Effects-Based Air Operations Planning Framework: A Knowledge-Based Simulation Approach

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Abstract— **Planning air warfare operations has always been a complex endeavor. However, as technology evolves at an increasingly fast pace, so does the complexity of managing its resources. In modern air operations, planners have to deal with a highly changing environment influenced by enemy air defenses, weather forecasts, among many other factors, demanding much effort to handle the great number of constraints and uncertainties presented by them. As a result, a number of decision-support systems have emerged attempting to facilitate the planning of air warfare operations. These systems usually rely on a wide variety of methodologies, which sometimes present a challenge in themselves when it comes to assessing the feasibility and effectiveness of the produced plans. Computer simulations are a practical way of providing this assessment, usually by running the resulting plans multiple times and checking the results against key criteria. Yet, establishing the right criteria, properly accounting for the "fog of war," and avoiding impractical simulation run times and costs are still major challenges. This paper addresses such challenges by proposing the development of a decision-support framework that combines ontology-based agile knowledge and a simulation-based mission planning methodology that accounts for the inherent uncertainties that air operations face. We avoid costly computation times required by simulation-intensive course-of-action analyzers by initially pruning the solution space through ontological reasoning. Moreover, the approach complies with the Effects-Based Approach to Operations, having a clear correspondence of processes with it. The explanations are focused on a specific scenario concerning intelligence, surveillance, and reconnaissance operations.**

Keywords—ontologies; effects-based planning; modeling and simulation; semantic matchmaking

I. INTRODUCTION

The fast pace by which complexity of current military operations is increasing has become a major challenge for mission planners, requiring a much more meticulous planning process to handle all the factors that might influence the outcomes of an operation. Several planning methodologies have been observed in the last years, yielding a number of systems to support air operations planning. To deal with complexity, these systems usually rely on heavy computing power, as well as on specialized operators that must be highly trained in the methodology associated with the system. Such requirements make the planning process brittle, as both the hardware and the operators become scarce resources that usually are centralized and not easily accessible by those who conduct the operations.

To put from a different perspective, this centralization of the planning resources results in distancing the plan development from those who will execute it, since the required planning resources are hardly available on the operations commands. It also impacts the agility of the process, especially when considering highly dynamic mission planning contexts that usually require re-planning to address emerging situations.

The framework presented in this paper leverages semantic technologies to formalize the knowledge required for planning air warfare operations. The reasoning behind this approach is two-fold, (1) to avoid the need for highly trained system planners, and (2) to decentralize the plan building and evaluation process, thus reducing the dependence on heavy computing power.

The planning knowledge to be captured is based on the Effects-Based Approach to Operations (EBAO). This paradigm has been extensively sought by several research and development efforts in the last decades, paving the way to its fruition and further application on the field [1]. According to [2], "EBAO informs every aspect of how the Air Force designs, plans, executes, assesses, and adapts operations." Therefore, it should guide any framework that proposes to aid the planning process of air operations. Following this premise, the backbone of the matchmaking process within this work is the Effects-Based Approach to Planning (EBP), which ultimately defines the semantic description of the domain and how it relates to the planning procedure.

Once the initial states of the EBAO knowledge is made explicit through ontology engineering, the focus of our development becomes to provide a solution that does not require large amounts of computing power and time. Rather, it may be done using portable computers by the operations planners. We achieve that by leveraging the EBAO mission concepts via a logical engine that pre-selects the possibilities given the planning data provided, greatly limiting the solution search space. This way, optimization methods can be used in a much more effective way, applied to scenarios that are simulated in a simplified fashion, and allowing for a quick means of assessing the optimization parameters. In a second step, these generated low-resolution solutions are evaluated based on criteria derived from the EBAO ontology. The most promising ones then go through a more complex simulation environment that, through entity-level simulation, would provide a much more detailed outcome that includes mission-specific prognostics.

For providing a clearer view of how this framework can be operationalized, an ISR (intelligence, surveillance, and reconnaissance) scenario is built with unclassified data from the Brazilian Air Force. The database includes a number of platforms and sensors that have to be assigned to tasks, leading to actions that generate the desired operational effects. Since not all sensing sources can provide the needed information to task requirements, because the sources are context sensitive [3], this assignment can be very challenging to the planning staff.

ISR operations proved to be a good choice for this initial scenario, since they contain multiple factors that directly affect the planning process, and also make its optimization very important. Also, since ISR assets are oftentimes highly complex and valuable, a less than adequate planning will lead to the loss of costly flight hours and very specialized crews work. Nevertheless, the application on the planning process of other air operations can be made based on the same framework structure, converting the sensor matchmaking phase to a weapon to target matching in the case of airstrike or managing electronic warfare (EW) measures on a suppression of enemy air defense (SEAD) mission, both sharing many complexities with ISR operations.

At this stage of our development, we did not yet reach full circle or obtained conclusive results of a detailed simulation. Thus, our focus on this paper is to provide the long-range vision of the framework, its goals, and an overview of the technical approaches determined by our preliminary research efforts to solve the challenges encountered so far.

The paper is organized as follows. Section II gives a brief overview of previous research on operation planning frameworks like the one proposed, as well as on semantic matchmaking efforts. Section III provides the main concepts involved on EBAO, emphasizing the EBP process. Section IV presents the framework, including the description of the software applications to be used on its implementation. Section V focuses explicitly on the semantic part of the framework. Section VI displays the considered scenario, describing resources and critical conditions that may influence how the image requirements can be met. Finally, Section VII summarizes the paper, pointing to the next steps to be taken.

II. BACKGROUND

A. *Planning Simulation Framework*

Several planning frameworks are available within the military research context. However, much of the work available is either too complex or remains inaccessible (*e.g.*, classified). The complexity is often directly related to the high resolution required to generate reliable results.

While trying to present an alternative to this complexity problem, some authors have proposed the use of lower resolution simulation and optimization methodologies, which deal with less factors at a time.

Rosenberg *et al.* [4] suggest a collection of decision-support tools for planning generation that consists of "a method to define an operational scenario, an optimization engine to generate a diverse set of solutions, and a suite of visualization and analysis tools to review, analyze, and visualize generated plans." To provide a solution in a timely manner, the authors propose a rapid evaluation of candidate solutions through agent-based modeling and simulation (ABMS). They leveraged the same software used in our proposed framework.

Similarly, [5] – also using the same software application – focuses on a Joint Suppression of Enemy Air Defenses (JSEAD) scenario in which plans are generated, optimized, and simulated. The authors also rely on an ABMS of two sides containing different types of entities, usually targets and air defenses for the opposing side and strikers and JSEAD units for the friendly side. Their results illustrated the potential of low-resolution simulation as a rapid evaluation tool of generated plans, which will be in time described within our own approach.

Unlike in our approach, these research efforts do not apply semantic methods as a form of structuring the modeling and simulation process (*e.g.* [6]), or as a conceptual basis for the framework as those in the subsection below.

B. *Semantic Matchmaking Framework*

The literature on assigning sensors to missions or tasks is vast, but the use of semantic techniques for this purpose is rather limited. Therefore, it is worth pointing out [7], which advocates for an ontological problem-solving architecture to facilitate automated inference of assigning sensors to missions. This work limits the solution domain as a means of including a coordination system to emulate the assets and complete bears similarities with the aforementioned planning simulation frameworks and the one we propose in this paper.

One of the most productive solutions is sponsored by the U.S. Army Research Laboratory and the United Kingdom Ministry of Defence ([8], [9], [10], [11], [12], [13]). Its authors conceive a system that relies on a series of ontologies for assigning sensors to missions. The backbone of this process is the "Mission and Means Framework" that is claimed to "provide a model for explicitly specifying a military mission and quantitatively evaluating the mission utility of alternative warfighting solutions" [12]. The three basic elements of their methodology are [14]:

- Top-to-bottom solution to the problem of deploying sensors to meet the information needs of tasks in a mission context;
- Combination of reasoning at mission-planning time, and optimization algorithms at mission execution-time; and
- Dynamic deployment configuration of selected sensor instances by means of a sensor infrastructure.

The work includes modular ontologies that cover task requirements, sensor capabilities, and a structured framework to associate tasks with sensors. The ontologies specify the requirements of the missions and the capabilities of the sensors so that the framework is able to decide between combinations of sensors to satisfy the requirements of a given mission [12].

Even though providing a proven assignment system [3], with very well-structured ontologies, this work does not focus on dealing with the uncertainties that a planning scenario presents. This is due to the use of logical reasoners and mostly deterministic functions. Stochasticity is not considered, just comparisons between deterministic possibilities. In addition, the Mission and Means Framework ontology focuses on tasks instead of effects. Thus, although providing a direct and clear way of breaking down missions [9], the approach does not emphasize the holistic view advocated in our work. Finally, [15] also provides more details on how this framework may be structured as an ontology.

III. EFFECTS-BASED PLANNING

Even though utilizing the Mission and Means Framework, [9] states that alternative mission planning approaches, such as effects-based planning, may be structured in a similar way, with the goal of assigning resources to missions.

"Planning to achieve an effect" has been used naively as a rather straightforward definition of EBP. However, the vast majority of planners would argue that any previous approach to military planning would include this asseveration [16]. Therefore, it is imperative to clearly define this concept upfront.

The US Air Force doctrine [2] holds that "there is no single 'effects-based planning' methodology or process. Rather, understanding the principles of an effects-based approach to operations should yield certain insights and enhance comprehension of many general planning concepts". This is the reason why it is important to first understand what EBAO means.

Reference [17] presents the US Joint Forces Command definition of EBAO as "a process for obtaining a desired strategic outcome or effect on the enemy through the synergistic and cumulative application of the full range of military and nonmilitary capabilities at all levels of conflict". Another definition presented on [1] is that "effects-based operations are operations conceived and planned in a systems framework that considers the full range of direct, indirect, and cascading effects, which may—with different degrees of probability—be achieved by the application of military, diplomatic, psychological, and economic instruments".

What both of these definitions emphasize is that the process of planning has to be much more intentional on the pursuit of a holistic view of the operation. There is a focus on addressing not only direct physical effects, but several types of indirect effects, which are influenced by each other. Planners are encouraged to maintain a very broad view of the "big picture", especially during execution, not being caught up in details that can tarnish the end state visualization.

A better understanding of our approach requires exploring EBO's main concepts, which are described in the next Section. However, our framework greatly relies on the EBO principles listed below, which were suggested by [1].

A. *Uncertainty*

The first principle says that effects-based operations (EBO) planners have to rely on methods that explicitly deal with probabilities and randomness to properly address the inherent uncertainties contained in the air operations. EBP has to fully confront the scope and magnitude of these uncertainties, especially when dealing with outcome predictions.

B. *Qualitative modeling*

Secondly, in this uncertainty-sensitive framework it is imperative to possess a trustworthy qualitative modeling, including frictional, credibility and cognitive factors that are oftentimes closely related to indirect effects. This is highly dependable on the availability of subject matter experts (SME) to provide information about systems and operations.

C. *Agent-based modeling*

The qualitative modeling also requires a focus on decision-making, which can be addressed by agent-based modeling approaches, accurately depicting the C4ISR aspects of the operations. Cognitive models may be housed in agent architectures, allowing analyzes of emerging scenarios closer to the reality and with a clear focus on the command and control structure.

D. *Capability planning*

Is expected from EBP to determine a range of circumstances that provides degrees of confidence towards the meeting of the conditions that characterize a desired end state. These operational circumstances have to be linked to the necessary capabilities to provide this confidence, not only the necessary means.

E. *Empirical information*

As stated when speaking of the qualitative modeling, empirical information provided by SMEs is extremely important for a successful EBP. In addition to that, information from history, war-gaming, simulations and experiments should be strongly pursued so that the complex models can be modelled and uncertainties reduced.

F. *Adaptation*

The last principle relates to planning for adaptation. Since a lot of uncertainties are present and the scenarios may present emergent behavior, it is very important to be able to adapt and dynamically change plans even during execution time.

IV. FRAMEWORK

Before presenting our framework itself, we must first provide the necessary context, which is conveyed in Fig. 1. In EBAO, effects are defined as results of actions. These actions are simply assigned tasks. The ontology described in Section V, is used to support a matching process between effects and resources. The resources in the analyzed scenario are platforms and sensors, which may be mounted to the platforms or not. The objectives that defined the desired effects are then translated to fitness values within the simulation, providing a means for the plans optimization. On the tactical level, these objectives form a specific mission that, on the operational level, leads to the desired end state.

ABMS is used to represent this mission, possessing cognition models that encompass the available expert information as well as showing the interaction and coordination between the agents, representing the C4ISR processes involved. With several runs of the simulation scenario, uncertainties can be added mostly on the hostile units' locations, on available capabilities, and on different behavior patterns employed. Also, time issues may be initially addressed, since the agents' interactions allow for identifying some of the interferences they generate on each other through the simulation run.

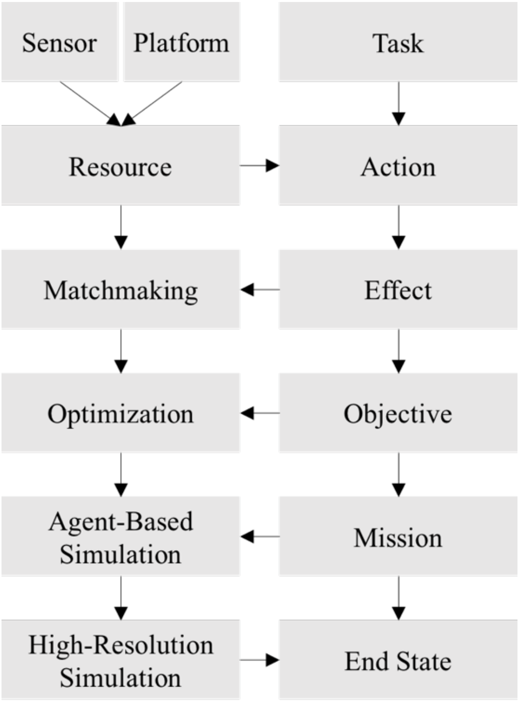

Fig. 1. Air operations planning framework.

Generating cognition models can be a strenuous process, especially when dealing with rule-based scripts for the agent behavior definition, which, besides being hard to implement, do not capture the uncertainties present on military operations. This is why the approach for the friendly and enemy forces' threat assessment process relies on probabilistic models, such as Bayesian networks, capable of representing the dependencies between the entities' actions and the evidence accrued from the C4ISR sources available.

From the ABMS, each of the generated plans can be properly simulated and consequently evaluated based on criteria originated from the three superior goals defined by [18]: flight safety, combat survival, and mission accomplishment. The first goal relates to the need of the pilot to concentrate on flying the aircraft in a safe way, for instance assuring that it has the necessary amount of fuel, that it flies through proper fly zones, avoiding collisions with other aircrafts and the terrain. The second focuses on the chances of enduring through the mission, considering the capabilities of the hostile forces and the exposure to them. Lastly, the third goal illustrates the original objective of the mission performed, such as gathering intelligence information, striking a ground target, or suppressing the enemy's air defenses.

During the optimization parameters definition there is a need of defining a prioritization of these three basic goals. This process depends on several factors, such as rules of engagement, value of the assets, and criticality of the mission. These factors have to be properly valued by the leadership and then parametrized by the analysts to correctly represent the commander's intent (CI) on a top-to-bottom fashion.

At the end, the framework consists of a deeper and more thorough entity-level simulation with the goal of determining if the conditions that define the end state are met within a feasible timeframe by the previously selected best plan. Also, this phase allows for mission rehearsal and order generation.

To summarize, as extracted from [2] and [19], the right-hand side terms of Fig. 1 can be individually defined as:

- **Resources**: all the available assets to generate the desired effects;
- **Tasks**: an action or actions that have been assigned to someone to be performed;
- **Actions**: result of assigned tasks;
- **Effects**: all the physical, functional or psychological outcomes, events or consequences that results from specific military or nonmilitary actions;
- **Objectives**: the clearly defined, decisive, and attainable goals towards which every operation is directed; and
- **End state**: the set of required conditions that defines achievement of the commander's objectives.

As one can notice, the elements presented in the previous Section are met, since the resources are approached as capabilities and contain several qualitative and empirical information, which also permeates the other concepts of the framework. Uncertainty is handled through simulation layers, with the ABMS suggestion alongside. Lastly, the design for adaptation is taken in consideration through the process of generation of multiple plans, and mostly by the ontological reasoning that can quickly change the initial constraints, leading to a faster plan evaluation during dynamic re-planning.

Each of the last four boxes on the left-hand side of Fig. 1 is performed by a different software application that are respectively described as follows:

A. *Semantic Modeling: Protégé*

Protégé is one of the most popular knowledge-modelling environments. It not only allows users to interactively edit knowledge-bases within its graphic user interface, but also presents a series of plugins that add a number of functionalities and services, such as ontology management tools, multimedia support, querying and reasoning engines, and problem solving methods. Also, it has experienced several actualizations in the last decades and has a vast user community, featuring high stability and usability ratings. As well as the two following applications, it is written in Java, allowing for a smoother integration in the future ([20], [21], [22]).

B. *Optimization: ECJ*

ECJ is a general-purpose evolutionary computation and genetic programming framework designed for large, heavy-weight experimental needs. It is a free open-source application developed by the Department of Computer Science of George Mason University. In spite of being more than 10 years old, it shows great stability and an optimized design, attested by a large number of users in the genetic programming community.

Besides its main goal of attempting to permit as many valid combinations as possible of individual representation and breeding method, fitness and selection procedure, evolutionary algorithm, and parallelism, it contains multi-objective optimization algorithms, island models, master/slave evaluation facilities, coevolution, steady-state and evolution strategies methods, parsimony pressure techniques, and various individual representations ([23], [24], [25]).

C. *Agent-Based Simulation: MASON*

MASON is a single-process discrete-event multi-agent simulation toolkit written in Java that comprises a fast core engine and a fully separated visualization display. It is very versatile and easily expandable, providing friendly licensing options and excellent performance. In addition, it is designed to support large numbers of agents relatively efficiently on a single machine in models that are entirely encapsulated. Even the elements of the system itself are highly independent, providing a modular and consistent way to combine its different parts in various ways. Some of these parts form a large set of utilities that has the goal of supporting model design. Finally, as well as ECJ, it is developed and maintained by a research group from George Mason University ([26], [27], [28], [29]).

D. *High-Resolution Simulation: VR-Forces*

VR-Forces is a simulation environment created by VT MÄK for scenario generation [30]. The platform is widely used throughout the industry, and provides a well-engineered basis for integrating CGFs with urban, battlefield, maritime, and airspace activity. Apart from the graphical interface (front-end), VR-Forces consists of a back-end application, which is its actual simulation engine. As such, VR-Forces scenarios can be scaled up by running multiple front-ends and/or back-ends, communicating through its networking toolkit. Moreover, both the VR-Forces front-end and back-end can be extended either by being embedded into another application or through plug-ins, using the C++ API provided.

Reference [31] provides a study comparing several CGF simulation software in terms of autonomy, learning and adaptation, organization, realism, and architecture. VR-Forces was considered to be the most suitable as a development platform, mostly because its AI capability built-in, very good documentation and technical support, and support for data logger export. The same conclusion was drawn by [32] in a much more thorough analysis.

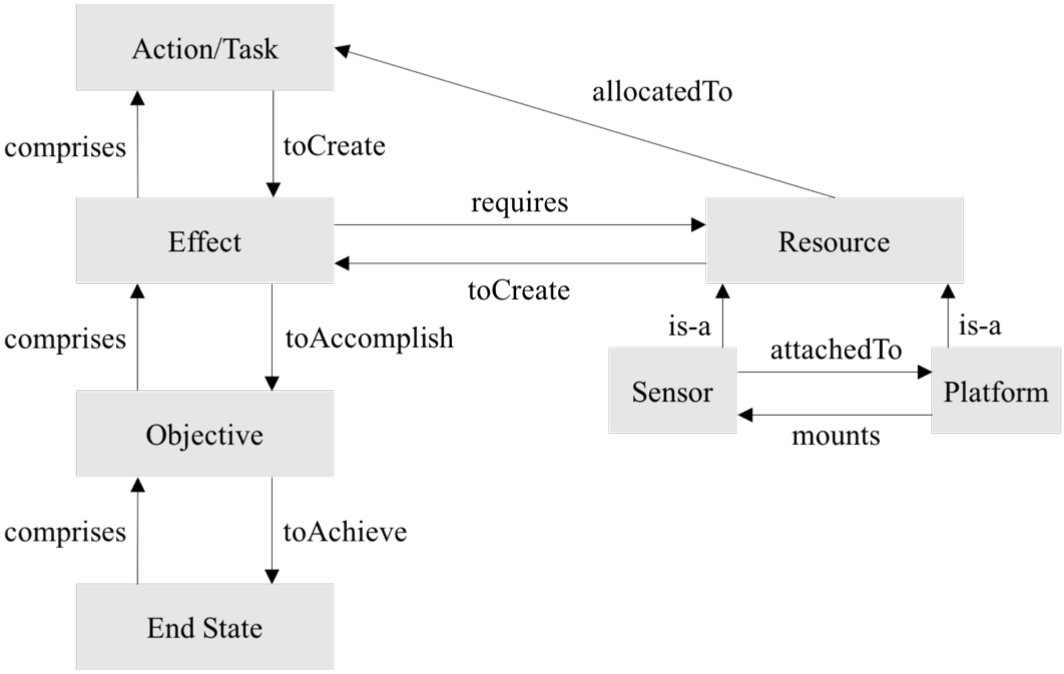

Fig. 2. EBP concepts and relationships.

V. EBO ONTOLOGY

A. *Knowledge-base*

One of the main reasons why this work advocates for the use of ontologies for EBP planning is that they can contain detailed information about the military domain in a very structured way. This is made very formally, explicitly expressing clear and precise definitions of concepts and relationships [33]. Besides, it provides a domain conceptualization of EBAO as expressed on Fig. 2, allowing for a better understanding and application of its features.

Some of the information contained on our knowledge-base will be presented on the next section, but Fig. 3 shows a screenshot taken from the proposed ontology on Protégé. It is structure from three basic domain concepts: capabilities, sensors and platforms. The two latter are the resource descriptions, with their properties and limitations taken into account. The first, is related to the actions that can generate the desired effects, but also to some of the constraints that can influence the mission, as discussed in the next section.

After properly modeling the domain with the most significant parameters and properties, the semantic component of the framework needs to perform the matchmaking between resources and the required tasks for effect generation. This calls for a semantic breakdown of the effects, so that the available capabilities may be used as generation factors for them. After that, the matchmaking methods are able to assign the proper resources as follows.

B. *Semantic matchmaking*

The notion of matchmaking consists of a procedure to find correspondences between entities in ontologies [34]. Whereas process is made by several existing techniques, this work will focus on a description logic approach as advocated by [35].

First, it is important to define that matchmaking takes place as a process in which a requester party triggers the mechanism of finding resources relevant to the request., while the provider party describes the available resources in advance. With that, the matchmaking is made through automated analysis and comparisons of the semantic descriptions of the involved resources.

For doing so, the entities of an ontology and their relationships have to be carefully modelled, representing the air operations domain as a set of concrete resources that vary on several properties. This variance is intended to allow the specification of the resources, having different parameters. However, due to incomplete information, these specifications not necessarily describe all the parameters completely. To deal with that, the notions of entailment and satisfiability back the testing if all request formulas hold in all models of a knowledge base and if these formulas are logical consequences of it.

There are several matching infrences that are able to account for this variance and that can be directly realised by description logic, ranked in the following way according to their degrees of matching [36]:

1) No match: empty intersection between two descriptions;

2) Intersection: non-empty intersection between two descriptions;

3) Non-Disjointness: non-empty intersection between two descriptions in every possible world;

4) Specialisation: subsumption between two descriptions holds from right to left;

5) Generalisation: subsumption between two descriptions holds from left to right; and

6) Equivalence: subsumption between two descriptions holds in both directions.

As stated in section VII, our next step is to test this implementations to verify if the limitations of classical description logic matchmaking are significant for in this context, generating undesired matching behaviors. If so, other methodologies may be embraced, such as the use of nonmonotonic formalisms, such as terminological defaults, autoepistemic and circumscriptive description logic [35].

Fig. 3. Air operations planning framework.

VI. SCENARIO

The proposed scenario represents the definition of a desired effect yielding intelligence requirements. These requirements are influenced by several factors including the resource availability, environment conditions, and hostile activity. Each factor imposes restrictions on the matching process. The availability is directly related to the instantiation, the environment produces constraints for some sensors and platforms, and the opposing forces impact on the survivability probabilities as well as on the mission success measurements.

To illustrate the EBP focus, the chosen scenario contains the requirement of an effect of assessing, gaining, and maintaining air superiority in support of land and maritime schemes of maneuver, as proposed by [37]. The author already exemplifies how this effect yields ISR actions, such as: detect, discover, and degrade key components of defense systems; confirm damage to target acquisition radars and height-finding radars.

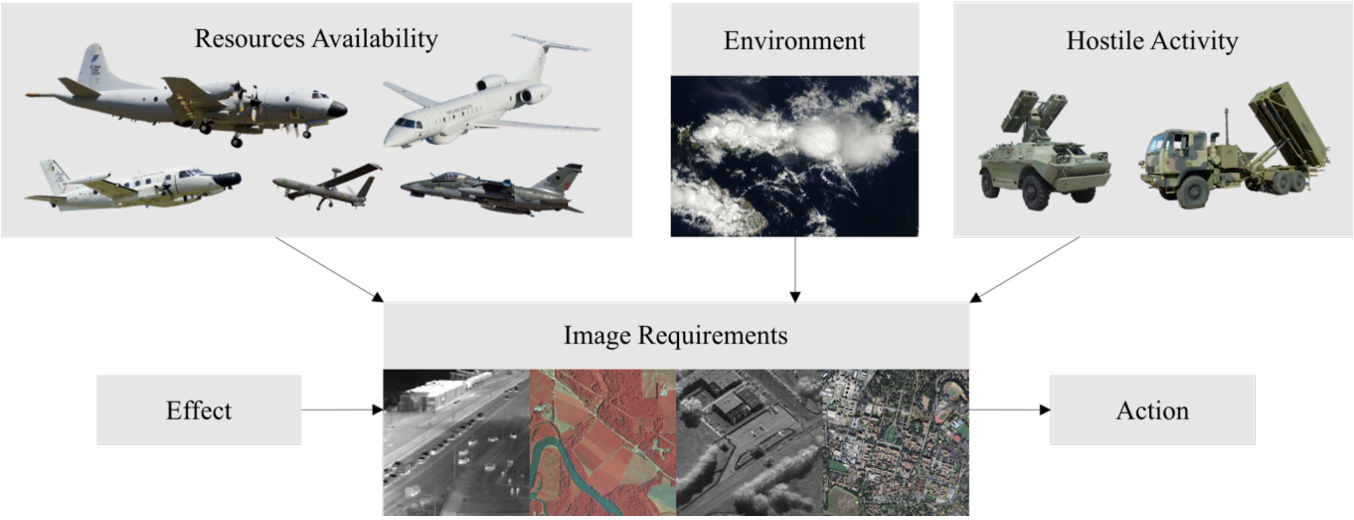

Fig. 4. Scenario factors of influence.

With these actions in hand, the system needs to take into consideration the available sensors and platforms to determine which ones are capable of properly performing them. However, their characteristics have also to be confronted with the instance availability, environment conditions and the hostile threats expected, since this will directly influence the matchmaking process, as depicted in Fig. 4.

A. *Sensors*

Aircraft mounted sensors present different characteristics that may also require different flight altitudes and visibilities in order to properly work. Besides, depending on the applications the image demands may be different, providing alternative information from various sensors. The available sensors considered in this work are:

- OPT: Optical sensors;
- FLIR: Forward-looking infrared cameras;
- MSS: Multispectral Sensors;
- SAR: Synthetic Aperture Radar;
- NCES: Non-communications exploitation systems; and
- CES: Communication exploitations systems.

B. *Platforms*

As showed in Fig. 4 the considered platforms are some of the aircrafts used by the Brazilian Air Force as ISR assets. These platforms mount the aforementioned sensors according to TABLE I. Besides, each one presents different values for range and average speed, which may considerably influence the operations. The aircrafts are:

- Elbit Systems Hermes 450 (RQ-450): medium size unmanned aerial vehicle (UAV);
- Lockheed P-3 Orion (P-3AM): four-engine turboprop maritime surveillance aircraft;
- Embraer EMB-111 Bandeirante Patrulha (P-95BM): twin-turboprop maritime patrol aircraft;
- Embraer EMB-145 RS (R-99): twinjet remote sensing aircraft; and
- AMX International AMX-R (RA-1): ground-attack aircraft for reconnaissance.

TABLE I. SENSORS ATTACHMENTS TO PLATFORMS

Platform	**Sensors**
RQ-450	FLIR, SAR
P-3AM	FLIR, NCES, SAR
P-95BM	NCES, SAR
R-99	CES, FLIR, MSS, NCES, OPT, SAR,
RA-1	FLIR, OPT

VII. CONCLUSION AND FUTURE WORK

The main goal of this paper was to provide an analysis of the problem and a preliminary structure of the framework advocated to solve it. The work focused on establishing a theoretical basis for delineating this solution, adapting it to effects-based approach to operations concepts. An added constraint was to utilize free and open source applications to form the framework, at least on its initial phases (the only exception being VR-Forces, because of the lack of open alternatives that would provide similar simulation capabilities). Moreover, these applications should be light enough to allow for the execution of the framework on a single machine, what they arguably are.

The development of the framework not only justifies itself as being an explicit representation of EBAO, but also on the combination of simulation methods with an initial semantic matchmaking process that reduces the solution space, allowing for a potentially more agile way of determining operational plans. Additionally, the ABMS phase allows for numerous and fast simulation runs, acting as a fitness evaluation tool for the optimization process as well as an analyzer of emerging behaviors and complex C4ISR interactions.

At the time of this writing, only the initial implementations of the ontology described have been performed. Next steps include the full development and implementation of the matchmaking process. This step is needed so the optimization can be executed giving continuity to the proposed methodology.

Finally, more information regarding the scenario has to be gathered, also allowing for an expansion of its scope, including gradually more Air Force related activities, for instance airstrike.

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