Confidence Estimation in the Application of Simulation in the Development of Aircraft Self-Protection Measures

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***Abstract*—This paper describes the application of simulation in the development of aircraft self-protection countermeasures against infrared missiles. The integrated approach followed here consists of repeated cycles of materiel[1] characterisation, analysis and modelling, design synthesis, solution implementation and deployment. Results from the activities in this workflow are used to support the estimation of confidence in the simulation tools. The well known Qualification, Verification and Validation (QVV) model is extended by adding the notion of quality of scenario information to the physical characterisation, the conceptual modelling and the computer modelling of system elements. It is shown that a simulation with high confidence requires extensive validation testing. Some measure of confidence can be achieved by ensuring that the conceptual and computer models support extrapolation between fewer validated 'islands'. To express simulation confidence, a 'potential field' is proposed; the value of this potential is determined by the degree to which the QVV requirements are met. The results from an infrared simulation model is used to demonstrate this principle.**

***Index Terms*—infrared, electronic warfare, image simulation, infrared missile, scene modelling, weapon evaluation, qualification, verification, validation**

I. INTRODUCTION

During the Vietnam war the first Soviet made SA-7b (Strela-2M) man portable air defence (ManPAD) missiles were deployed [1]. Since that time, missile technology evolved to employ sophisticated two-colour seekers, some even with imaging sensors. The proliferation of these ManPAD shoulder launched missiles poses a serious threat to military and civilian aircraft. As many as 150 000 of these missiles are available on the black market [2]. Several attacks on civilian and military aircraft have been recorded in recent times [3].

To counter the infrared missile threat, a variety of countermeasures are used, including flares and directed infrared (laser) countermeasures (DIRCM). These countermeasures must match the complexity of the missile threat. As complexity of both the missile and the countermeasures increase, it becomes progressively more difficult to verify the effectiveness of the countermeasure. The approach described here is to use simulation models, in conjunction with field trials, to predict and verify countermeasure effectiveness. When analysing the simulation predictions, one key question persists: "What confidence can I have in the simulation and its results?"

The bounds within which a practical simulation system is valid, are determined by the quality of information of the materiel, the applicability and completeness of the computer models and accuracy of scenario description. Within these bounds, the simulation can be applied with varying levels of confidence. Estimating simulation confidence requires careful consideration of the underlying real world phenomena, the conceptual models of the phenomena, the computer models and the scenario descriptions used in the simulation.

This paper provides an overview of this field of research and a discussion on a new perspective for simulation confidence assessment.

II. INTEGRATED APPROACH TO ELECTRONIC WARFARE

The CSIR approach to aircraft self-protection is depicted in Fig. 1 and 2. Simulation plays a very important role in this process, in that it provides a sandbox environment to support solution development. The materiel characterisation activity provides inputs for modelling. The characteristics are analysed with the objective to build conceptual and computer models. The completed models are then used to synthesise (or optimise) a solution, through repeated design and testing *in the simulation environment.* Once the designs are implemented in material form, these are deployed for evaluation and operational use.

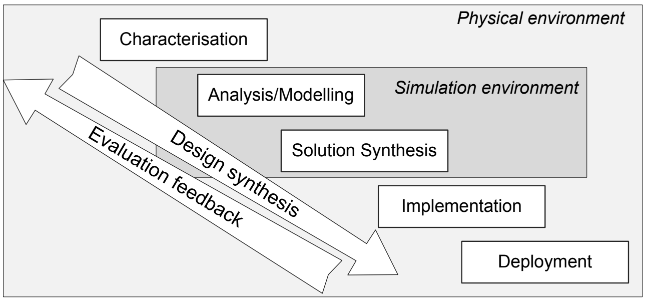

Fig. 1. Design synthesis and evaluation flow

A key factor in this process is the re-evaluation and continual improvement of solutions. As shown in Fig. 2, the work

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[1] The word 'materiel' refers to the equipment and supplies in military and commercial supply chain management domains.

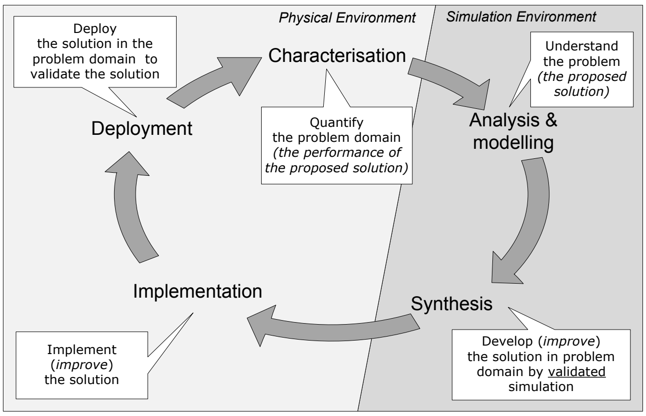

Fig. 2. Continual evaluation cycle

flows in a never-ending cycle — never-ending since there is a continual evolution in the threat and in own materiel. Hence, the deployment of a solution immediately provides the opportunity, nay, the *necessity* for re-evaluation and the process repeats. This repeated cycle provides a growing body of information and experience, directly contributing to the confidence in simulation models.

III. AIRCRAFT SELF-PROTECTION SOLUTION SYNTHESIS

A. Characterisation

In order to solve the problem of missile threats to own aircraft it is necessary to understand the complete domain. Understanding begins with characterisation. Characterisation quantifies the domain parameters by one of many techniques: measurement during experimentation, co-operation with foreign intelligence organisations, research from open literature, or first principle physics.

Missile threat and own aircraft parameters are considered highly sensitive by the military. It is unlikely that either the missile or aircraft supplier will divulge materiel design or detailed performance parameters.

Missile exploitation is the activity where a missile is 'opened up', inspected and experimentally characterised in an attempt to quantify the missile parameters. Earlier generation missiles are 'white-box'[2] circuit traced and mechanically characterised. Modern, digital missiles require a 'black-box'[3] approach where sets of input vectors are imposed on the black-box and the resultant reaction is observed. Theoretically, black-box characterisation requires an infinitely large set of input vectors, but in practice this is impractical; only limited sets of input vectors are used.

Missile exploitation requires the characterisation of a multitude of parameters, including optical parameters, signal processing (guidance, tracking and countermeasure) algorithms, mechanical properties and parameters, servo parameters, motor parameters, and aerodynamics parameters. This process is expensive and time consuming.

The characterisation of own aircraft and countermeasures requires access to the materiel for measurement under (somewhat) controlled conditions. Trials are typically executed on an instrumented test range where the spatial location of all objects can be measured. The infrared signature (imaging and spectral) is measured, concurrently with object position, range and aspect angle. A typical characterisation programme requires a large number of test events, at different altitudes and speeds.

B. Analysis and Modelling

The characterisation results are used to construct conceptual models, using the measured information to identify, build and scale the models, through a process called 'analysis and modelling'. These conceptual models can be physical constants, mathematical formulations, algorithms, lookup tables or similar. Conceptual models can be quite complex and building such models requires considerable operational domain and technical know-how.

The mechanical properties, electro-mechanical properties and tracking, guidance and flight control algorithms and behaviour of dynamic systems are implemented in the form of control system models. These models, when implemented in Laplace or state-space formulations, can become quite complex for a missile or an aircraft. An example of a very simple flare dynamics model is shown in Fig. 3. Current dynamics system simulation packages are reliable and well tested; the accuracy of the user model designs implemented in the simulation packages must, however, be qualified and verified.

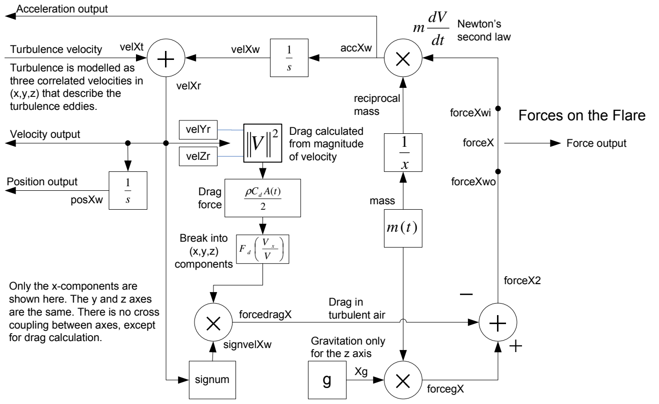

Fig. 3. Countermeasure flare dynamics model

Infrared measured data are used to assemble a structured data set comprising the geometrical distribution of temperature, reflectance and emissivity of object elements (e.g. panels, polygons or three-dimensional voxels). From this structured data set, the signature at any view angle can be computed. An infrared structured data set can be quite detailed for a comprehensive model.

A conceptual model must implement an object's real-world behaviour acceptably. When reviewing the quality of the conceptual models to represent their corresponding real-world objects, the models are *qualified*, meaning: "Determination of

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[2] White-box means that we can know the inside of a unit or box.

[3] Black-box means that we have no information on the inside of a unit.

adequacy of the conceptual model to provide an acceptable level of agreement for the domain of intended application" [4], [5]. In other words, does the conceptual model reflect reality?

Once the conceptual models have been qualified, these models are implemented in appropriate software codes. Each software model code must correctly implement its conceptual model; this must be verified. When reviewing the quality of the computer models, for correct implementation of the conceptual models, the models are *verified*, meaning: "Substantiation that a computerised model represents a conceptual model within the specified limits of accuracy" [4], [5]. In other words, is the conceptual model correctly implemented?

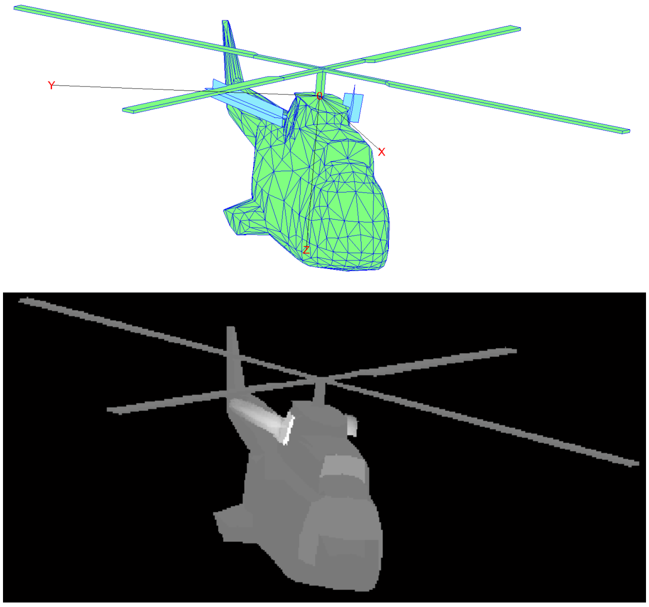

Fig. 4. Helicopter geometrical model and simulated thermogram (image values highly compressed)

The various computer models are combined into a larger simulation environment that allows the computation of the behaviour of the full system. At this level, it is required to consider the overall quality of the computer model for its (final) intended application. The models as implemented in code are *validated* meaning "Substantiation that a computerised model within its domain of applicability possesses a satisfactory range of accuracy consistent with the intended application of the model" [4], [5]. In other words, does the simulation model reflect reality?

C. Synthesis

The solution to the infrared missile threat can take many forms, ranging from hard-kill to soft-kill. Hard-kill options include kinetic projectiles or strong laser beams that destroy the missile seeker. Hard-kill options are not considered here. Soft-kill options attempt to decoy or confuse the missile, so as not to hit the aircraft. Soft-kill options include intense flashing lamps (effective only against older missiles), high intensity pyrotechnic flares (effective only against older missiles), towed decoys (not commonly used), spectrally adapted pyrotechnic or pyrophoric flares and low power lasers. Pyrotechnic flares are still the mainstay of current threat countermeasures, with pyrophoric flares and directed infrared (laser) countermeasures (DIRCM) relative newcomers.

The effectiveness of a proposed decoy must be evaluated prior to full scale production. Ideally, the effectiveness should be evaluated prior to any materiel development. A validated simulation can be used to evaluate the effectiveness of a proposed solution in an easy and cost-effective manner. Design changes merely require changes to a software model or parameter. Repeated simulation runs can then be used to optimise the proposed solution.

The challenge is to find a solution that will be effective against any type of missile. When considering a flare-based solution, one approach is to dispense a 'cocktail' of flares of different types, and with a special time sequencing between the flares. The specification of this cocktail must be optimised by careful design and evaluation. When considering a DIRCM, the design parameters for the DIRCM, as well as the jamming codes, must be obtained by a similar process.

The approach taken by the CSIR is to implement the proposed solution in a software model with the freedom to easily change the design parameters. Extensive Monte Carlo evaluation is then used to test the effectiveness of a particular design, and then optimising it further.

D. Implementation

After design and optimisation the solution can be implemented in hardware: flares can be manufactured to meet the required operational specifications, a DIRCM can be manufactured or the jamming codes can be entered into an existing DIRCM. After this step the materiel is ready for field trial under operational deployment conditions.

E. Deployment

The proposed countermeasure is deployed for evaluation under real-world conditions; as close to the final deployment as possible. From the set of all possible deployments, a subset is selected for field trial evaluation. Clearly, is it not safe to fire real missiles at own aircraft!

The purpose with these trials is to determine if the system behaves as expected for the selected trials. On the assumption that the simulation models are validated, and the selected set of field trial test points were successful, it is reasonable to expect the solution to be valid over all deployment scenarios.

IV. SIMULATION MODEL VALIDATION

The model generally used for verification and validation, as formally defined by the Society for Modelling and Simulation International (SCS) [4] and expanded by [5], [6], recognises three distinct elements of the item under investigation: (1) the physical reality, (2) the conceptual model and (3) the simulation implementation. Fig. 5 shows the relationships between the three elements. The very important definitions for qualification, verification and validation (QVV) is given in Section III-B.

The definitions given in [4] imply that the computer model consists of both data and executable code. The model discussed in [5] sensitises the role and value of data by stressing data validity throughout the process. Extending the SCS definition, [7] adds a new element, that of the accuracy and validity of computer model setup, referred to as the 'scenario description quality' here. While the extension may be small, a new awareness for set-up and calibration of a simulation is established. Knepell [6] points out that the process by which the model is created must also be considered in the QVV analysis.

Extending on [4] and [7], the scenario description quality is now applied to all three processes: (1) quality of scenario understanding during characterisation, (2) quality of conceptual model across all scenarios (extendability beyond measured inputs) and (3) quality of computer model building and data describing the simulation scenario set-up. It is important to trace the validity of transfer between the three models, but just as important to ensure the scenario description quality when constructing these models.

When performing missile exploitation or infrared measurements, it is important that the data gathered must be 'true', calibrated and correctly interpreted. When building the conceptual model, the model should reflect physical reality as closely as possible, even when extrapolated beyond measured data sets. The computer model must be set up correctly against calibrated input scenarios; and the scenarios must be understood and set up correctly.

Verification and validation of simulation models are not easy; Oreskes even deems this impossible [8]. Most would agree that validation and verification become increasingly difficult with increasing dimensionality of the problem space. Verification and validation are generally done by a combination of objective (statistical or mathematical procedures) and subjective evaluations. A number of tests are described in [5], [9], [10]. Techniques for validation and verification of infrared models are described in [11].

The QVV model departs from the perspective that the validity is not known and must be determined. Knepell [6] points out that there normally are *known* minor or major problem areas. In such areas it is already determined that the simulation carries risk. For the purpose of this paper, both minor and major problems are considered together as one set.

V. SIMULATION FITNESS FOR USE

The availability of a computer model in a simulation does not automatically declare it fit for use. The simulation coverage of the intended operational domain can be depicted as shown in Fig. 6 and Table I in mathematical set notation. The set $\mathcal{O}$ denotes the full operational (real-world) application domain of the system. The set ($\mathcal{C}$ denotes the subset of the domain that has been characterised. The set $\mathcal{Q}$ denotes the subset of the domain where the models have been qualified. The set $\mathcal{E}$ denotes the subset of the domain where the models have been verified. The set $\mathcal{A}$ denotes the subset of the domain where the models have been validated. The set $\mathcal{Z}$ denotes the subset of the domain where the models have known minor or major problems.

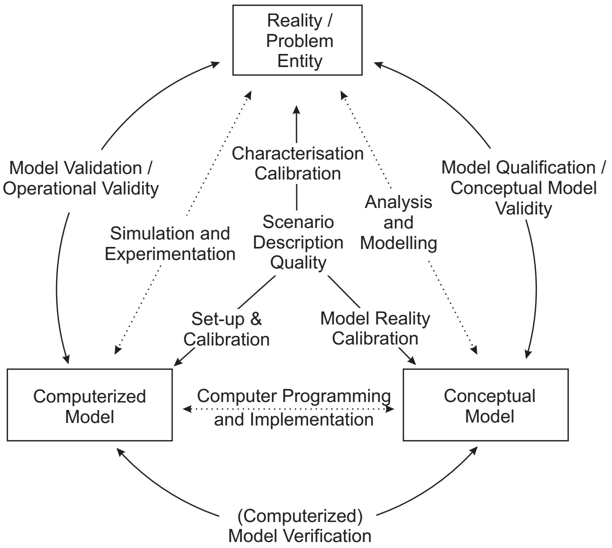

Fig. 5. Extended version of the verification and validation process, covering the physical world, the theoretical model and the computer implementation of the model. [4], [5].

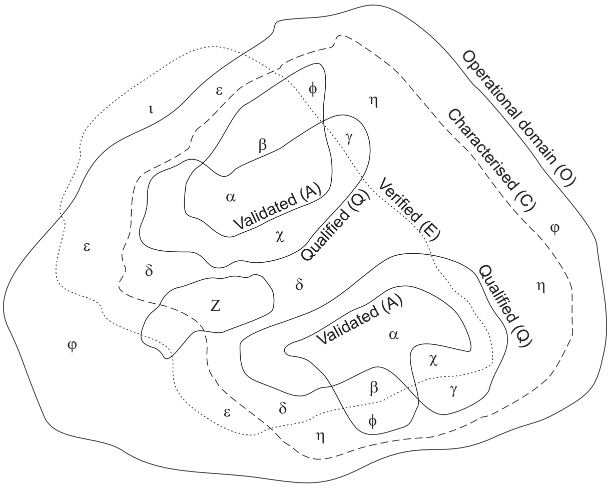

Fig. 6. Simulation verification and validation application analysis

Fully qualified, verified and validated models can only be applied over the domain subset α. In the strictest sense, the simulation models and hence the results are only valid for α. For most real-world systems, α is relatively small compared to $\mathcal{O}$. To what extent is it possible to use the simulation in $(\alpha' \cap \mathcal{O})$?

One way to achieve $(\alpha' \cap \mathcal{O}) \rightarrow \emptyset$ is to characterise, qualify, verify and validate over all of $\mathcal{O}$; ($\mathcal{C} \rightarrow \mathcal{O}$, $\mathcal{Q} \rightarrow \mathcal{O}$, $\mathcal{E} \rightarrow \mathcal{O}$, $\mathcal{A} \rightarrow \mathcal{O}$ and $\mathcal{Z} \rightarrow \emptyset$, but this is expensive and not really practical.

It is unwise to use the simulation models where these have not been verified $(\mathcal{O} \cap \mathcal{E}')$, since the quality of the computer models is not determined. So $(\mathcal{E} \cap \mathcal{Z}')$ is regarded as the outer limit of applicability. However, as shown in Fig. 7, the simulation is only validated in small islands (darker colour in the figure). In order to use the simulation in $(\mathcal{E} \cap \mathcal{Z}' \cap \mathcal{A}')$, the matter of extrapolation arises. If the models in $\mathcal{E}$ can

TABLE I
SIMULATION DOMAIN COVERAGE

Set	Description	Definition	Applicability	Field potential
α	Fully validated	$(\mathcal{C} \cap \mathcal{Q} \cap \mathcal{E} \cap \mathcal{A} \cap \mathcal{Z}')$	High confidence	Very high
β	Not qualified, validated, verified	$(\mathcal{C} \cap \mathcal{Q}' \cap \mathcal{E} \cap \mathcal{A} \cap \mathcal{Z}')$	High confidence	High
χ	Qualified, verified, not validated	$(\mathcal{C} \cap \mathcal{Q} \cap \mathcal{E} \cap \mathcal{A}' \cap \mathcal{Z}')$	Good confidence	Medium high
δ	Not qualified, not validated, verified	$(\mathcal{C} \cap \mathcal{Q}' \cup \mathcal{A}' \cap \mathcal{E} \cap \mathcal{Z}')$	Acceptable if good model	Medium
ε	Not characterised, not validated, verified	$(\mathcal{C}' \cap \mathcal{A}' \cap \mathcal{E} \cap \mathcal{Z}')$	Acceptable if good model	Medium
ϕ	Not qualified, validated, not verified	$(\mathcal{Q}' \cap \mathcal{E}' \cap \mathcal{A} \cap \mathcal{Z}')$	Risky, not verified	Low
γ	Qualified, not verified, not validated	$(\mathcal{Q} \cap \mathcal{E}' \cap \mathcal{A}' \cap \mathcal{Z}')$	Risky, not verified	Low
η	Characterised, not qualified, not verified, not validated	$(\mathcal{C} \cap \mathcal{Q}' \cap \mathcal{E}' \cap \mathcal{A}' \cap \mathcal{Z}')$	Questionable, don't use	Very low
ι	Outside domain, verified	$(\mathcal{O}' \cap \mathcal{E} \cap \mathcal{A}' \cap \mathcal{Z}')$	Irrelevant	Zero
φ	In domain, not verified, not validated	$(\mathcal{O} \cap \mathcal{E}' \cap \mathcal{A}' \cap \mathcal{Z}')$	Risky, not verified	Low
$\mathcal{Z}$	Known problems area	$(\mathcal{Z})$	Problem area, don't use	Negative

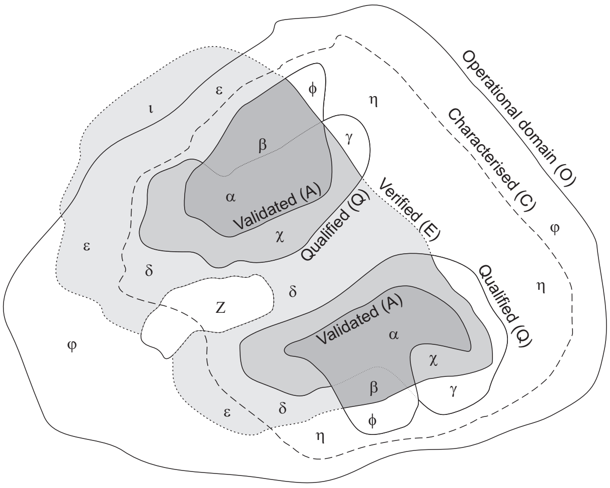

Fig. 7. Verified and partly validated potential field

be extrapolated beyond $\mathcal{A}$, then the simulation can be used beyond $\mathcal{A}$, at least as far as the validity of the extrapolation.

The validity of extrapolation depends on the type of conceptual model employed. If the model is physics based (e.g. Newton's second law) or can perform its function according to a mathematical formulation (e.g. a validly executable Laplace transfer function) then it may be extrapolated — at least as far as it has been verified. The important issue is that valid extrapolation must be demonstrated. If the model is an empirical lookup table, its range of use is limited to the range of the table, with little or no valid extrapolation.

Non-linearity in real-world processes increases the risk of erroneous modelling. A complicated[4] non-linear problem can be partially addressed by increasing the level of detail in models and by modelling the lower level non-linearity in mathematical terms. Level of detail has to be to down to the level where the models can be validated. If modelled at sufficiently low level, such models can be extrapolated.

Some processes, e.g. complex decision-making in humans or digital processes, contain some measure of unpredictability (sometimes referred to as 'non-linear' behaviour). These systems remain very difficult to model, validate and extrapolate. Simplifications have to be made, but such simplifications introduce risk and force only small islands of validation. with poor extrapolation in-between.

Modelling the effect of chaotic processes, e.g. turbulent air flow or the emergent behaviour of a complex system[5], presents a particularly tough challenge. Such models typically include stochastic elements with behaviour that approximates the real-world process in probabilistic terms. The matter of extrapolation then requires consistency in random behaviour.

In any modelling process, there is always the risk that an important real-world phenomenon that will affect extrapolation is not recognised, characterised and modelled. This challenge remains.

The first criterion for validity of extrapolation is already hidden in the formulation above: extrapolation is at least valid over $\mathcal{Q}$, since the conceptual model is qualified and verified (just not validated). The model might be valid beyond $\mathcal{Q}$ as well, but not provably so from the information in $\mathcal{Q}$.

It is reasonable to consider the application domain of a simulation in the form of a potential field. This field has its highest values in the validated regions $\mathcal{A}$, possibly dropping to the limits of qualification $\mathcal{Q}$ and dropping off further towards the boundary of $\mathcal{E}$, beyond which it is zero. The potential field in known problem areas $\mathcal{Z}$, will be low, zero or even negative! The potential field can also be considered as an 'envelope of certainty' where the certainty is highest in the validated regions $\mathcal{A}$, dropping to lower certainty towards the boundary of $\mathcal{E}$ or over problem areas $\mathcal{Z}$.

It is well nigh impossible to actually calculate the confidence of a simulation as a single number; other formats may be more effective (e.g. see [11]). It is however possible to provide guidelines for improving the confidence. Given the model of the potential field, it follows that the best way to achieve high potential for validity over $\mathcal{O}$ is to (1) have an even distribution of $\mathcal{A}$ islands across $\mathcal{O}$ (ideally covering critical points), (2) employ models with reliable extrapolation between $\mathcal{A}$ islands and (3) test for model extrapolation quality between $\mathcal{A}$ islands.

How are the "critical points" identified where validation is performed? Several criteria can be employed: (1) scenarios of most probable use, (2) scenarios of expected divergent or unstable behaviour, (3) scenarios with safety or cost driver implications, (4) scenarios of risk as identified by exhaustive

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[4] A complicated problem is defined as a problem with many interacting sub-elements, such that the higher level behaviour can be predicted from the behaviour of the sub-elements.

[5] A complex system is a system comprising interacting elements, where the behaviour of the system cannot be predicted from the behaviour of the individual elements.

Monte Carlo simulation and (5) scenarios identified by stakeholders. In the final analysis, the selection of scenarios must be tempered by non-technical considerations such as practicality and cost of execution.

Since the extensive testing required to characterise many $\mathcal{A}$ islands is expensive, model extrapolation becomes an important means to improve confidence in the simulation. Extrapolation is most accurate when conceptual and computer models reflect the underlying physics of the real world process.

VI. SIMULATION CONFIDENCE ASSESSMENT

In [11] the validation of infrared models were discussed. It was proposed that the area inside a 'radar plot' can be used as a simple graphical means to portray simulation confidence as shown in Fig. 8.

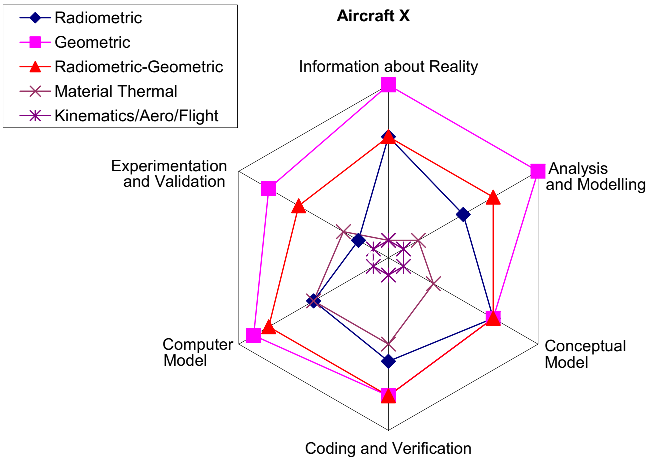

Fig. 8. Simulation confidence radar plot (arbitrary scale) [11]

The approach in [11] failed to provide norms, hence subjectivity can affect confidence assessment. It is proposed here that the 'potential field' described above be used as a norm. In this objective norm, a fully validated model scores the maximum value of 1. Lesser potentials scores between 0 and 1, depending on the potential. An example of such normative assessment is shown in Fig. 9. The QVV criteria norm provides a relatively easily testable and objective means to assess simulation confidence.

The continual cycle of characterisation and evaluation shown in Fig. 2 provides an opportunity to improve the quality of the models and hence the confidence of the simulation.

VII. CONCLUSION

The development of missile countermeasure systems requires careful evaluation of countermeasure effectiveness and aircraft safety. Modern missile systems require complex countermeasure responses that can only be cost-effectively evaluated and optimised in simulation systems.

The applicability of a simulation system was shown to have high confidence only in subsets of the application domain where the simulation was validated against real-world scenarios. Such scenarios are expensive or unsafe to evaluate in the case of missile threats. It was shown that with careful model design, supporting the ability to extrapolate, the number of validity test points can be minimised.

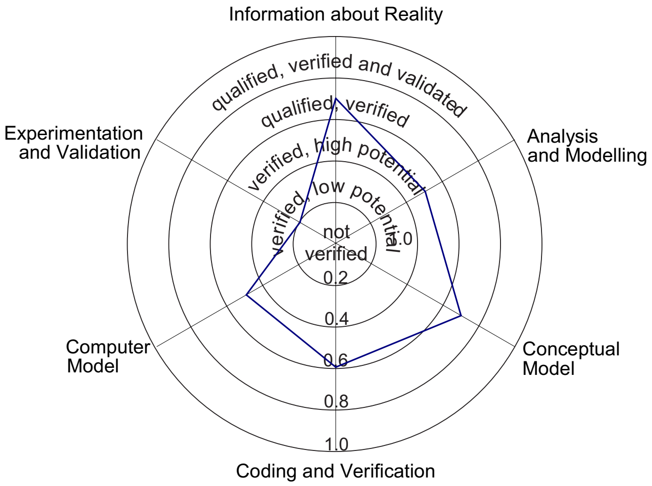

Fig. 9. Simulation confidence scaled to validation and verification criteria

Simulation remains a key element, in conjunction with field trials, to evaluate countermeasure effectiveness. The confidence in such a simulation can be determined in objective terms by employing a QVV normative measure.

ACKNOWLEDGMENT

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