secondly, the result of the engagement, meaning the possible damage to the unit attacked, is calculated on the base of a preset table combat and a random number, like it is done through a dice roll in the manual wargame.

The difference between the updated attacker's firepower and the defender's protection level is the column input of the combat table (between 0 and 9)

The raw input of the table is the result of the dice roll (a random number between 0 and 9).

Finally, the combat table provides the damages suffered by the attacked unit.

This table has been extrapolated from a more complicated table used by DSTL to give the result of a simulated engagement phase between two units. As the data in this table are restricted, a simpler table was used in this project, without significant impact on the results achieved.

e.g. a Blue Force MBT posted in a woodland area engages a Red Force AFV posted in a housing area. Differential is 9-5=4

The dice roll gives 2.

The engagement results in 5 points damage to the Red Force AFV.

Damage made to the defender		Differential (fire_power – protection_level)									
		0	1	2	3	4	5	6	7	8	9
	0	0	5	5	5	5	10	10	10	10	10
	1	0	0	5	5	5	10	10	10	10	10
	2	0	0	5	5	5	5	10	10	10	10
	3	0	0	5	5	5	5	10	10	10	10
Dice	4	0	0	0	5	5	5	5	10	10	10
	5	0	0	0	0	0	5	5	5	10	10
	6	0	0	0	0	0	0	5	5	10	10
	7	0	0	0	0	0	0	0	5	10	10
	8	0	0	0	0	0	0	0	0	5	10
	9	0	0	0	0	0	0	0	0	0	10

Table 4-6: Combat Table

4.3.6.3 Operational status management

When a target has been hit, the suffered damages are subtracted to its current operational status, modelled through Health Points (HP). As initial HP is set to 10, it means that 1 or 2 successful fires from a powerful unit (MBT) are usually enough to destroy a light armoured unit.

4.3.7 C4I modelling

The acronym C4I stands for "Command, Control, Communications, Computers, and Intelligence". One important capability that C4I systems provide to commanders is situational awareness, meaning information about the location and status of enemy and friendly forces.[37]

In the simulation, a first initial situational awareness is provided to the Blue Force player by revealing the position of a part of the Red Force before the beginning of the game.

During the game, the Blue Force has the capability to launch UAVs to get updated information about the position of the Blue Force units. The UAV trajectory is fixed in advance and can not be modified by the player. Obviously, only the units visible from air can be discovered.

4.3.8 Mission modelling

The scenario was designed to put the BES UGV in various situations, in order to get the most versatile insights about the impact of the BES UGV on four main areas of interest: Operational Tempo, Situational Awareness, Lethality and Survivability.

Operational Tempo is defined by the ability to make decisions and execute faster than the enemy.

Situational Awareness is the perception of environmental elements within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future.

Lethality refers to the ability of a weapon system (or a system of system) to destroy a target.

Survivability is defined as the ability of a system (or a SoS) to remain mission capable after a single engagement.

4.3.8.1 Global context of the mission

In order to get a realistic scenario from the operational point of view, the scope of the mission scenario has been provided by LtCol Desbois from the French Army, who was notably the operational advisor in the 'Evolution of mounted combat in contact', dealing with the collaboration between manned and unmanned platforms.[38]

The scenario was set in 2020. After a revolutionary takeover in BRAKISTAN, the government has established a fundamentalist religious structure and ethnic cleansing against specific religious factions was occurring. A coalition force was authorised to conduct operations to restore the democracy. BAKUL is the administrative capital of BRAKISTAN and also contains a number of sites of key religious significance.

In this offensive scenario, the Blue Force has to conquer different strategic positions in the suburb of BAKUL, which are supposed to be occupied and defended by insurgents.

The Blue Force UTE is made of 6 cavalry platoons, split in B1 and B2 groups.

Group B1 is in charge to take over the objective 1, getting over the KILO crossroad.

The mission of the group B2 is to take over the ALPHA crossroad, in order to cover the action of B1 face to South.

Moves of enemy AFVs have been reported, as well as the possibility to face to RPG attacks from buildings. The presence of mines and IEDS also is highly probable.

Obviously, Blue Force units are required to absolutely avoid civilian victims. As the operation area has not been entirely evacuated, that makes the mission even more delicate.

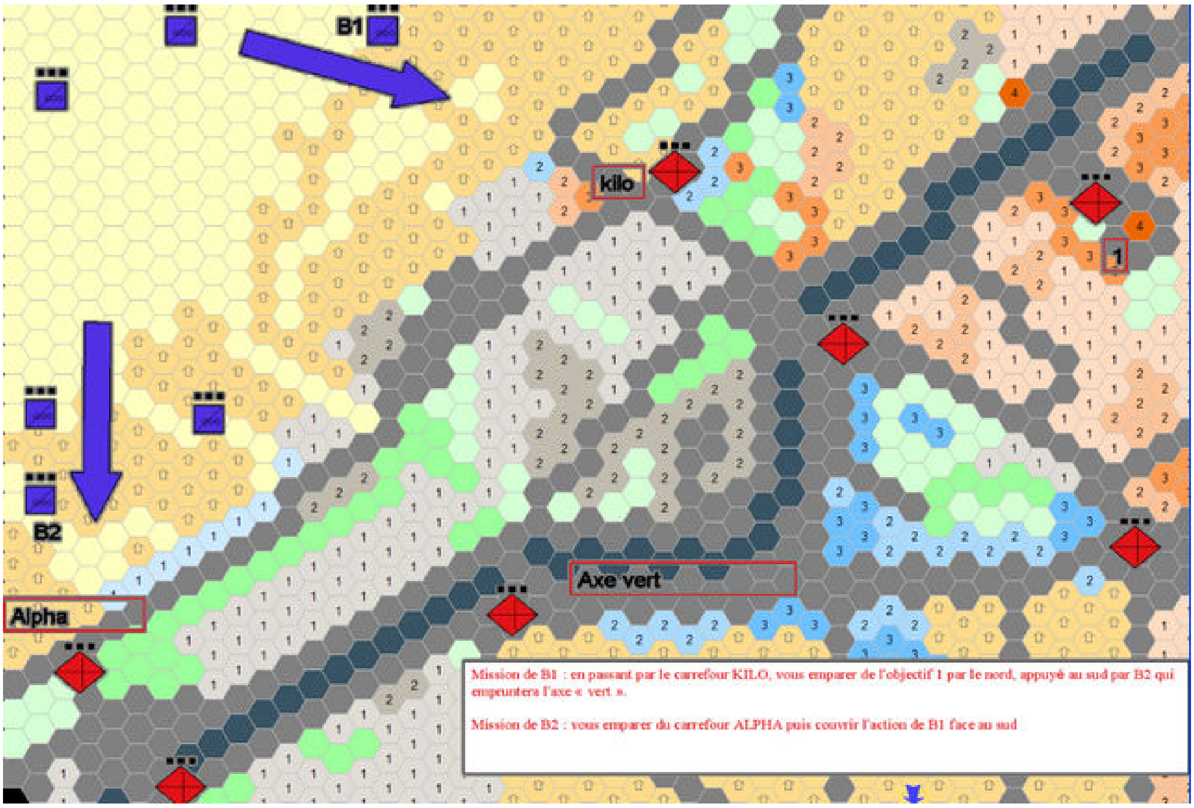


Figure 4-13: Global map of the mission

4.3.8.2 Blue ORBAT

As the B2 group is only made of manned platforms (1 reconnaissance + 2 heavy tanks platoons), B1 group involves robotic platforms and UAVs. So, the scenario focuses on the progression of the B1 group up to its objective, while the B2 group is guarding B1 against threats coming from South.

B1-1 Recce Platoon	B1-2 Infantry Platoon	B1-3 Cavalry Platoon
- 8 BES-UGV carried by UR-UGV + 2 WR-C2 AFVs - 2 FCLV - 1 UAV	- 2 FRES-UV AFVs (each with 8 infantry soldiers mounted) - 2 WR AFVs	- 4 CH2 MBTs

Table 4-7: Detailed ORBAT of B1 group

<u>Detailed instructions:</u>

B1-2 is tasked to move to KILO objective by the West, paying a particular attention to inspect and secure the FACTORY area. B1-2 is supported by B1-1 to detect and defuse possible IEDs in the area.

B1-3 is tasked to conquer KILO objective by using the South-West road, taking care of possible RPG fights from the buildings on the sides.

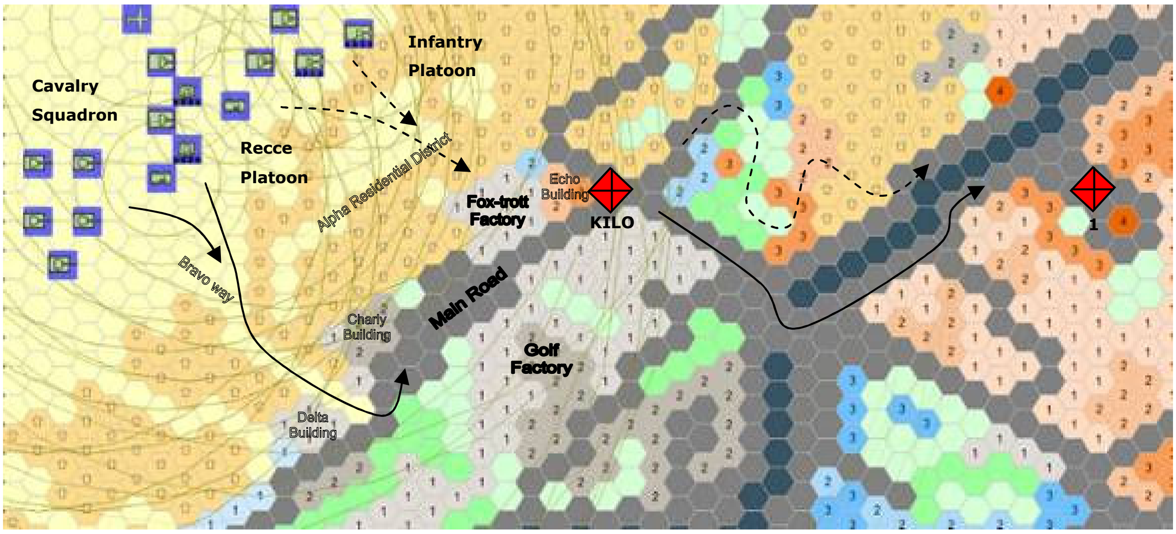


Figure 4-14: B1 group road map

4.3.8.3 Red ORBAT

The Red Force ORBAT definition has to obey two main rules:

- Red Force ORBAT has to be consistent with the played scenario and with the Blue Force ORBAT, to get interesting insights,
- Red Force initial ORBAT has to be unknown by the Blue Force Player, except through the initial tactical awareness like in the reality,
- In order to get quantitative data from different simulation runs, the Red Force ORBAT has to stay consistent but slightly different between the runs.

So the Red Force ORBAT is automatically generated by the computer, on the basis of the choice of the definition of areas of influence (type, perimeter and density of units) by the player.

Red Force units are of three types: AFV units (MBTs, AFVs, Light Armoured Vehicle) ATK snipers (infantry soldiers equipped with RPGs) and IEDs. The Figure 4-15: Example of Red Force ORBAT automatically created by the computer shows an example of ORBAT generated by the computer, on the basis of parameters entered by the Blue Force player. Obviously, Red Force units' positions have been discovered only for presentation purpose.

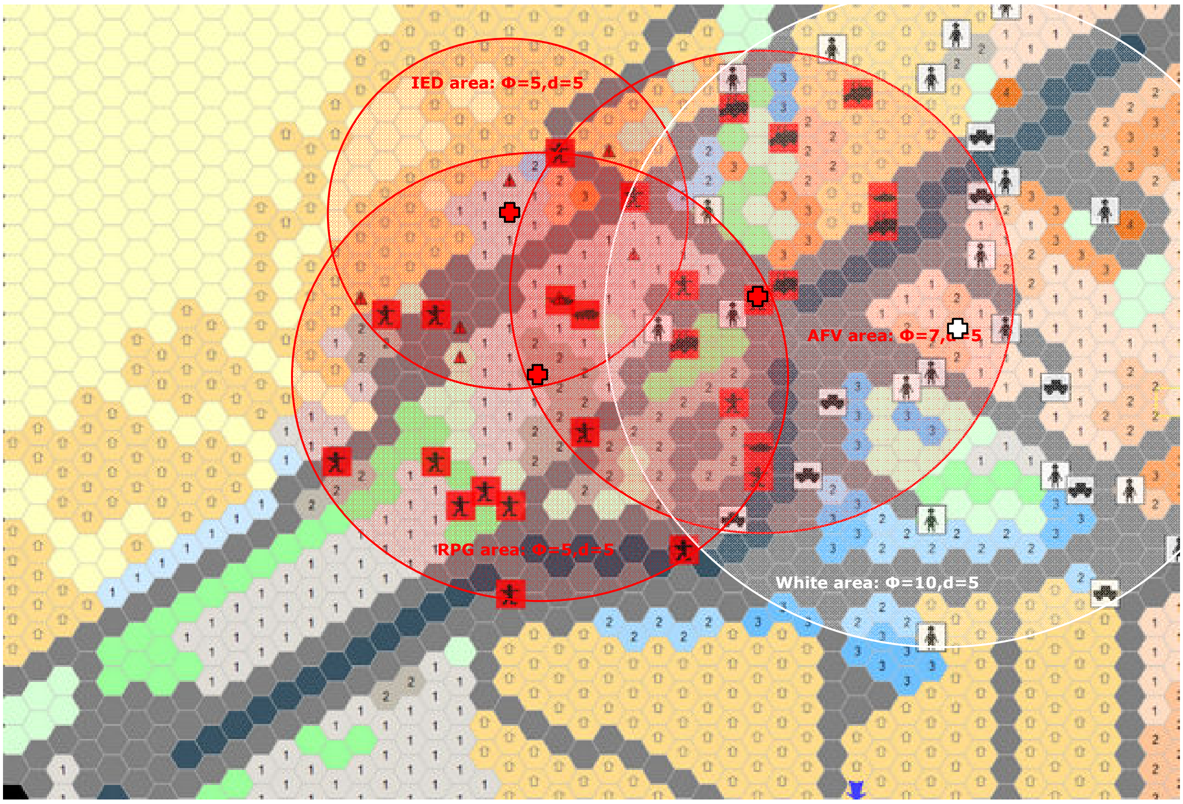


Figure 4-15: Example of Red Force ORBAT automatically created by the computer

4.3.9 Software implementation

A short survey of the most adapted tools for implementing the concepts described above, including high level languages, led to the interest in using a Game Development Environment called Game Maker [39] because of its events management and object-oriented programming already available features. That allowed focusing on the modelling of the elements themselves instead of wasting time to manage the MMI aspects, considering the timing constraints of this research.

4.3.9.1 The Game Maker development environment

Game Maker is a Windows computer program designed to allow the users to easily develop computer games without the requirement of prior computer programming experience, while allowing advanced users to create complex applications with its built-in scripting language.

Game Maker's primary development interface uses a drag-and-drop system, allowing users unfamiliar with traditional programming to intuitively create games by visually organizing icons on the screen. These icons represent actions that would occur in a game, such as movement, basic drawing, and simple control structures (Figure 4-16).

For users with computer programming experience, Game Maker contains a built-in scripting programming language called the Game Maker Language (GML), allowing more complex games to be made with the program. This language has been used to implement the CAWG models' different functionalities.

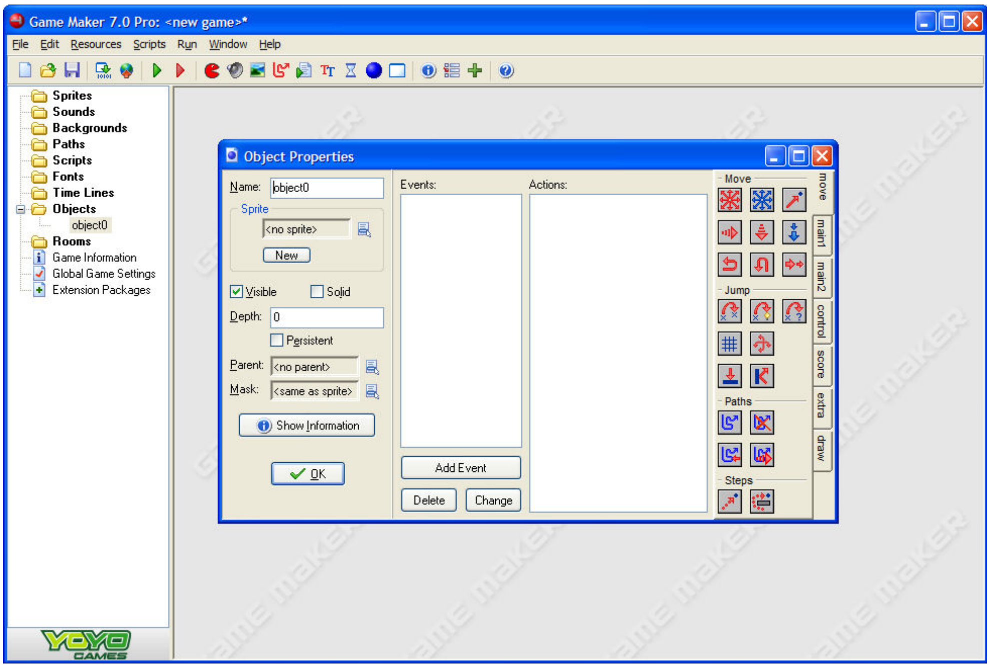


Figure 4-16: Game Maker main screen and object properties' window

4.3.9.2 Programming the concepts in Game Maker

All the concepts presented above have been programmed in GML, leading to the current version (V4.2) named CAWG (Computer Aided War Gaming). This version is the one that was used to run the different simulations and obtain the results presented below.

Three classes' packages have been defined: terrain, assets and control classes.

The different types of terrain were modelled as different classes with specific attributes reflecting their impact on units' capabilities. Then, instances of these classes (objects) were used to manually populate the background of the scene (map) as shown on Figure 4-17.

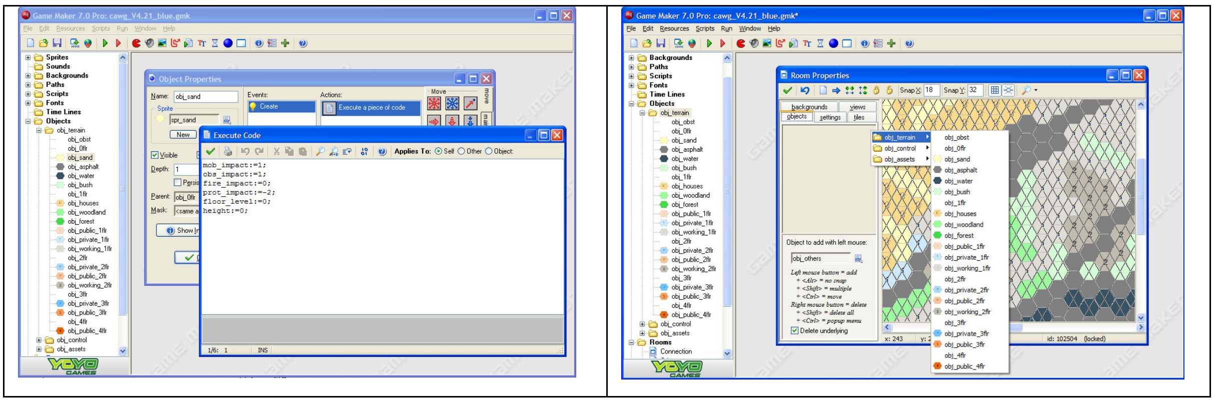


Figure 4-17: Terrain classes' definition and instantiations in the map

The general behaviour of the Blue Force units has been defined in the Obj_blue_units class. This is an important class, as it defines the behaviour of all the blue units, in reaction to the Blue player orders (e.g. right-click on a unit). The annex 7.3 details the way the possible events on the *obj_blue_units* class' objects are managed.

The Figure 4-18 shows examples of programming of some of these actions in GML, respectively for Blue and Red Force units.

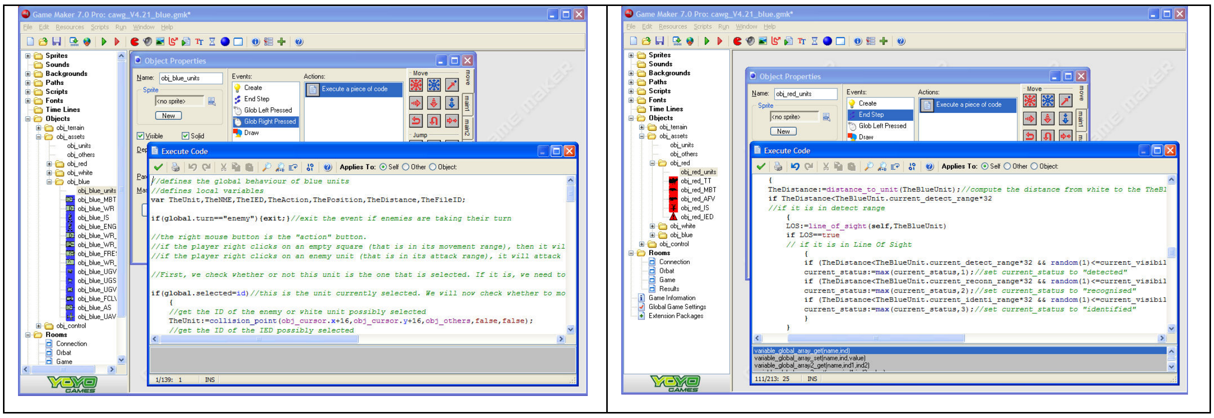


Figure 4-18: Examples of reactions' programming to events on Blue Force and Red Force units

Specific attributes (fire_function, protection, mobility … levels) and capabilities (mast deployment, embedding, designating …) are programmed in each individual type of unit's class as already presented on Figure 4-12.

In addition to the terrain and units classes, a third group of classes is made of the peripheral elements of the tool, like the buttons to create the orbat and to access map functionalities, the cursor to position the elements, etc. For instance, the Figure 4-19 shows the way transparency of the aerial picture was managed to implement a superimposition functionality on the CAWG map.

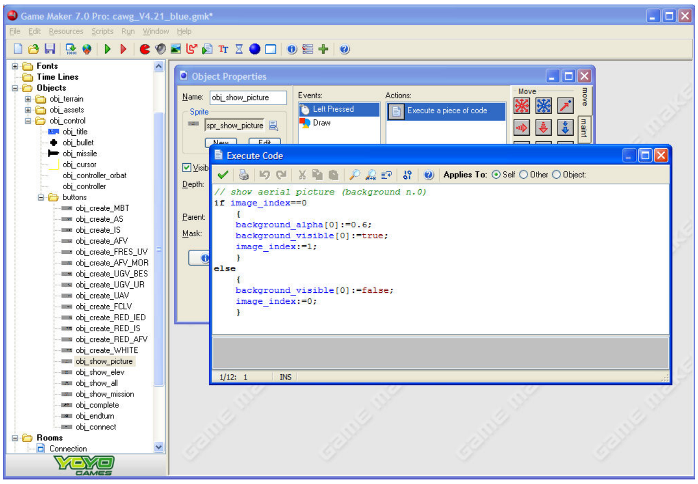


Figure 4-19: Programming of the picture superimposition function

Some high-level functions available in Game Maker libray have been exploited to model the capabilities of the assets (distance between two objects, collisions checking, path programming as in Figure 4-20). Unavailable functionalities (e.g. combat management, data recording …) have been programmed directly in GML as scripts. These functions can then be called by any of the classes.

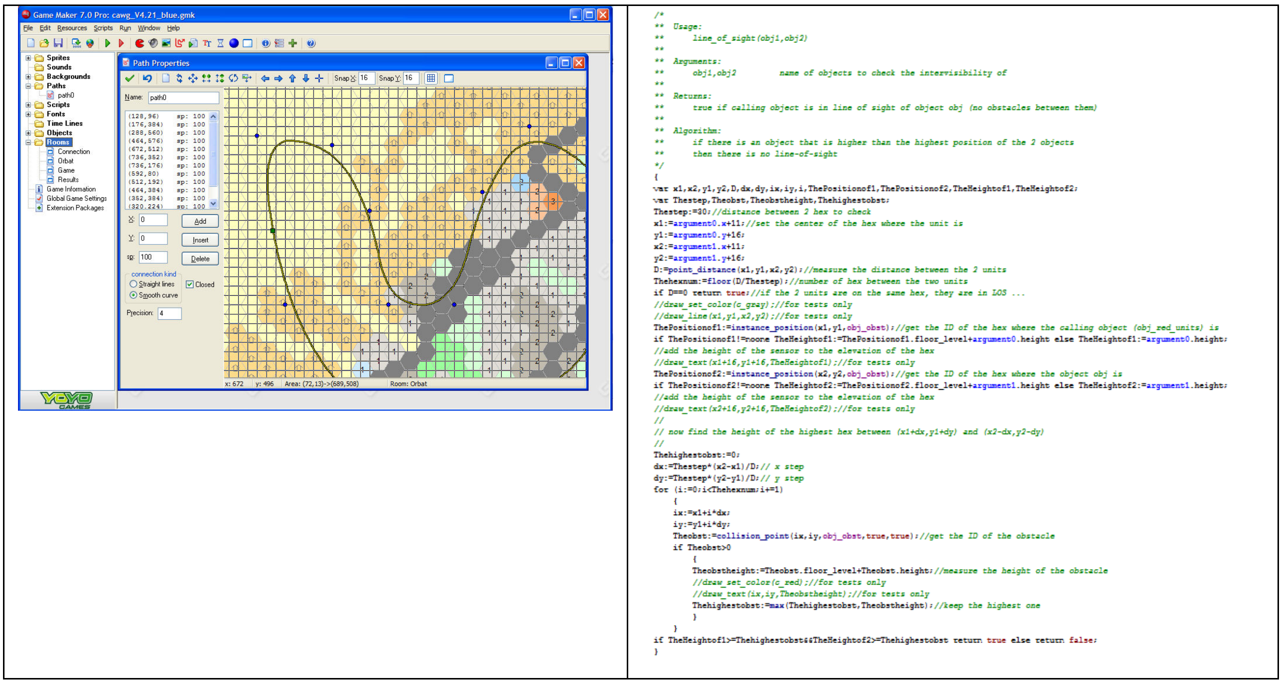


Figure 4-20: Examples of Game Maker preset function (path programming) and user-programmed function (Line of Sight Computation)

Finally, it has to be mentioned that, thanks to the choice of Game Maker and its development capabilities, a first functional version of the CAWG tool has been realised in about 3 months. This version was used to get first feedbacks from the DSTL users, and then decide about the most appropriate improvements.

4.3.9.3 Final aspect of the CAWG tool as developed in the GM environment

As shown on Figure 4-21, the overall using of the tool is split into four sequential phases, to manage the establishment of the communications with the Red Force Player computer (optional and not implemented yet in the current version), the definition of Blue and red Orbats, the gaming itself and the results analysis.

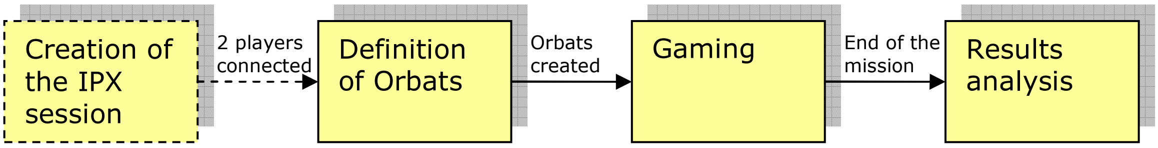
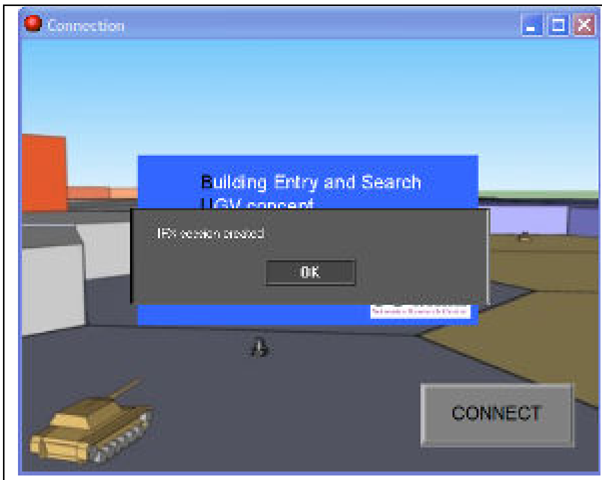


Figure 4-21: Typical sequence of CAWG game

4.3.9.4 Red Force computer connection management (optional)

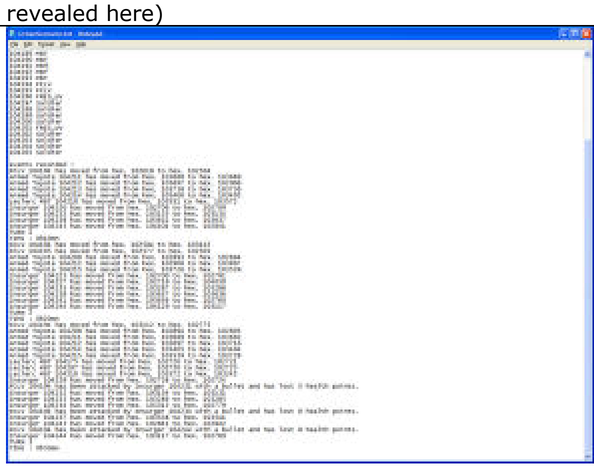
The tool offers the possibility to have the Red Force managed by a second player (like in manual wargames) from a second computer connected to the Blue Force player's one through Internetwork Packet eXchange (IPX) protocol. Despite the fact that the management of the connection is managed, the current version of the tool does not implement the "two players" mode yet, and this phase is skipped on the "one player" mode.



Creation of the connection with the second computer

Definition of the Blue and Red ORBAT (Red positions revealed here)

Gaming



Results analysis

Figure 4-22: CAWG screen captures

4.3.9.5 ORBAT definition

The second step is to define the Blue and Red Forces Orbats.

The Player picks the type of units he wants to involve in the Blue Force Orbat by clicking on the buttons on the left-down part of the screen.

The middle-down part of the screen is dedicated to the Ref Force Orbat definition. Different areas with different types of units can be specified (refer to 4.3.8.3) as shown on Figure 4-23: ORBAT definition GUI.

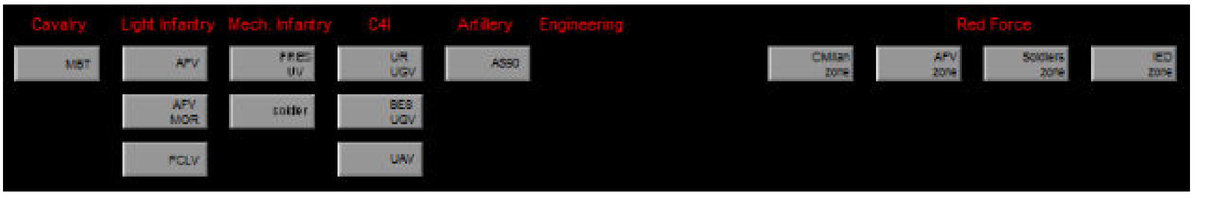


Figure 4-23: ORBAT definition GUI

The right-down buttons can be used by the player to superimpose the elevation map, the aerial picture or the mission map to the hex map. An additional button allows the player to temporarily reveal the position of all the assets, as shown in Figure 4-22: CAWG screen capture.

Once the BLUE and RED ORBAT are defined, the user is invited to leave the ORBAT screen by pressing the "ORBAT COMPLETED" button. After having filled in the scenario identification pop-up boxes, the gaming phase can start.

4.3.9.6 Gaming

As manual war gaming, computer aided war gaming is based on turns, during which each player (or computer) has the opportunity to:

- move a unit,
- attack with a unit,
- make specific operations with a unit, when it is implemented in its model.

Moves and attacks are possible according the rules already defined in chapters 4.3.5 and 4.3.6.

Additional specific operations have been implemented through pop-up menus (see , to allow the player to interact with the unit's model special capabilities (Table 4-8).

Specific operation	Description
Mount	Allows a unit (e.g. infantry soldier or BES UGV) to embed in another one (e.g. troop carrier or UR UGV)
Unmount	Allows a unit to disembark
Go up	Allows a unit (e.g. soldier or BES UGV) to go up to a floor in a building
Go down	Allows a unit to go down a floor in a building
Drop off UGS	Allows a unit to drop off a ground sensor

Direct fire	Allows a unit to attack an other with direct fire
Indirect fire	Allows a unit to attack an other with indirect fire (available only if the target has bee designated before)
Designation	Allows a unit to designate an other with laser designator

Table 4-8: Specific operations allowed on some units

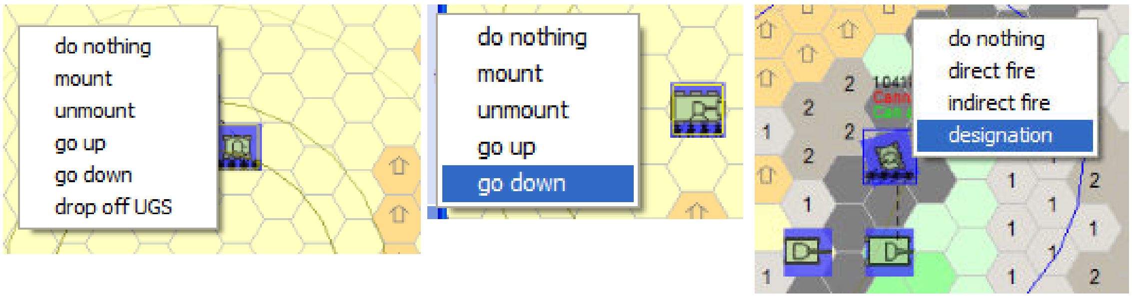


Figure 4-24: Conceptual menus to access to specific operations

4.4 Results

As mentioned in chapter 4.3.1.3, the CAWG tool was designed to provide qualitative and quantitative results.

Qualitative results:

On the basis of the simulated scenario developed above (4.3.8), an example of simulation session providing qualitative results is attached in chapter 7.3. In addition to the comments made by the player, all the events occurring during a turn are recorded in a text file for after-action review.

This qualitative analysis is well adapted to the global assessment of different designs of UGV concepts, with several parameters (dimensions, sensors elevation …) and capability performances (fire, mobility …) changing at the same time. When a parametric analysis is required, a quantitative analysis of the results is more appropriate.

Quantitative results:

For a more accurate analysis of the impact of the modification of a single parameter, a statistical analysis of quantitative results is recommended.

As the scenario development has been made non-deterministic by introducing random behaviour in the enemy Orbat (4.3.8.3), different simulation runs on the same scenario will provide different outputs, of which the trend will give a good indication of the impact of a parameter on the unit capabilities, while accounting for diverse enemy behaviour.

As it is almost impossible to realise a complete parametric analysis of the BES UGV capabilities, moreover considering different scenarios, only three specific analyses are reported here.

4.4.1 Case study 1: Impact of a mast deployment system on the Situation Awareness

4.4.1.1 Scenario

The simulated scenario was significantly simplified, in order to limit the simulation time. Similarly, no other blue unit was considered, as they have no impact on the UGV DRI observation in the context of this scenario.

Two UR UGVs were tasked to reach the same point through different paths (Figure 4-20). During their progression, they were not allowed to engage targets, or to react to engagements. The only parameter modified during the two different sets of 10 runs was the ability to elevate the sensor mast up to 6m.

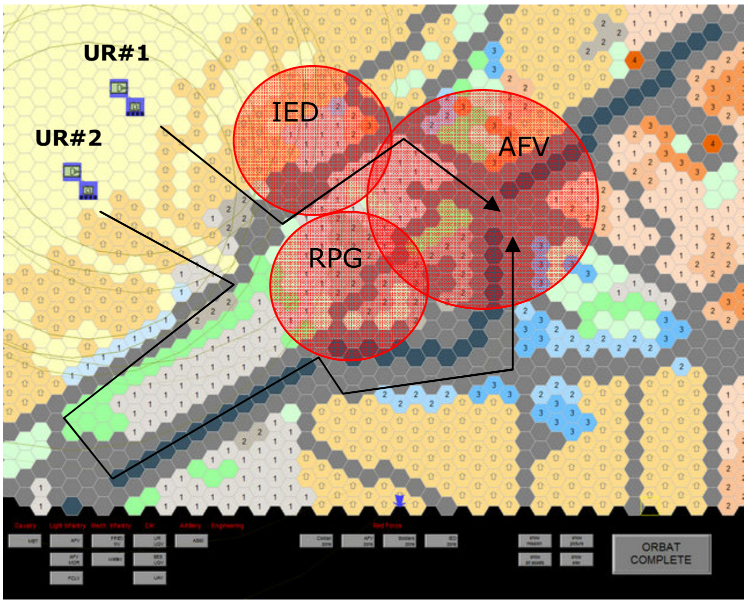


Figure 4-25: Mission scenario for DRI analysis capability

The criteria observed concerns the maximum number of enemy units in sight during each turn (numbers in Table 4-9). As the path and the speed of the UGVs remain constant, the position of the UGV at a given time is consistent for all runs. Then, it is possible to compare DRI results achieved in the different runs on the scenario.

4.4.1.2 Results

Time	Run1		Run2		Run3		Run4		Run5		Run6		Run7		Run8		Run9		Run10		Average	
	UR1	UR2	UR1	UR2	UR1	UR2	UR1	UR2	UR1	UR2	UR1	UR2	UR1	UR2	UR1	UR2	UR1	UR2	UR1	UR2	UR1	UR2
0h10	0	0	1	0	1	1	2	1	3	2	1	0	0	0	4	1	2	0	2	2	1.6	0.7
0h20	0	0	2	0	†	0	2	0	3	0	1	0	0	0	†	0	1	0	†	0	1.28	0
0h30	1	0	2	1		1	1	0	3	2	2	1	0	1		0	1	0		0	1.42	0.6
0h40	†	1	†	†		1	2	0	†	2	3	†	1	1		0	4	0		0	2.5	0.62
0h50		0				0	3	0		2	†		4	†		0	3	0		1	3.33	0.42
1h00		0				2	6	0		†			2			0	4	0		1	4	0.5
1h10		0				†	6	3					ok			5	†	1		3	6	2.4
1h20		2					†	3								†		3		†		2.66
1h30		2						3										3				2.66
1h40		3						4										†				3.5
1h50		3						ok														3
2h00		2																				
2h10		†																				

Table 4-9: Results of 10 simulation runs with UR UGVs not equipped with a mast

† : UR UGV destroyed before the completion of the task
Ok: the UR UGV has reached the objective

Time	Run1		Run2		Run3		Run4		Run5		Run6		Run7		Run8		Run9		Run10		Average	
	UR1	UR2	UR1	UR2	UR1	UR2	UR1	UR2	UR1	UR2	UR1	UR2	UR1	UR2	UR1	UR2	UR1	UR2	UR1	UR2	UR1	UR2
0h10	†	0	3	0	0	0	0	1	0	0	0	0	1	1	0	0	0	1	2	4	0.67	0.7
0h20		0	3	2	0	0	1	1	0	0	1	1	1	1	0	1	0	2	3	0	1	0.8
0h30		0	3	0	†	0	1	0	1	2	1	0	0	0	1	0	1	0	2	1	1.25	0.3
0h40		1	7	1		0	1	1	1	2	3	1	0	2	†	0	2	1	1	†	2.14	1
0h50		3	5	2		0	2	1	3	5	5	3	2	†		1	3	2	†		3.33	2.12
1h00		5	4	5		1	†	2	†	3	†	4	†			1	3	2			3.5	2.87
1h10		†	†	5		2		3		3		6				2	†	2				3.28
1h20				†		3		3		4		†				3		2				3
1h30						4		†		†						3		†				3.5
1h40						†										5						5
1h50																5						5
2h00																ok						

2h10

Table 4-10: Results of 10 simulation runs with UR UGVs equipped with a mast

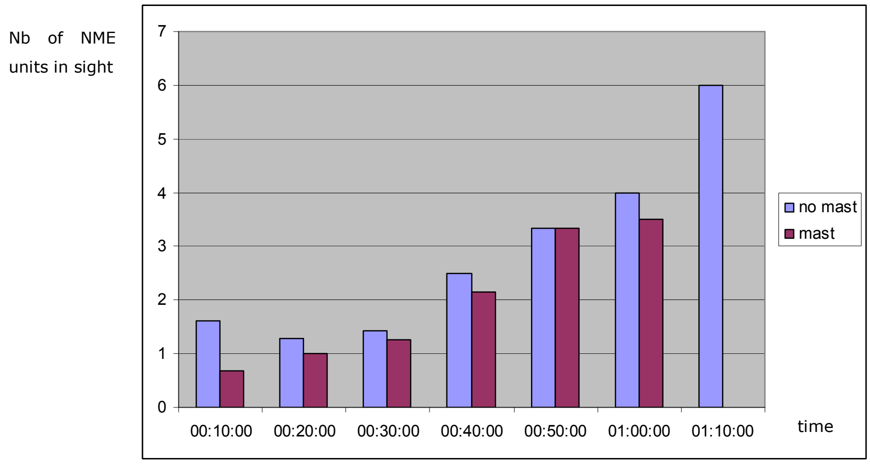


Figure 4-26: Average maximal number of enemies spotted by UR#1 at each turn

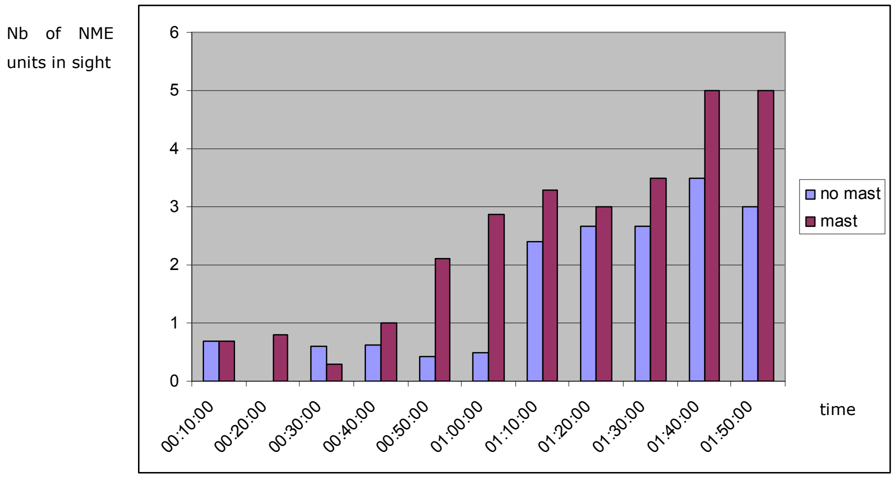


Figure 4-27: Average maximal number of enemies spotted by UR#2 at each turn

In this first scenario, the numbers of enemy spotted at each turn were manually collected from the events' record file and put into an Excel table. Considering the time required to perform this task, an additional module was developed to automatically collect the results during the game. This module was used in the study case 3.

4.4.1.3 Analysis

The Figure 4-26 and Figure 4-27 show that the benefits of an extendable mast can only be observed for the UR UGV #2 (15% of enemies spotted more). This explains by two different factors:

- The mission of UR UGV#1 is more risky, as it goes through areas occupied by the RED force. As UR can not engage any targets, its probability of being destroyed before the end of the mission is much higher.
- The UR UGV#1 mainly moves in very concentrated building areas, where the line of sight is not limited by the elevation of the sensors, but by the height of the buildings.

4.4.2 Case study 2: Impact of marsupial transportation mode on the tempo of the manoeuvre

4.4.2.1 Scenario

The considered scenario consists for the system UR-BES#1 to explore the building A with one BES UGV, then to reach the rallying point B and make the BES ready for a second building inspection (Figure 4-23).

The mission of UR-BES#2 has to rally the point B, using only main roads.

The only parameter modified between the two sets of simulation runs is the ability of the BES to be mounted, transported, and dismounted on the UR UGV.

As an element of the tempo of the overall manoeuvre, the criteria observed concerns the whole duration of the UGVs' mission, which has to be as short as possible. Again, during their progression, the BLUE units are not allowed to engage targets, or to react to engagements, in order to not distort the results.

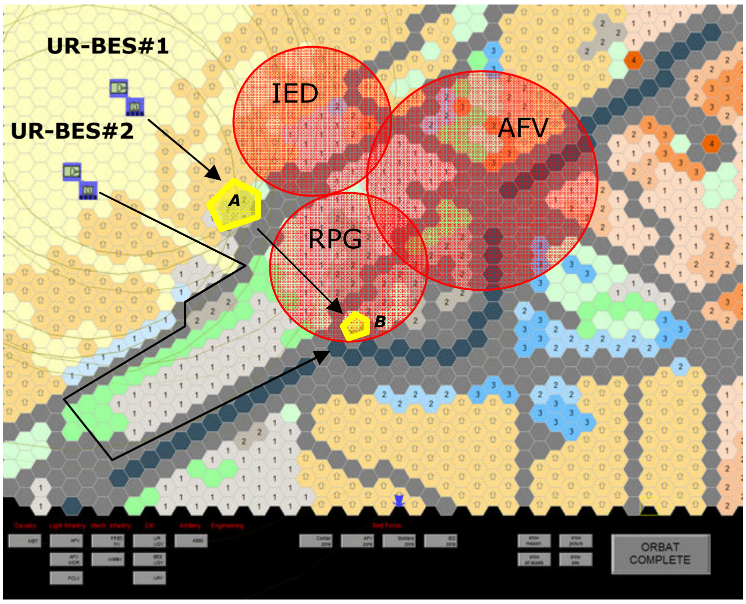


Figure 4-28: Mission scenario for marsupial transportation analysis

4.4.2.2 Results

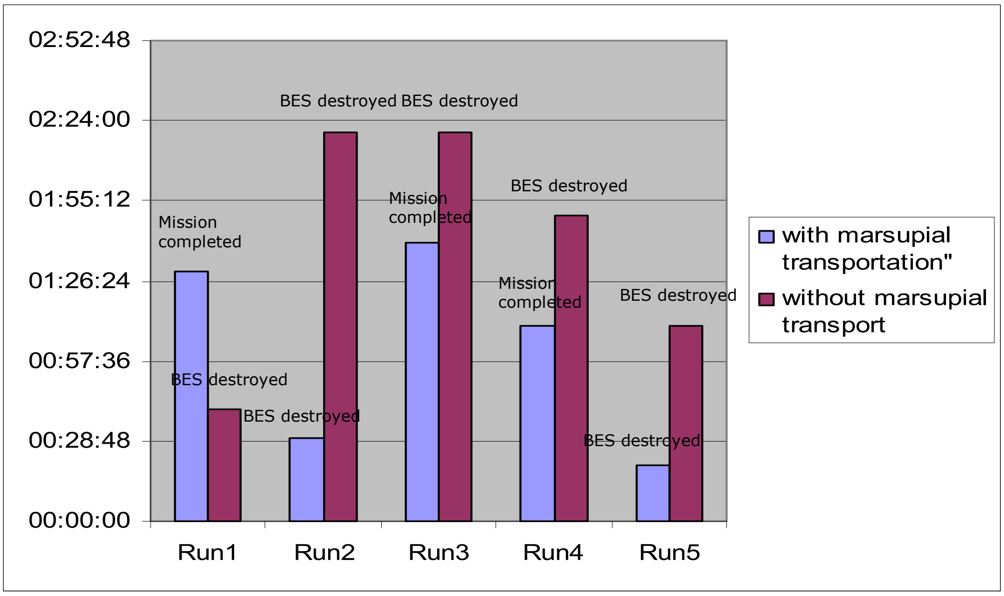


Figure 4-29: Mission completion period for BES-UR UGV#1

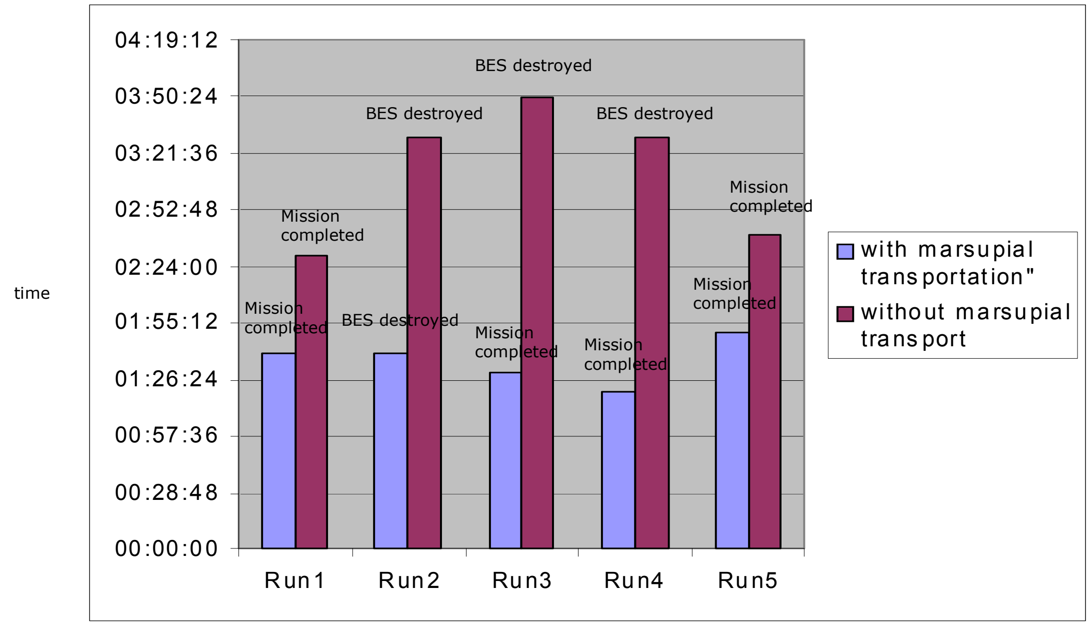


Figure 4-30: Mission completion period for BES-UR UGV#2

4.4.2.3 Analysis

Both Figure 4-29 and Figure 4-30 show that the marsupial transportation of the BES-UGV during the transition phases of the mission provides an operational benefit in terms of:

- Mobility: marsupial transportation makes the mission 30% faster in concentrated urban area and about 50% in semi-open areas.
- Survivability: marsupial transportation provides a very efficient additional protection to the BES-UGV (70% of the missions completed against 20% without marsupial transportation)

4.4.3 Case study 3: Impact of the laser designation on the lethality

4.4.3.1 Scenario

In this scenario, a subset of the UTE has to rally the KILO waypoint, using only the main roads. The criteria observed concerns the number of enemy units hit and destroyed by the whole subset during the mission, against the integration or not of a laser designator on the BES-UGV. It is quite obvious that a subset with more designation capability should be more lethal, but it is expected that the simulation provides quantitative results about this benefit.

The rules followed during all the runs of the simulation were:

- no direct fire is allowed
- target designation is allowed only if the target was identified before

- the scenario ends when all the units have reached the KILO waypoint or when the BES UGV has been destroyed
- NLOS ammunition reloading is not possible
- The BES-UGV is supposed to move in front of the rest of the group.

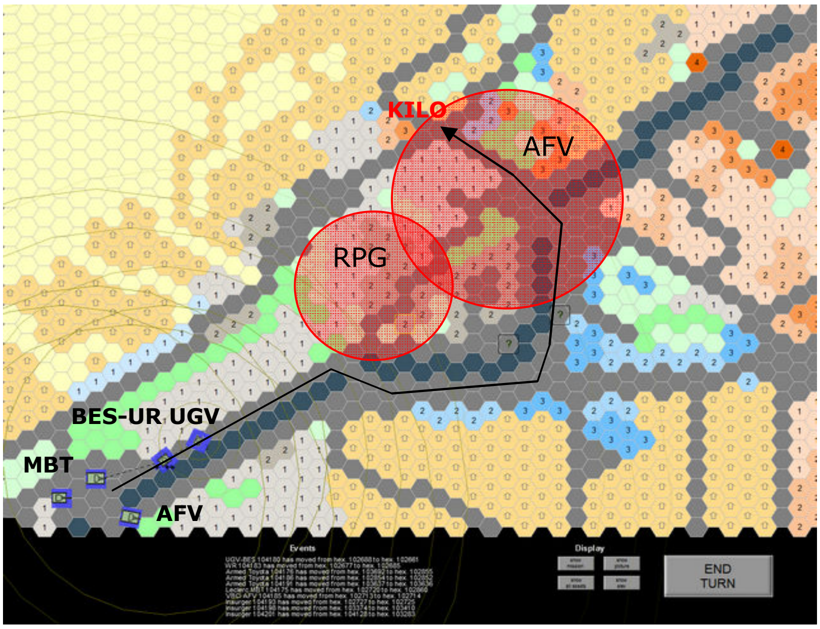


Figure 4-31: Scenario used for the BES-UGV target designation capability

In order to estimate the global benefit for the UTE subset from using a designator on the BES UGV, a comparative analysis was planned. For that, ten simulations were run with a UTE subset made of:

- 2 AFVs with designation and NLOS capabilities (2 missiles each)
- 1 MBT without NLOS capabilities

Ten other simulations were run with a UTE subset made of:

- 1 AFV with designation and NLOS capabilities (2 missiles)
- 1 UR-BES UGV system including an AFV command and control station with NLOS capabilities (4 missiles)
- 1 MBT without NLOS capabilities

Among these ten scenarios involving a UR-BES UGV, the detectability parameter of the BES UGV was modified in order to check the influence of this factor on the results. This detectability factor can be seen as the combination of different characteristics of the UGV (dimensions, stealth …). A detectability factor of 1 makes it as visible as a MBT. A detectability factor of 0 makes it invisible in all occasion. In a first approach, it can be a function of the volume of the unit.

4.4.3.2 Results

During the simulation, the CAWG tool automatically generates results files:

- the development of the scenario and the related tactical situation maps, which are used to make a qualitative analysis of the results as presented in the section 7.3,
- results table for each blue unit, summarising how the capabilities were used during the scenario. These tables are then imported in Excel for post-processing and visualisation. The section 7.5 presents rough results obtained during the run_19 of the scenario.

The individual results of the 20 runs of the present scenario have been synthesised in the graphs presented in section 7.6. The following graph synthesise some of the results obtained, considering only the "designation capability" aspects.

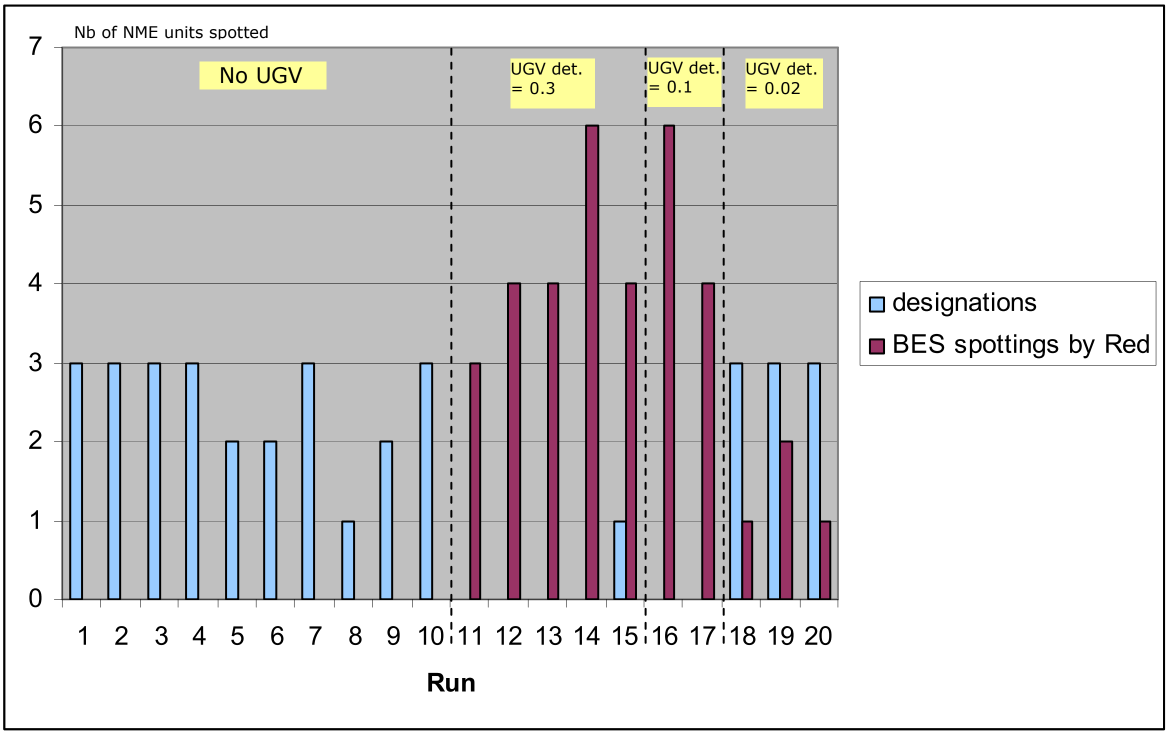


Figure 4-32: Synthesis of the study case 3 simulation runs regarding to the designation capability and the BES detectability parameters

4.4.3.3 Analysis

Many conclusions at different levels can be drawn from these results.

First, as underlined in the introduction of this chapter (section 4.1), it has to be reminded war gaming purpose is not to provide exact results that can be directly interpreted. Quantitative results can only be considered as valid if there is enough data to carry out a statistical analysis. Considering the number of influent parameters

involved in the current simulation, five runs are probably not enough to get consistent results about the interest of a target designator on the BES UGV.
Second, it has to be noticed that, for the same scenario involving very different Red Force initial positions and actions, the simulation still gives consistent results (e.g. number of designations made by the Blue Force in the first ten runs). That validates the principle of semi-random Orbat and pseudo-Artificial Intelligence for the Red Force adopted in the CAWG tool.

Third, the results obtained show a lack of efficiency of the NLOS missiles, as modelled in the tool. Several shots are necessary to destroy a target, which would not be the case in the reality. That demonstrates the importance of the setting (and the errors attached) of the initial parameters and units' attributes on the simulation results. A preliminary validation phase by comparison with real existing results is probably necessary to adjust the parameters.

Finally, with the precautions followed from the conclusions above, we can conclude from the quantitative results obtained that the mounting of a target designation capability on the BES-UGV does not provide a substantial benefit to the UTE subset when the detectability of the BES-UGV is above 0.1 (a medium-range UGV). In that case, considering its short DRI range capabilities, the UGV detects the enemy units very late and it is easily spotted and destroyed.
If the UGV is made stealthier (0.02, a small-range UGV), the efficiency of the global designation capability achieves the same level as the one of the full manned UTE subset, with an additional advantage provided by keeping the designator non-visible by the Red Force.

4.5 Discussion and conclusions

4.5.1 About Computer Aided Wargaming

During the Manual War Gaming sessions observed at DSTL, strengths and weaknesses have been noticed, which are confirmed by the analysis of some of the conclusions reported in [36], chapter 5.10.
MWG is a good support to sustain the technical discussions between the military experts and to get insights from them. It does not need any special means to prepare and manage a game session. However, MWG is vey time consuming and requires three full time participants. Players do not have a good perception of the UGV capabilities and the main highlighted drawback is that it does not provide any quantitative outputs or support for after-action review.

Computer Aided War Gaming allows to remedy to some of the MWG drawbacks, while keeping its advantages. The results obtained show that the CAWG tool provides the ability to:

- Develop multiple scenarios with a faster tempo,
- Model the units' capabilities with a better accuracy,
- Get qualitative insights but also quantitative results that can be compared together in a parametric analysis,
- Easily configure the environmental parameters.

However, some precautions have to be taken:

- BES functionalities which are supposed to have an effect on the sequence of events in the considered scenario have to be identified,
- The modeller has to make compromises between the complexity of the model and the benefits expected on the accuracy of the results. Parameters used have to be validated at an individual level first.
- For a quantitative analysis, the number of simulation runs as to be enough to provide data for a valid statistical study.

At the occasion of the CAWG presentation meeting, simulation experts from DSTL have insisted on the importance to position the CAWG within the set of the simulation tools already used by DSTL in this area (PSOM, ISAAC, STOAT). Conclusions of the DSTL war gaming experts were that "*there was potential utility (applicability to analyse future stabilisation Ops) for the Computer Assisted Wargame (CAWG) Tool developed by the VRC*" [36].

4.5.2 About the BES-UGV concept

The results of the different simulation runs were gathered, compared and assessed according to the 4 operational criteria already defined in 4.3.8. Conclusions about the BES-UGV concept as modelled in the CAWG are:

4.5.2.1 Operational tempo

a) The ability to **mount and dismount the BES UGV in the UR UGV** (marsupial transport) is a key factor of the operational tempo. Indeed, it allows to bypass the slowness of the BES-UGV in open areas, where its ability to get over obstacles is no useful anymore.
b) A consequence of the low level of autonomy of the BES-UGV (navigation on designated waypoints) is the high level of attention required from the operator. That means that each **BES-UGV will probably have to be controlled by a**

dedicated operator, as well as the UR-UGV, to get the most of each BES while not slowing down the global operational tempo. Considering that all the operators of the BES UGV system are mounted in the same command and control AFV, **a crew made of 2 BES-UGV and 1 BES-UR operators** seems to be a maximum.

c) The C2-UR and UR-BES communication ranges were found efficient in all the situations, as well as the **ability to inform the operator before the communication is lost**.

4.5.2.2 Situational awareness

a) Operations in housing areas have shown that the situation awareness of the Recce Platoon could be highly improved if the UR was able to see over the walls, which could be done by **mounting the sensors on a 3 to 4 meters length telescopic mast**.

b) The **ability to dismount one or two Unmanned Ground Sensors from the UR** would have been very useful in certain situations, when the area has been explored and no moving sensor is required anymore. Combined with the b) conclusion above, a configuration of 2 BES-UGV + 2 UGS mounted in the UR UGV seems to be a good compromise.

4.5.2.3 Lethality

a) The **ability of BES-UGV to designate a target** before its NLOS engagement by another unit was a key element of many successful combats. It allowed the manned units to keep well protected in the housing area while taking benefit of the BES-UGV stealth.

b) In many simulation runs, BES-UGVs have been hit by infantry soldiers without being able to return fire by itself. A basic **direct fire weapon system would be useful** in many situations.

4.5.2.4 Survivability

a) The BES-UGV was found easy to shoot by infantry soldiers, mainly because of its slowness and its very light armour. **BES-UGV has to be equipped with a self-defence system** (e.g. anti-personal grenades) to make it more survivable.

b) The BES-UGV was very efficient to discover IEDs in buildings during the advance, even if the operator was forced to inspect the rooms in detail because of the **low range of the IED sensors**.

c) The **robustness of the UR UGV** allowed him to resist to several shoots.

5 Conclusions, Thesis Achievements and Future Work

"Life is short, Art long, Occasion sudden and dangerous, Experience deceitful, and Judgment difficult."

Hippocrates

The first achievement of this study is the proposal, the evaluation then the partial validation of a modelling approach for helping architects to refine system requirements at the stage of the concept.

Starting from the life-cycle analysis, a segmentation of the modelling process was proposed, based on operational, system of system and behavioural modelling phases.

The results of each phase are used to improve and complete the user requirements database. Further research has to be carried out in the future on the ways to use a standard language (e.g. XML) as a gateway between each modelling phase. The same is true of the modelling of the BES-UGV concept in the MODAF architectural framework, which would deserve to be considered as an entire project.

The second objective of this research was to focus on the early validation of the operational capabilities of the system, and by doing it, to bridge the gap between existing requirements management and system modelling tools.

A prototype of a Computer Aided War Gaming (CAWG) tool was developed, based on the feedbacks from manual war gaming sessions observed at the UK MOD.

This mock-up was used to model the capabilities of a MOD Building Entry and Search robot concept and to assess by simulation some capabilities of particular operational interest, leading to propose improvements of the initial MOD concept.

In addition to the further BES UGV insights obtained, interest in CAWG tool compared to manual war gaming has been demonstrated: increased gaming tempo, better immersion of the players, and ability to get quantitative results. Feedbacks from the MOD/DSTL simulation experts were positive [40], even though the current mock-up still presents weaknesses that have to be addressed now to make the tool exploitable by system architects. Four directions for future work have been identified:

- Modularity (model different types of AFV/UGV and threats as add-ons)
- Scalability (model detailed scenarios e.g. IED search inside a building)
- Accuracy (by improving the Artificial Intelligence of the enemy)
- Productivity (user friendly outputs)

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7 Annexes

7.1 UGV concepts issued from the FGMC study

This table is quoted from the Qinetiq report [27]. Information that has been judged as security sensitive has been removed from the table.

Type of UGV	Key features
 **Reconnaissance and Surveillance (RS) UGV** All terrain highly mobile ISTAR vehicle for close recce. Deployed in advance of ground troops for recce and to alert friendly forces to any ground based threat. Capable of acquiring targets for rapid precision IF. Acts as integrated mobility trailer to C2 vehicle until deployed.	- Light/medium weight (approx. 6 tonnes) low profile vehicle, similar dimensions to Combat Vehicle Reconnaissance Tracked (CVR(T)) - Extensive sensor suite for reconnaissance tasks (including Electro optic (EO), Infra Red (IR), Radar, and Burst Illumination Laser (BIL)); - High degree of mobility in urban and rural terrain, with similar speeds to manned vehicles; - Semi autonomous, intelligent route planning; - Target acquisition capability, linked to other assets (including UWP) for engagement; - Layered system for survivability, high resistance to small arms and Heavy Machine Gun (HMG), multiple redundancy in vehicle electronics; - Two RS UGVs in BLUE Order of Battle (ORBAT), replacing 2 Future Rapid Effects System (FRES) Scout variants;
 **Urban Recce (UR) UGV** Highly mobile urban ISTAR vehicle for close recce, able to manoeuvre in alleyways and narrow streets.	- Small lightweight vehicle (approx 600kg) for manoeuvre in urban areas; - Sensor suite optimised for urban areas (elevated EO and IR sensor capability, for hemispherical coverage); - Optimised for urban rubble mobility, rapid acceleration for gap crossing. Carried on mother vehicle (e.g. WR) until deployed; - Semi autonomous, intelligent route planning; - Equipped with .50 cal machine gun, plus target acquisition capability linked to other assets (including UWP) for engagement; - Layered system for survivability, high resistance to small arms and HMG, multiple redundancy in vehicle electronics: - Two UR UGVs in BLUE ORBAT in addition to WR Infantry Fighting Vehicles (IFVs);
 **Building Entry and Search (BES) UGV** A short range/endurance system for investigating the interior of structures/buildings.	- Very lightweight (approx 20kg) 1m long snake like platform; - Sensor suite optimised for human detection at short ranges (Thermal Imaging (TI), acoustic, personnel 'sniffer'); - Able to climb stairs and traverse urban obstacles, and raise sensors approximately 1m above ground level; - Limited endurance of one hour, with a slow speed of approx. 4km/hr; - Advanced semi-autonomous, able to navigate complex building environments; - Target acquisition capability, linked to other assets (including UWP) for engagement;
 **Unmanned Weapons Platform (UWP) UGV** Unmanned weapons platform for use behind the forward line of engagement, providing instant precision GPS guided IF support to friendly forces and other UGVs	- Medium weight (15-20 tonnes) vehicle, similar dimensions to FGMC UTE vehicles (e.g. FRES Protected Mobility (PM)); - Minimal sensor suite for self protection and security only (EO/TI); - Medium degree of mobility in urban and rural terrain, with similar speeds to manned vehicles; - Semi autonomous, intelligent route planning; - Equipped with low cost Global Positioning System (GPS) guided Small Precision Attack Munitions (SPAM), consisting of a range of munitions including Anti Structures Munition (ASM), anti-armour, anti-personnel etc. for engaging targets identified by friendly forces and other UGVs; - Layered system for survivability, high survivability from small arms and HMG; - Two UWPs in BLUE ORBAT, in addition to IF assets;
 **Route Prover (RP) UGV** Robust survivable vehicle for route clearance in both urban and rural terrain. Able to detect, mark and eliminate mines and IEDs en route	- Medium weight (15-20 tonnes) vehicle, similar dimensions to FGMC UTE vehicles (e.g. FRES Protected Mobility (PM)); - Sensor suite optimised for countermine operations (explosives sniffer, ground penetrating radar, Micro-Electrical-Mechanical-Systems (MEMS) launched sensors); - Equipped with mine clearance/elimination weapons (flail, plough, machine gun); - High degree of mobility in urban and rural terrain, with similar speeds to manned vehicles; - Semi autonomous, intelligent route planning; - Layered system for survivability, high survivability from small arms and HMG, multiple redundancy in vehicle electronics. Some survivability from IED/mine detonation through heavy armour; - Two RP UGVs in BLUE ORBAT, in addition to Engineer assets;

7.2 User Requirements for the BES-UGV (extract of DOORS database)

As explained in the body of the thesis, the requirements' writing is an iterative process. The BES UGV requirements draft presented here shows how the outputs from the different tools were used to enhance and complete the initial user document. However, this should not be considered a complete document for the rest of the development process, rather a first step towards that goal.

/BES UGV

BES UGV requirements

Version: 0.0
Printed by: stan
Printed on: 12 September 2010

Generated from DOORS 8.3.0.0

Contents

ID		Source
1	**1 Introduction** This document describes the requirements for a Building Entry and Search (BES) Unmanned Ground Vehicle (UGV) concept. It is the result of the merging of several already existing documents (initial requirements in black) as well as the analysis of the results from : - technical-operational modelling (additional requirements in green) - system-of-system modelling (additional requirements in orange) - behavioural modelling (additional requirements in blue)	
18	**1.1 The BES UGV concept**	
19	**1.2 References**	
20	Spécification Technique de Besoin n° 03-36 438/SPART/ST/ELEC du 22 juillet 2003	MINIROC study
21	UGV for Future Ground Manoeuvre: technology Survey and Concept Development (QinetiQ, 2008)	FGMC study
22	Operational Benefits of Unmanned Ground Vehicles (UGVs) for Future Ground Manoeuvre (DSTL, 2006)	FGMC study

ID		Source
2	**2 General Description**	
9	**2.1 Product perspective**	
54	BES UGV is a 30 kg tracked platform with stairs climbing capabilities. It is made to conduct reconnaissance missions in urban areas, for intelligence purposes or self-defence. The BES UGV can inspect a whole building by itself.	FGMC study MINIROC study
55	BES UGV is required to search and identify dismounted threats (including Improvised Explosive Devices) in complex structures, as buildings (inside and outside)	FGMC study CAWG results
61	BES UGV system, including operator control unit, has to be considered as consumable	FGMC study
10	**2.2 Operational capabilities**	
35	BES UGV has to be able to operate in urban environment, with human beings around	FGMC study MINIROC study
26	BES UGV has to be able to participate and reinforce a combat phase in urban area	MINIROC study
27	BES UGV has to be able to participate to and reinforce an intelligence mission in urban area. It has to be able to improve the situational awareness of building occupancy.	FGMC study MINIROC study CAWG results
28	BES UGV has to be able to participate and reinforce a zone control operation in urban area	MINIROC study CAWG results
46	Whatever the mission is, the safety of the people (operators, infantry soldiers, civilian) and equipment around has to be insured	FGMC study MINIROC study
82	Dismounted IS have to be able to watch video information acquired by the BES UGV	CAWG results
83	Dismounted IS has to be able to localize the BES UGV on a map	CAWG results
12	**2.3 User characteristics**	
60	BES UGV has to be able to be operated by infantry and from other manned manned vehicle (C2 vehicle)	FGMC study
13	**2.4 Operational environment**	

ID		Source
3	**3 Operational Requirements**	
4	**3.1 Mobility**	
23	BES UGV has to be manually driven or transported in a manned vehicle to and from the area of operation	FGMC study
36	BES UGV has to be able to be carried by an infantry soldier, without impacting the operational effectiveness of the team	FGMC study MINIROC study
25	BES UGV has to be able to be transported by a Urban Reconnaissance UGV up to the area of operation	FGMC study CAWG results
72	BES UGV has to be able to be dismounted/mounted in the UR at a distance	CAWG results
65	4 BES UGV per vehicle or 2 BES UGV and 2 UGS per UR	FGMC study CAWG results
32	BES UGV has to be able to move in urban environment (crossroads, narrow streets ...) considering usual (doors, stairs ...) and unexpected obstacles (collapsed buildings, bomb holes ...)	FGMC study MINIROC study CAWG results
33	BES UGV has to be able to automatically follow a preset path, by avoiding unexpected obstacles	FGMC study MINIROC study CAWG results
34	BES UGV has to be able to move in sewer pipes	MINIROC study
24	BES UGV has to be able to enter (through doors, windows, roof), move and go out from buildings and facilities	FGMC study MINIROC study CAWG results
84	BES UGV operator in C2_AFV has to be able to localize the BES UGV on a map with GPS precision outside and with dead recknoning precision inside buildings	CAWG results
5	**3.2 Survivability**	
43	BES-UGV has to be stealth in the visible, acoustic, IR spectrum	FGMC study MINIROC study CAWG results

ID		Source
47	BES UGV has to be able to detect, identify and track threats, using personnel and explosives sniffers, human detectors, EO/IR detectors, acoustic detectors	FGMC study MINIROC study CAWG results
44	BES UGV has to be able to react when a threat was detected (escape, smoke grenades launcher, loud sound ...)	FGMC study MINIROC study
56	BES UGV has to be able to interact with the built environment and humans	FGMC study
49	BES UGV has to be able to easily and fastly manipulate an object	FGMC study MINIROC study
58	BES UGV has to be able to withstand small arms fire or other active (jammers) or passive (cover on sensors) measures operated by enemies	FGMC study CAWG results
59	BES UGV has to protect against hostile subversion of command and control the autonomous system	FGMC study
6	**3.3 Lethality**	
48	BES UGV has to be accurate enough to aim a human target	FGMC study MINIROC study
57	BES UGV has to be able to operate various lethal and non-lethal payloads	FGMC study CAWG results
77	BES UGV has to be able to designate a target	CAWG results
88	BES UR has to be able to operate indirect fire armament (e.g. missiles)	CAWG results MODAF analysis
7	**3.4 Observation**	
62	BES UGV has to be able to transport different types of observation sensors to meet a range of different task requirements	FGMC study
67	BES UGV has to be able to localise a target	FGMC study
75	UR UGV has to be able to raise observation sensors up to 3 to 4m	CAWG results
76	UR UGV has to be able to deploy and relay information from Unmanned Groud Sensors	CAWG results
8	**3.5 C4I**	

ID		Source
29	BES UGV has to be able to communicate with the dismounted infantry soldier	MINIROC study
30	BES UGV has to be able to communicate with enemies and neutral population	MINIROC study
31	BES UGV operator has to be able to localise it on a map in all circumstances and environments (inside and outside buildings)	MINIROC study
45	BES UGV has to be integrated in a collaborative protection system	MINIROC study
50	BES UGV has to be usable at a distance up to 100m	MINIROC study
53	Information shown to the operator have to allow him to estimate a situation and to react to warnings	FGMC study MINIROC study
70	Information to/from the BES UGV have to be able to be relayed by the UR to increase the operation range	CAWG results MODAF analysis
74	BES UGV has to be able to inform the operator when it is about to be out of communication range	CAWG results
66	BES UGV has to be able to operate in the digitised battlefield	FGMC study
78	UR UGV has to be able to transmit video information to C2 AFV	MODAF analysis
79	UR UGV has to be able to transmit video information to IS	MODAF analysis
80	BES UGV has to be able to transmit video information to UR UGV	MODAF analysis
86	C2_AFV has to be able to merge the information issued from UAV observation with the ones issued from UGV observation	MODAF analysis
81	C2_AFV has to be able to update the tactical situation awareness with information issued from BES_UGV and UR_UGV observation	CAWG results MODAF analysis
87	C2_AFV has to be able to acquire BES_UGV target designation information and order an indirect fire	CAWG results

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ID		Source
15	**4 Technical Requirements**	
37	**4.1 Design**	
38	BES UGV electrical and mechanical design has to be modular enough to adapt to the different types of mission the UGV has to realise	FGMC study MINIROC study
40	BES UGV electrical and mechanical design has to be robust and able to resist to falls, throws, reversals ...	FGMC study MINIROC study
42	BE UGV power range has to be high enough to complete the different types of mission without recharging. The power range has to be extendable by adding energy storage modules.	MINIROC study
41	BES UGV electronic and mechanical design has to comply with environmental conditions met in European and Middle East countries	MINIROC study
51	BES UGV has to be ready to use in a few minutes after it was dismounted	MINIROC study
52	BES UGV has to be able to switch from semi-autonomous to remote-control mode in a few seconds	MINIROC study
63	Mechanical and electrical integration of payloads into the UGV architecture has to be optimised	FGMC study
68	Safety modes have to be implemented to insure graceful degradation	FGMC study
64	HUMS have to be implemented to reduce the logistic burden	FGMC study
73	BES-UGV has to be controlled by a dedicated operator	CAWG results
16	**4.2 Standardisation**	
91	VSI standards and guidelines (in particular the inter-system communications)	Behavioural modelling
17	**4.3 Technology**	
69	Low cost technology and COTS components have to be favoured	FGMC study Behavioural modelling
89	Technologies allowing to develop open architectures have to be favoured.	Behavioural modelling

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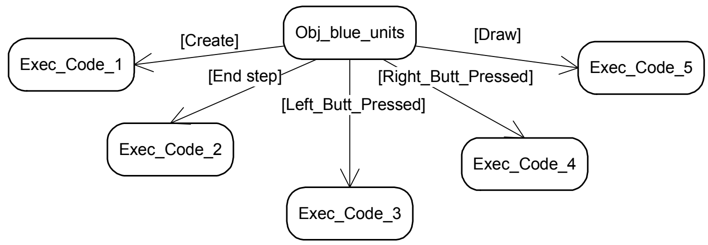
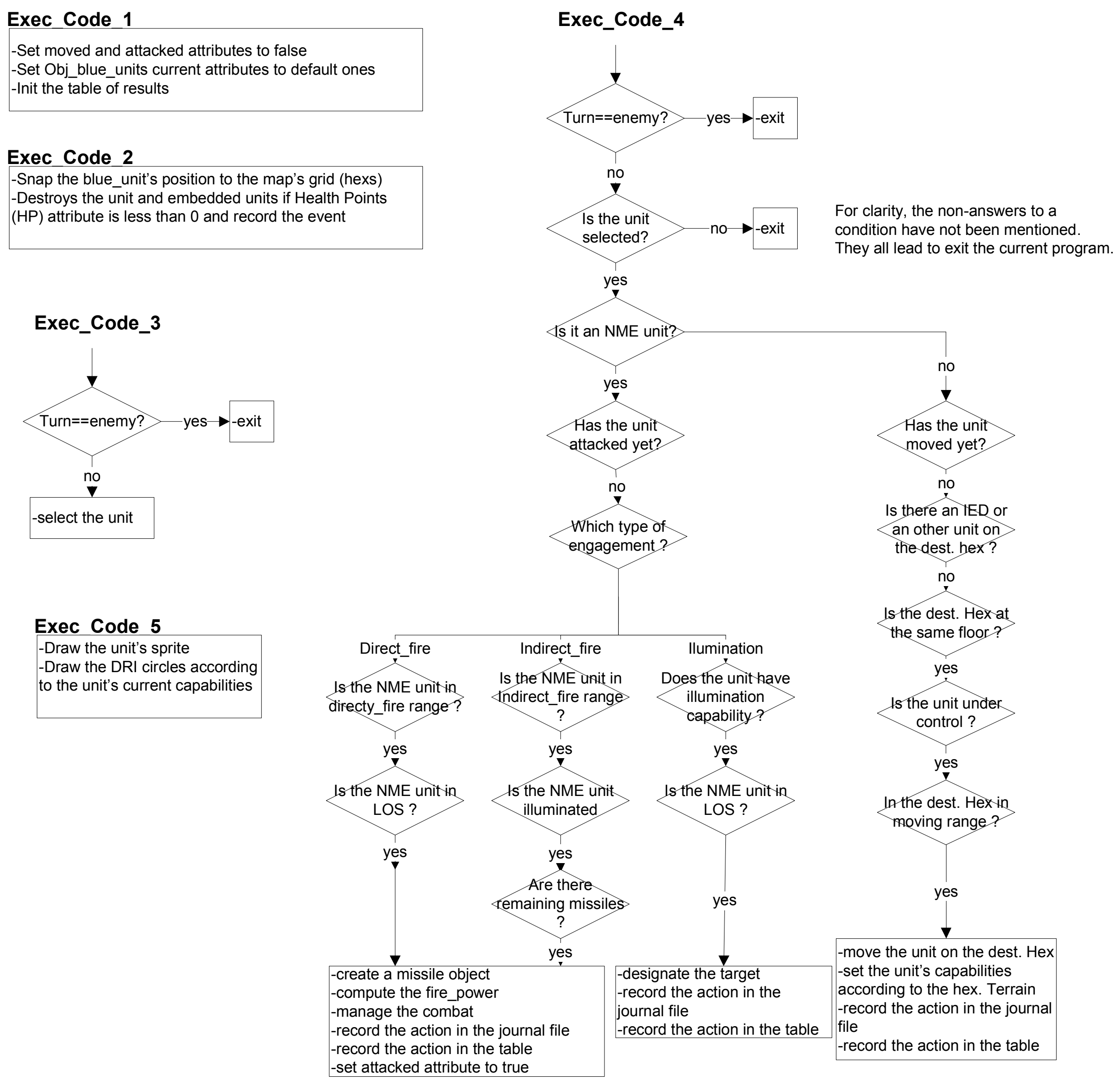
7.3 Example of Units' behaviour programming in Game Maker (Obj_blue_units class)



[Create] transition happen sat the creation of the object, in the Orbat definition phase.
[End_step] transition happens every step of the game, meaning that the actions are executed continuously.
[Left_Butt_Pressed] transition happens when the Blue player presses the mouse's left button.
[Right_Butt_Pressed] transition happens when the Blue player presses the right's left button.
[Draw] transition happens each time the unit's sprite is refreshed.



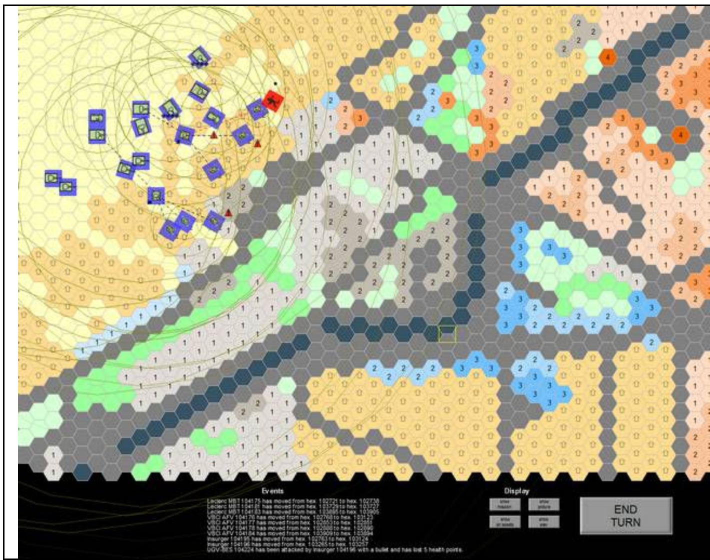
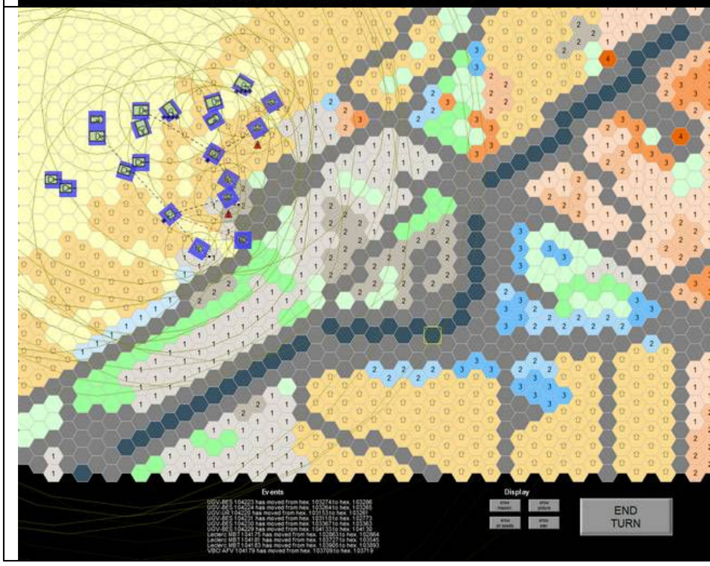
7.4 Example of CAWG scenario development and qualitative analysis

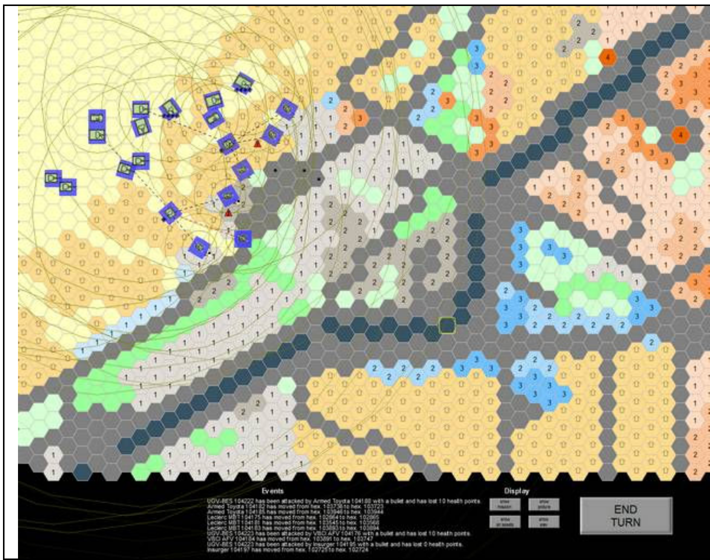
During the simulation, every event (moves and fires) are recorded in a text file that can be analysed after the action.

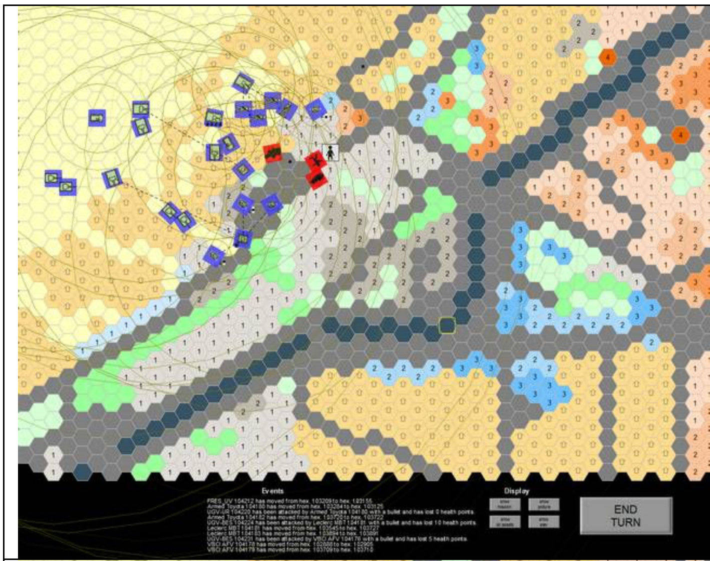
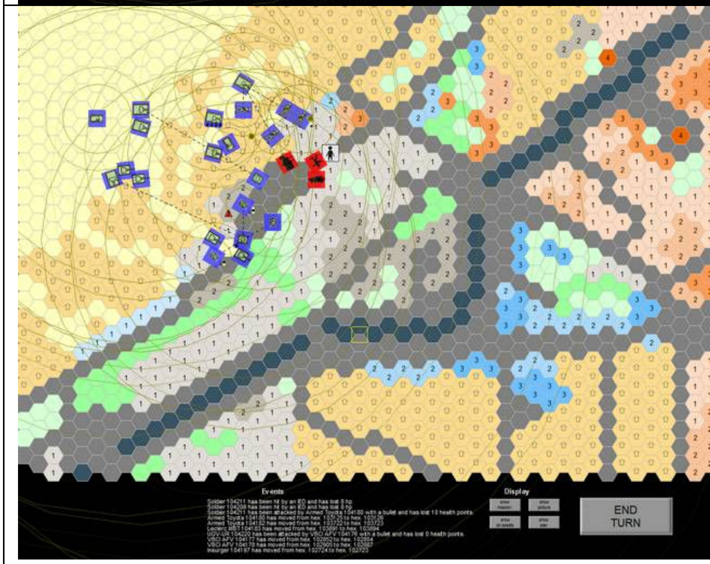
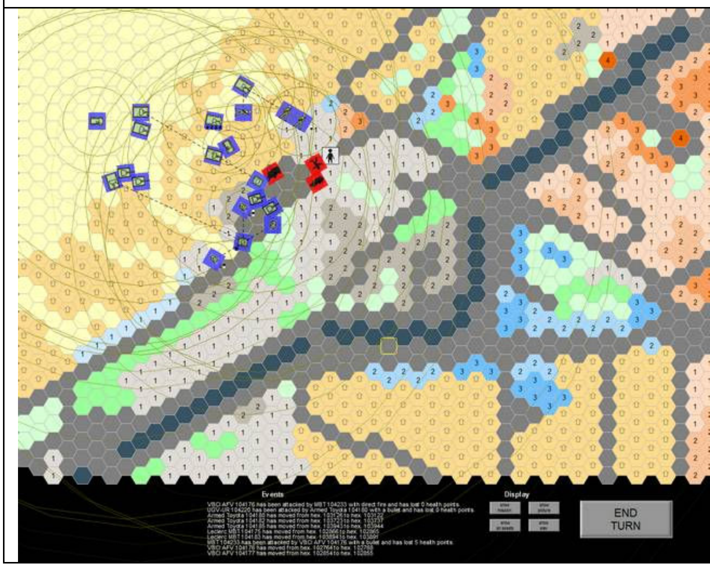
```
scenario : UrbanScenario6
created the 28/04/2009 15:25:15

Orbat definition :
104207 FRES_UV
104208 Soldier
104209 Soldier
104210 Soldier
104211 Soldier
104212 FRES_UV
104213 Soldier
104214 Soldier
104215 Soldier
104216 Soldier
104217 WR
104218 WR
104219 WR C2 station
104220 UGV-UR
104236 MBT
104221 UGV-BES
104222 UGV-BES
104223 UGV-BES
104224 UGV-BES
104225 FCLV
104226 WR C2 station
104227 UGV-UR
104228 UGV-BES
104229 UGV-BES
104230 UGV-BES
104231 UGV-BES
104232 FCLV
104233 MBT
104234 MBT
104235 MBT

events recorded :
UGV-UR 104220 has moved from hex. 102505 to hex. 103220
UGV-BES 104222 is now dismounted.
UGV-BES 104223 is now dismounted.
UGV-BES 104224 is now dismounted.
UGV-BES 104224 has moved from hex. 103269 to hex. 103155
UGV-BES 104223 has moved from hex. 103269 to hex. 103154
UGV-BES 104222 has moved from hex. 103269 to hex. 103151
FCLV 104225 has moved from hex. 102581 to hex. 102510
UGV-UR 104227 has moved from hex. 102568 to hex. 103116
UGV-BES 104229 is now dismounted.
UGV-BES 104230 is now dismounted.
UGV-BES 104230 has moved from hex. 103114 to hex. 103175
UGV-BES 104229 has moved from hex. 103114 to hex. 103219
Armed Toyota 104182 has moved from hex. 103738 to hex. 103551
Armed Toyota 104185 has moved from hex. 103947 to hex. 103948
Leclerc MBT 104183 has moved from hex. 103904 to hex. 103896
VBCI AFV 104176 has moved from hex. 102769 to hex. 102768
VBCI AFV 104184 has moved from hex. 103909 to hex. 103894
Insurger 104195 has moved from hex. 103124 to hex. 102763
Insurger 104197 has moved from hex. 103651 to hex. 102725
TURN 1
TIME : 0h10mn
UGV-BES 104229 has moved from hex. 103219 to hex. 103282
UGV-BES 104230 has moved from hex. 103175 to hex. 103365
WR 104217 has moved from hex. 102631 to hex. 103224
FRES_UV 104212 has moved from hex. 102625 to hex. 103209
WR 104218 has moved from hex. 102622 to hex. 102571
…
…
…
```

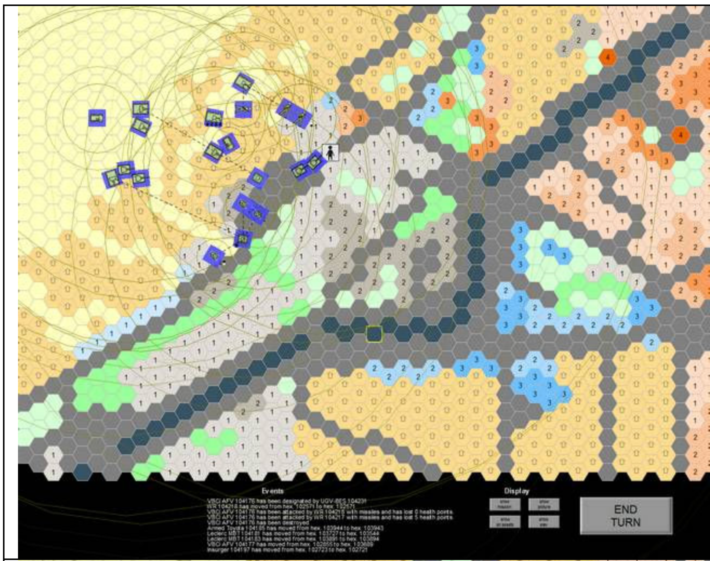
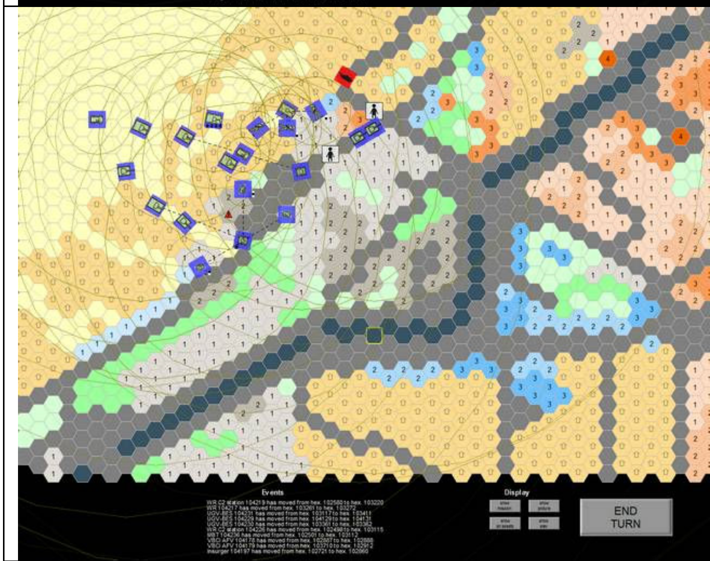
Figure 7-1: Events recording file (UrbanScenario6.txt)

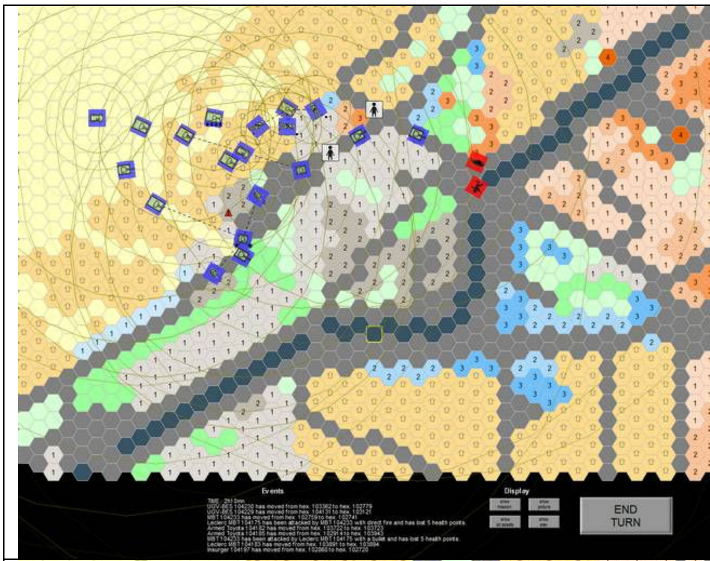
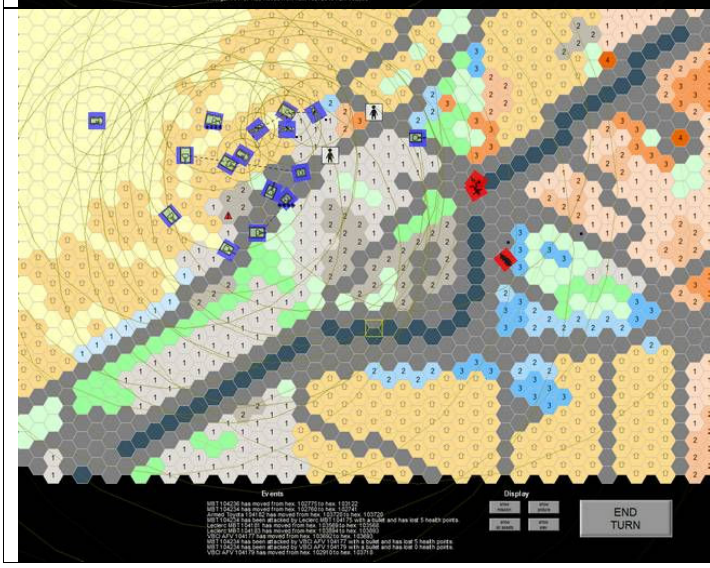
Map and Tactical situation	Time	Major events reported	Actions	Analysis
	0:00	ORBAT	No action	All the units are shown for demonstration purpose
	0:00	ORBAT	No action	Initial Tactical Situation as perceived by the BLUE Force
	0:00	Mission starts	The Infantry Platoon progresses to the SE. UR 104189 dismounts 3 BES UGV in order to inspect the building zone before entering it. UR 104196 dismounts 2 BES UGV to inspect the road sides buildings.	

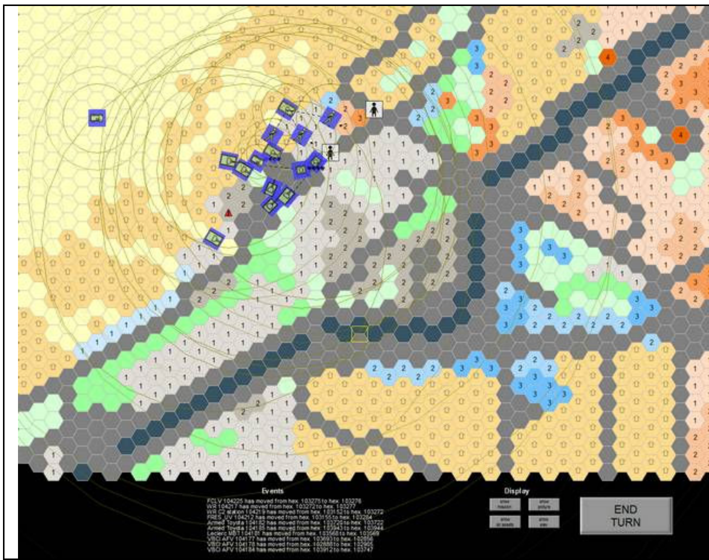
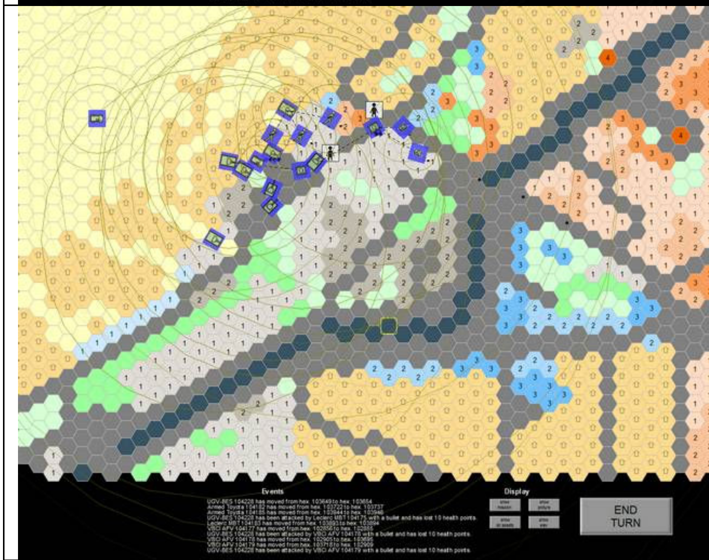
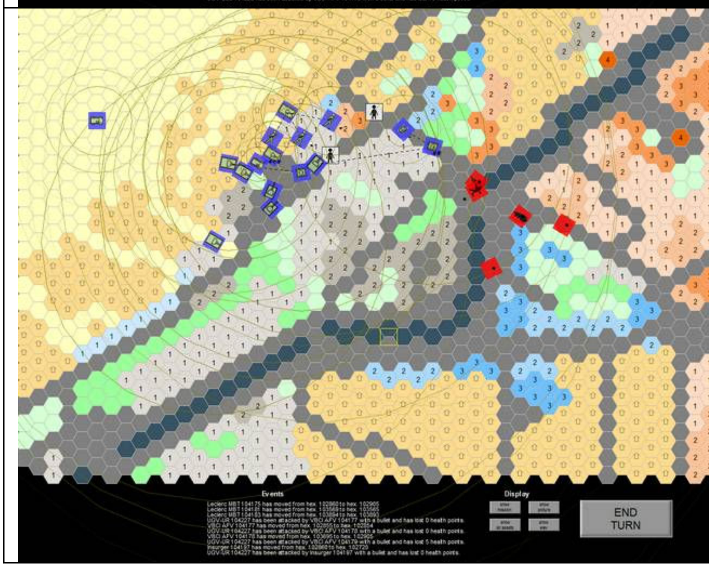
	0:10	BES 104223 discovers an IED BES 104224 discovers an IED	The IP continues its progress to the NE, lead by the UR and its 3 dismounted BES UGVs. BES 104231 is dismounted to detect the presence of mines on the road.	A mast to elevate the UR sensors above the walls would significantly increase the DRI range
	0:20	WR 104217 has been hit by an IED FRES_UV 104207 has been hit by an IED	Now the 3 BES progress to the NE in the direction of the factory. As the road has been cleared, MBT progress behing the UR	Both units were progressing without any UGV coverage
	0:30	BES 104224 has been hit by an insurger BES 104223 has discovered an IED BES 104229 has discovered an IED at the ground floor of the building	BES 104229 begins to explore the building at the North (ground and first floor). BES 104230 explores the building on the opposite side of the road. AFV 104217 engages an insurger but misses its target. FCLV 104225 finally shoots the target. As BES 104224 is in remote control range limit, UR progresses towards the east	BES is not equipped with light armament to strike back

	0:40	UR 104220 was to close to the IED and has detonated it	BES 104231 takes position at the entrance of the main street. Other BES continue their inspection	
	0:50		BES 104224 and 104223 start to explore the factory. BES 104229 and 104230 explore now the first floor of the buildings	
	1:00	BES 104222 and 104223 have been hit and destroyed	BES 104231 is moved in the possible direction of the fires. UR 104220 dismounts its last BES 104221 to complete the task of the one that has been destroyed. FRES 104207 deploys 4 IS soldiers in the area inspected by the BES	BES destruction has allowed to know the direction the fights were coming from

	1:10	BES 104221 has been hit and destroyed	UR 104227 and its BES progress to the NE, followed by the MBT platoon As they are almost out-of-range, C2 104226 moves	
	1:20	BES 104224 has been hit and destroyed BES 104231 has been hit	BES 104231 has identified 3 enemies (1 AFV, 1 truck and 1 RPG launcher) BES 104231 designates the AFV with Laser Target Designator and requests a NLOS fire. WR 104127 is nominated to engage the target and launches a missile. The enemy has activated decoys and the missile has missed its target. WR 104218 launches a second missile that hits the target but does not destroy it. BES 104231 moves back to be protected by the woodland	
	1:30	2 soldiers have been killed by IEDs	MBT 104234 has moved to engage the NME AFV with direct fire but has missed it. MBT 104233 has moved to engage the NME AFV with direct fire and has missed it.	

	1:40		MBT 104234 engages NME truck and destroys it MBT 104233 engages NME RPG and destroys it BES 104231 moves to be in LOS of NME AFV and designates it. WR 104218 launches a missile and misses it. WR 104217 launches a missile and destroy it.	
	1:50		Now the blue force progresses to the NE.	
	2:00	IS 104208 has spotted an NME MBT to the NE	BES at the North have completed the building exploration. BES have to be mounted on the UR again in order to increase the speed of the moves	

	2:10		BES go on the ground floor again to move towrd the UR MBT 104232 moves toward an NME MBT to be in LOS and hits it with direct fire	
	2:20	The NME MBT struck back and destroyed the MBT 104232	All the BES are mounted on the UR and the UR moves	
	2:30		All the units progress to the NE	

	2:40	MBT 104234 has been destroyed	All the units progress to the NE	
	2:50		UR moves up to the crossroad and dismounts 2 BES to detect possible NME units	
	3:00	BES 104228 has been destroyed by fires coming from the SE	UR takes the risk to enter the road to detect NME units	BES DRI range is not long enough to detect NME unit

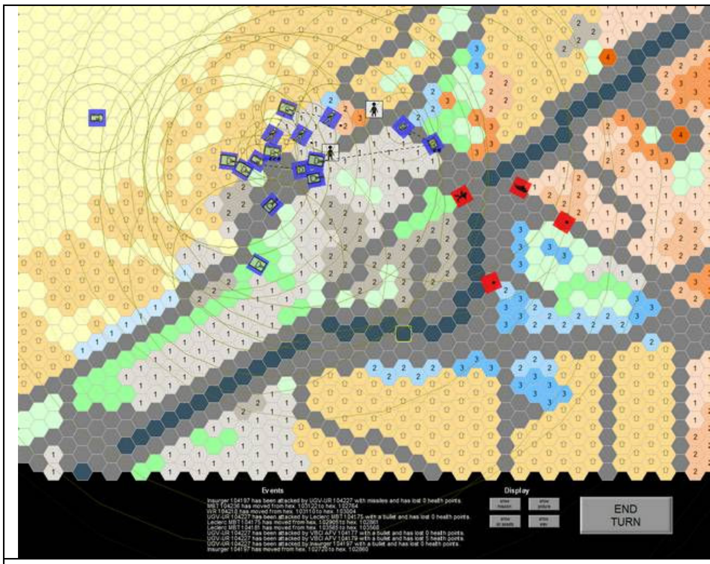
	3:10	UR 104227 has been hit by several bullets but has detected several NME units	UR 104227 designates an NME AFV and ask for NLOS fire. A missile is fired by C2 104226 that misses the target. A missile is fired by C2 104219 that hits the target. A missile is fired by FRES 1042221 that destroys the target. UR 104227 designates the RPG launcher and shoots him with NLOS. Missed.	UR UGV protection allowed it to resist to several hits. Lack of light Direct Fire capability on UR.
	3:20	UR 104227 has been destroyed.	End of the mission.	

Figure 7-2: Example of after-action qualitative results and analysis

7.5 Example of CAWG scenario development and quantitative results obtained

The following tables are automatically generated during the simulation.

The results presented here are the ones obtained during the run_19 of the "designation capability" scenario.

Run_19
created the 16/09/2009
19:17:47
Unit: WR104183

	Mobility			Situation Awareness						Survivability					Lethality		
TURN	dist		flr	D	R	I	ied			Hits					NLOS	LASR	Hits
1	0	0	0	2	1	0	0	0	0	0	10	0	0	0	0	0	0
2	0	0	0	1	1	0	0	0	0	0	10	0	0	0	0	0	0
3	0	0	0	1	1	0	0	0	0	0	10	0	0	0	0	0	0
4	0	0	0	2	1	0	0	0	0	0	10	0	0	0	0	0	0
5	94	0	0	1	1	0	0	0	0	0	10	0	0	0	0	0	0
6	94	0	0	2	2	0	0	0	0	0	10	0	0	0	0	0	0
7	0	0	0	2	2	0	0	0	0	0	10	0	0	0	0	0	0
8	94	0	0	1	1	1	0	0	0	0	10	0	0	0	0	0	0
9	94	0	0	2	2	2	0	0	0	0	10	0	0	0	0	0	0
10	0	0	0	2	2	2	0	0	0	0	10	0	0	0	0	0	0
11	0	0	0	2	2	2	0	0	0	0	10	0	0	0	0	0	0
12	83	0	0	3	3	3	0	0	0	0	10	0	0	0	0	0	0
13	63	0	0	3	3	3	0	0	0	1	10	0	0	0	0	0	0
14	83	0	0	3	3	2	0	0	0	1	10	0	0	0	1	0	0
15	108	0	0	2	2	2	0	0	0	0	10	0	0	0	0	0	0
16	0	0	0	2	2	2	0	0	0	0	10	0	0	0	0	0	0
17	63	0	0	3	3	2	0	0	0	0	10	0	0	0	1	0	1
18	84	0	0	3	3	2	0	0	0	0	10	0	0	0	0	0	0
19	84	0	0	1	1	1	0	0	0	0	10	0	0	0	0	0	0
20	94	0	0	1	1	1	0	0	0	0	10	0	0	0	0	0	0
21	96	0	0	2	2	2	0	0	0	0	10	0	0	0	0	0	0
22	55	0	0	2	2	1	0	0	0	1	10	0	0	0	0	0	0

Run_19
created the 16/09/2009
19:17:47
Unit: WR C2 station104177

	Mobility			Situation Awareness						Survivability					Lethality		
TURN	dist		flr	D	R	I	ied			Hits					NLOS	LASR	Hits
1	0	0	0	0	0	0	0	0	0	0	10	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	10	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	10	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	10	0	0	0	0	0	0
5	83	0	0	1	1	0	0	0	0	0	10	0	0	0	0	0	0
6	94	0	0	2	2	1	0	0	0	0	10	0	0	0	0	0	0
7	0	0	0	2	2	1	0	0	0	0	10	0	0	0	0	0	0
8	94	0	0	1	1	1	0	0	0	0	10	0	0	0	0	0	0
9	63	0	0	1	1	1	0	0	0	0	10	0	0	0	0	0	0
10	0	0	0	2	2	2	0	0	0	1	10	0	0	0	0	0	0
11	83	0	0	3	3	3	0	0	0	1	10	0	0	0	0	0	0
12	108	0	0	3	3	3	0	0	0	2	10	0	0	0	0	0	0
13	83	0	0	4	4	4	0	0	0	0	10	0	0	0	0	0	0
14	54	0	0	3	3	3	0	0	0	0	10	0	0	0	1	0	0
15	54	0	0	3	3	2	0	0	0	0	10	0	0	0	1	0	1
16	84	0	0	3	3	2	0	0	0	0	10	0	0	0	0	0	0
17	64	0	0	2	2	1	0	0	0	0	10	0	0	0	0	0	0
18	55	0	0	1	1	1	0	0	0	0	10	0	0	0	0	0	0
19	64	0	0	1	1	1	0	0	0	0	10	0	0	0	0	0	0
20	94	0	0	1	1	1	0	0	0	0	10	0	0	0	0	0	0
21	110	0	0	2	2	1	0	0	0	0	10	0	0	0	0	0	0
22	0	0	0	2	2	1	0	0	0	0	10	0	0	0	0	0	0

Run_19
created the 16/09/2009
19:17:47
Unit: UGV-
UR104178

	Mobility			Situation Awareness						Survivability					Lethality		
TURN	dist		flr	D	R	I	ied			Hits					NLOS	LASR	Hits
1	72	0	0	2	0	0	0	0	0	0	10	0	0	0	0	0	0
2	0	0	0	1	0	0	0	0	0	0	10	0	0	0	0	0	0
3	0	0	0	2	0	0	0	0	0	0	10	0	0	0	0	0	0

4	63	0	0	2	1	0	0	0	0	0	10	0	0	0	0	0	0
5	63	0	0	1	1	1	0	0	0	0	10	0	0	0	0	0	0
6	94	0	0	2	2	2	0	0	0	0	10	0	0	0	0	0	0
7	63	0	0	2	2	2	0	0	0	1	10	0	0	0	0	0	0
8	83	0	0	3	3	3	0	0	0	2	10	0	0	0	0	0	0
9	0	0	0	3	3	3	0	0	0	3	10	0	0	0	0	0	0
10	94	0	0	3	3	3	0	0	0	1	10	0	0	0	0	0	0
11	54	0	0	3	2	2	0	0	0	1	10	0	0	0	0	0	0
12	54	0	0	5	4	3	0	0	0	0	10	0	0	0	0	0	0
13	63	0	0	5	5	3	0	0	0	0	10	0	0	0	0	0	0
14	54	0	0	4	2	2	0	0	0	0	10	0	0	0	1	0	0
15	84	0	0	3	2	0	0	0	0	0	10	0	0	0	1	0	1
16	64	0	0	1	1	1	0	0	0	0	10	0	0	0	0	0	0
17	64	0	0	1	1	1	0	0	0	0	10	0	0	0	0	0	0
18	63	0	0	1	1	1	0	0	0	0	10	0	0	0	0	0	0
19	84	0	0	1	1	1	0	0	0	0	10	0	0	0	0	0	0
20	63	0	0	2	2	1	0	0	0	0	10	0	0	0	0	0	0
21	94	0	0	3	2	2	0	0	0	1	10	0	0	0	0	0	0
22	0	0	0	3	2	1	0	0	0	1	10	0	0	0	0	0	0

Run_19
created the 16/09/2009
19:17:47
Unit: UGV-BES104181

	Mobility				Situation Awareness					Survivability						Lethality	
TURN	dist		flr	D	R	I	ied			Hits					NLOS	LASR	Hits
1	0	0	0	0	0	0	0	0	0	0	10	0	0	0	0	0	0
2	64	0	0	0	0	0	0	0	0	0	10	0	0	0	0	0	0
3	63	0	0	0	0	0	0	0	0	0	10	0	0	0	0	0	0
4	63	0	0	0	0	0	0	0	0	0	10	0	0	0	0	0	0
5	63	0	0	0	0	0	0	0	0	0	10	0	0	0	0	0	0
6	63	0	0	0	0	0	0	0	0	0	10	0	0	0	0	0	0
7	63	0	0	1	1	0	0	0	0	0	10	0	0	0	0	0	0
8	54	0	0	1	0	0	0	0	0	0	10	0	0	0	0	0	0
9	54	0	0	0	0	0	0	0	0	0	10	0	0	0	0	0	0
10	54	0	0	0	0	0	0	0	0	0	10	0	0	0	0	0	0
11	63	0	0	0	0	0	0	0	0	1	10	0	0	0	0	0	0
12	54	0	0	0	0	0	0	0	0	0	10	0	0	0	0	0	0
13	63	0	0	0	0	0	0	0	0	0	10	0	0	0	0	0	0
14	55	0	0	0	0	0	0	0	0	1	10	0	0	0	0	1	0
15	64	0	0	0	0	0	0	0	0	0	10	0	0	0	0	1	0
16	64	0	0	0	0	0	0	0	0	0	10	0	0	0	0	0	0
17	64	0	0	1	1	0	0	0	0	0	10	0	0	0	0	1	0
18	63	0	0	1	1	1	0	0	0	0	10	0	0	0	0	0	0
19	55	0	0	1	0	0	0	0	0	0	10	0	0	0	0	0	0
20	63	0	0	0	0	0	0	0	0	0	10	0	0	0	0	0	0
21	63	0	0	0	0	0	0	0	0	0	10	0	0	0	0	0	0
22	0	0	0	0	0	0	0	0	0	0	10	0	0	0	0	0	0

Run_19
created the 16/09/2009
19:17:47
Unit: MBT104184

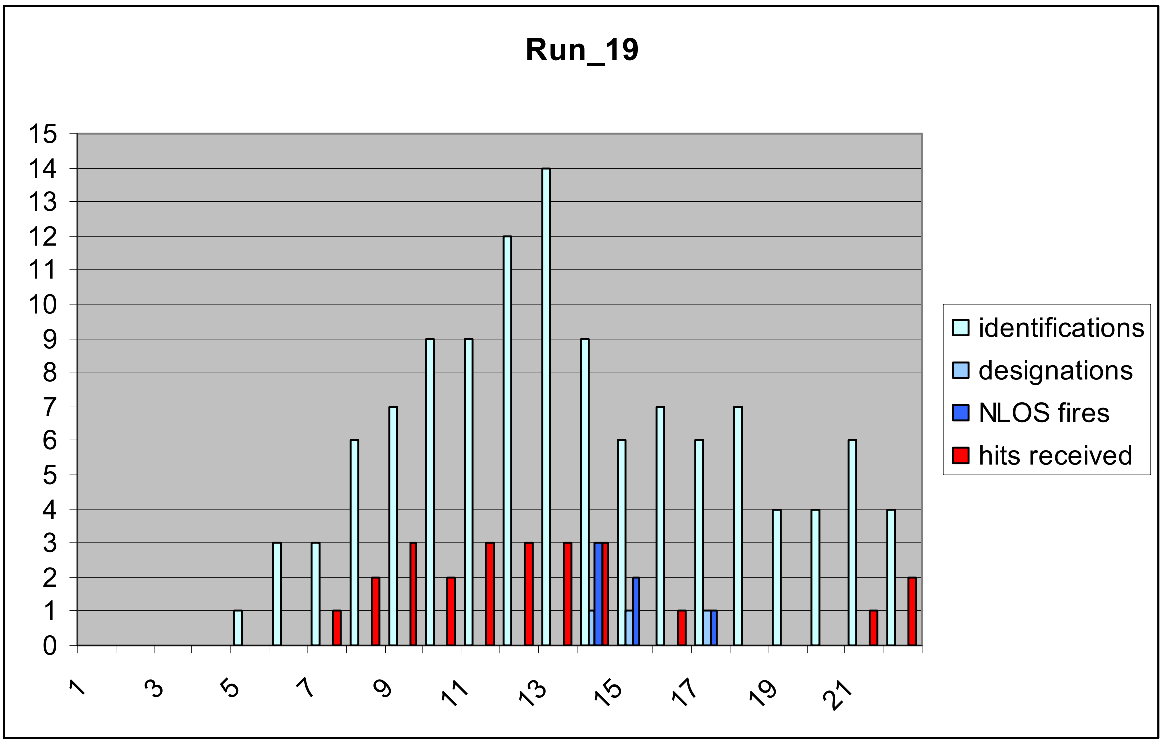
	Mobility				Situation Awareness					Survivability						Lethality	
TURN	dist		flr	D	R	I	ied			Hits				LOS	NLOS	LASR	Hits
1	0	0	0	2	2	0	0	0	0	0	10	0	0	0	0	0	0
2	0	0	0	1	1	0	0	0	0	0	10	0	0	0	0	0	0
3	0	0	0	2	2	0	0	0	0	0	10	0	0	0	0	0	0
4	0	0	0	2	2	0	0	0	0	0	10	0	0	0	0	0	0
5	94	0	0	1	1	0	0	0	0	0	10	0	0	0	0	0	0
6	0	0	0	2	2	0	0	0	0	0	10	0	0	0	0	0	0
7	0	0	0	2	2	0	0	0	0	0	10	0	0	0	0	0	0
8	126	0	0	1	1	1	0	0	0	0	10	0	0	0	0	0	0
9	94	0	0	1	1	1	0	0	0	0	10	0	0	0	0	0	0
10	0	0	0	2	2	2	0	0	0	0	10	0	0	0	0	0	0
11	0	0	0	2	2	2	0	0	0	0	10	0	0	0	0	0	0
12	63	0	0	3	3	3	0	0	0	1	10	0	0	0	0	0	0
13	94	0	0	4	4	4	0	0	0	2	10	0	0	0	0	0	0
14	84	0	0	2	2	2	0	0	0	1	10	0	0	0	0	0	0
15	108	0	0	2	2	2	0	0	0	0	10	0	0	0	0	0	0
16	0	0	0	2	2	2	0	0	0	1	10	0	0	0	0	0	0
17	83	0	0	2	2	2	0	0	0	0	10	0	0	0	0	0	0
18	94	0	0	3	3	2	0	0	0	0	10	0	0	0	0	0	0
19	115	0	0	1	1	1	0	0	0	0	10	0	0	0	0	0	0
20	0	0	0	1	1	1	0	0	0	0	10	0	0	0	0	0	0
21	128	0	0	1	1	1	0	0	0	0	10	0	0	0	0	0	0
22	138	0	0	2	2	1	0	0	0	0	10	0	0	0	0	0	0

The table below was designed in Excel to synthesise the results of interest from the units' tables and make some statistical basic analysis.

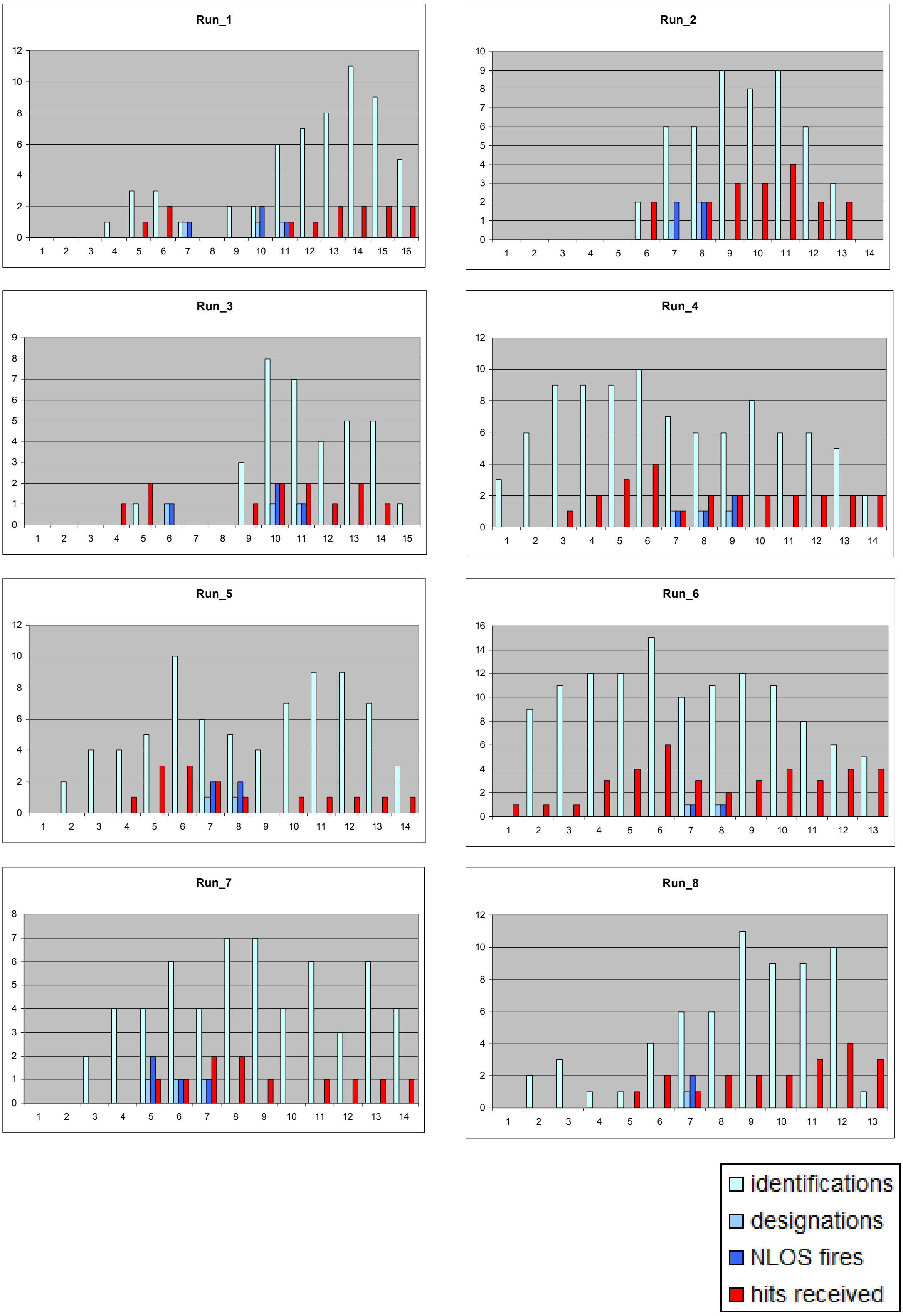
Run_19
created the:
global results

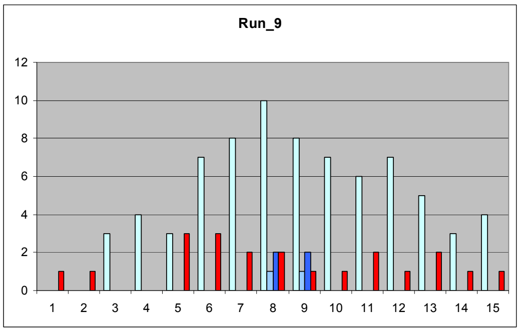
TURN	Average distance covered			Total number of D	R	I				Total number of Hits received					NLOS fired	Laser Designations	
1	14			6	3	0				0					0	0	
2	13			3	2	0				0					0	0	
3	13			5	3	0				0					0	0	
4	25			6	4	0				0					0	0	
5	79			4	4	1				0					0	0	
6	69			8	8	3				0					0	0	
7	25			9	9	3				1					0	0	
8	90			7	6	6				2					0	0	
9	61			7	7	7				3					0	0	
10	30			9	9	9				2					0	0	
11	40			10	9	9				3					0	0	
12	72			14	13	12				3					0	0	
13	73			16	16	14				3					0	0	
14	66			12	10	9				3					3	1	
15	84			10	9	6				0					2	1	
16	42			8	8	7				1					0	0	
17	68			9	9	6				0					1	1	
18	72			9	9	7				0					0	0	
19	80			5	4	4				0					0	0	
20	63			5	5	4				0					0	0	
21	98			8	7	6				1					0	0	
22	39			9	8	4				2					0	0	
Total				179	162	117				24					6	3	

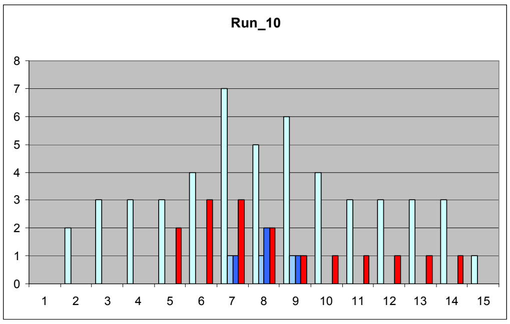
The results are finally presented as graphs that make the results easier to compare each other.



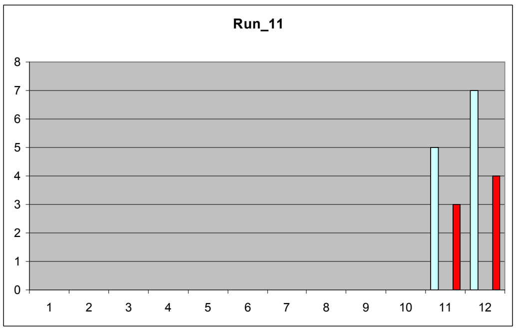
7.6 Results of the "designation capability" simulation runs

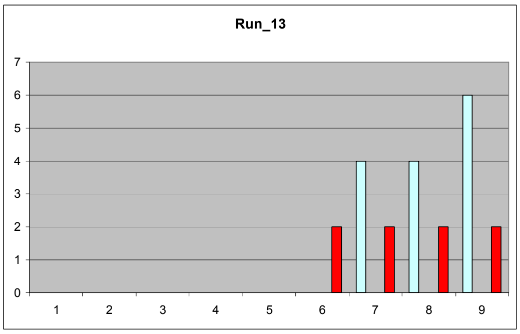


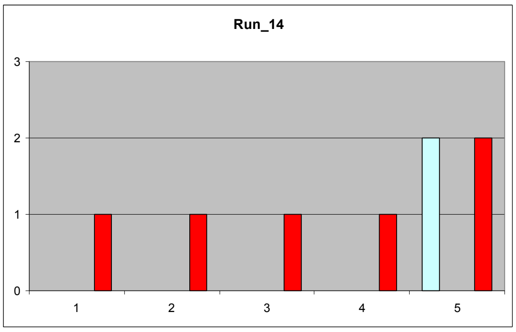


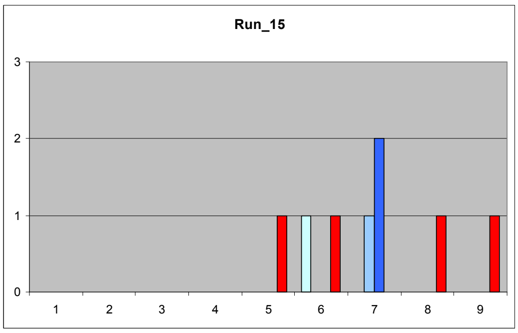


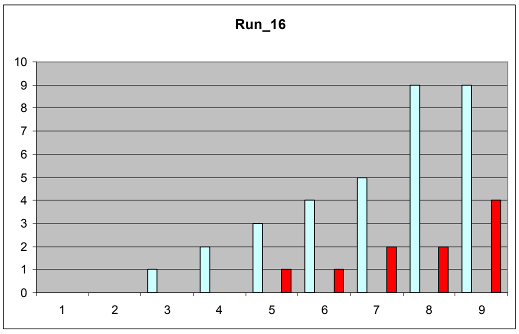
Runs 1 to 10 (no UGV in the battle group) show the high DRI performances of the AFVs, but also their weak stealth (many hits received).

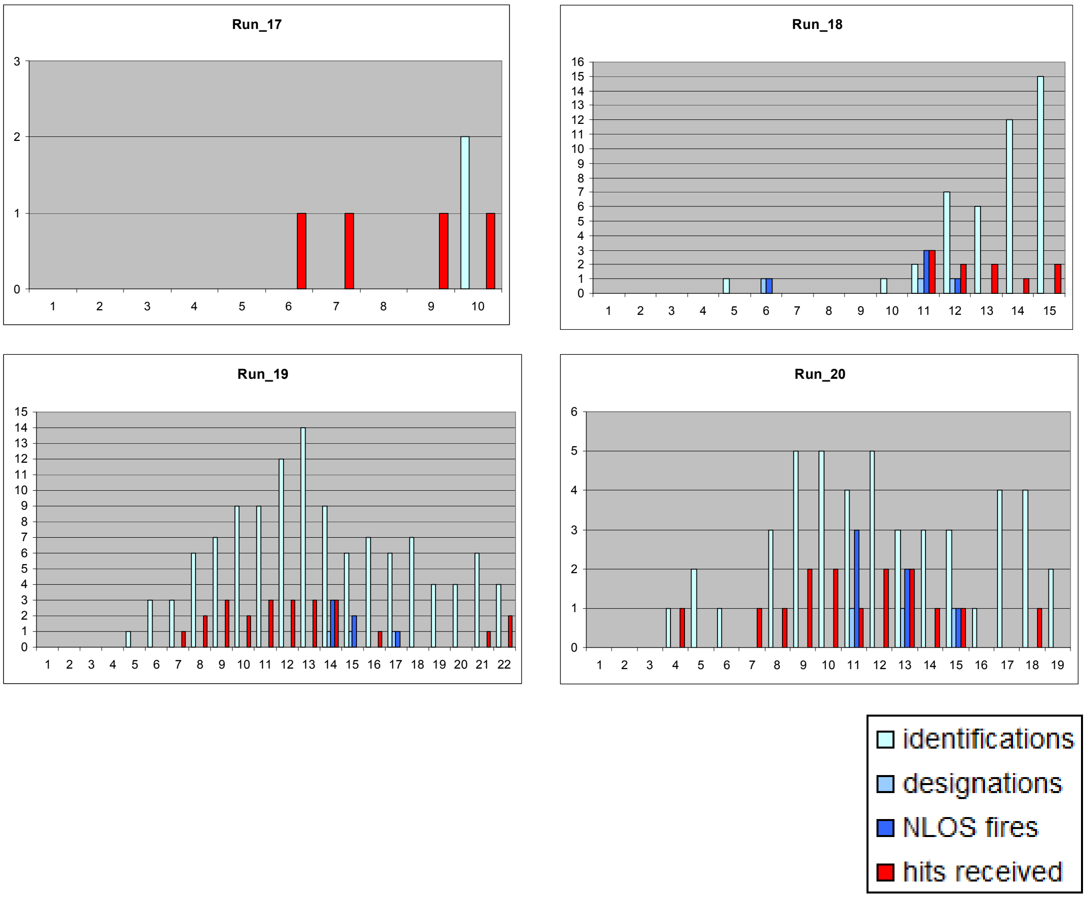












Runs 11 to 17 show that a medium size BES-UGV is easily detected and shot, making it unable to designate a target before being destroyed.

Run 18 to 20 show that the same performances of designation as AFVs ones can be achieved with a small size BES UGV.