Application of Image Simulation in Weapon System Development

Cornelius J Willers[†], and Maria S Wheeler[‡]
Council for Scientific and Industrial Research (CSIR) & Denel Dynamics, South Africa

***Abstract*—The development of sophisticated electro-optical equipment requires radiometrically calibrated imaging scene simulators in order to evaluate and optimise system performance under diverse environmental conditions. A brief overview of a working simulation system is presented, highlighting the issues relevant to physics-based radiometry, signature measurement, signature modelling and software implementation. The article briefly describes the application of the simulation in the development of various weapon systems; including sensor development, image processing algorithm development and knowledge management. The simulator environment has proved invaluable in the development and evaluation of complex optronics weapon systems.**

***Index Terms*—image simulation, scene modelling, weapon evaluation, infrared**

I. INTRODUCTION

Simulation is used increasingly to support military system development throughout all the product life cycle phases, from concept analysis, development and doctrine development. The advent of imaging weapon systems presented the need for simulation providing accurate image rendering in the optical spectral ranges [1]. Physics-based infrared scene simulators are used in the development, evaluation and optimisation of electro-optical systems, such as infrared missile seekers and thermal imagers.

The objective is to create computer synthetic images of arbitrary complex scenes in the visual and infrared (IR) bands, covering the 0.35 to 20 μm spectral region. These images must be radiometrically accurate, based on theoretical physics models.

These simulations are required to model the effect of diverse environmental conditions, such as adverse atmospheres, varying altitudes and different types of terrain scenes and backgrounds. It is particularly important to account for atmospheric effects on the operation of optical systems.

The simulation described here is used over a wide spectrum of applications from scenario analysis and theoretical concept studies, to supporting infrared measurements and signature modelling, finding application in imaging system algorithm development, performance prediction, hardware development and support for flight tests.

The key focus areas for the simulation are: (1) radiometric accuracy using physics-based, spectral radiometric floating point image calculation, (2) accurate target signatures including self-emitted flux and reflected sunlight, ambient and sky radiance, (3) accurate atmospheric spectral transmittance and background modelling and (4) accurate weapon models (camera, signal processing, gimbals, missile aerodynamics and flight behaviour).

This paper presents a brief description of a simulation system used extensively in imaging weapon system development, testing and evaluation.

II. PHYSICS-BASED IMAGE SIMULATION

A. Geometric Modelling

The geometrical shape, of objects and the terrain topography, is described in terms of a complex hull, consisting of polygons (Fig. 1). Each polygon is assigned radiometric properties for the different wavelength regions in the simulation.

Some object polygons are rendered with texture, enabling the modelling of spatial variations on the object's surface. Polygons can also be partially transparent to represent gas clouds. Most importantly, each polygon's radiometric properties can be spectrally varying, supporting the modelling of gaseous radiators, such as plumes.

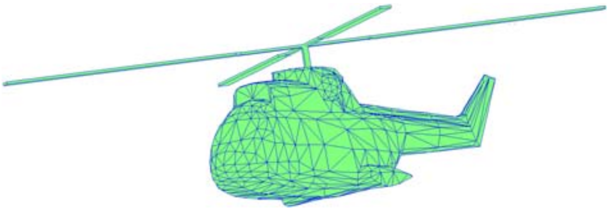

Fig. 1. Geometrical wireframe model forming the basis for simulation models.

B. Radiometric Modelling

All objects in the world are modelled in terms of emitted, reflected and transmitted energy (Fig. 2). The emitted radiance of objects is determined by the objects inherent temperature and surface emissivity. The sun radiance, sky radiance and ambient background radiance are reflected from objects in the scene. Objects in the scene can also be partially transparent (e.g. a gas plume) allowing the transmittance of background radiance. These radiance components are all attenuated by the atmosphere between the sensor and the radiance source. The emitted radiance of the atmospheric path between the sensor and the scene is added to the total radiance. As demonstrated

---

[†] CJ Willers, Defence Peace, Safety and Security (DPSS), Council for Scientific and Industrial Research (CSIR), PO Box 395, 0001 Pretoria, South Africa, nwillers@csir.co.za.

[‡] MS Wheeler, Denel Dynamics, PO Box 7412, 0046 Centurion, South Africa, riana.wheeler@deneldynamics.co.za.

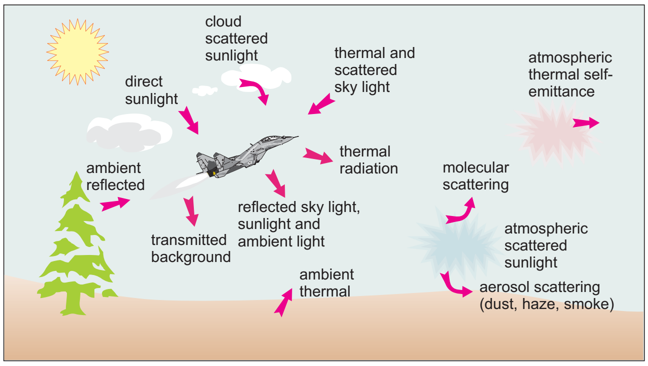

Fig. 2. Main contributors to the radiometric signature in the simulation.

in Fig. 3, both reflected sunlight and thermal self emission are required to accurately model object signatures in all the optical spectral bands. The main contributors [2] to signature radiance from an arbitrary surface in open sunshine are shown in (1), where the terms are defined in Table I.

$$
\begin{aligned}
L_{\Delta\lambda} \;=\; & \overbrace{\int_\lambda L_p \mathcal{S} d\lambda}^{\text{atmospheric path radiance}} + \overbrace{\int_\lambda L_{bb}(T_o)\epsilon_o\tau_a \mathcal{S} d\lambda}^{\text{thermally emitted}} \\
& \overbrace{\int_\lambda L_{bb}(T_b)\tau_o\epsilon_b\tau_{abo}\tau_a \mathcal{S} d\lambda}^{\text{transmitted background}} \\
& + \overbrace{\int_\lambda L_{bb}(T_a)\rho_o\epsilon_a\tau_{ao}\tau_a \mathcal{S} d\lambda}^{\text{reflected thermal ambient}} \\
& \overbrace{+\alpha_s\cos\theta_s\int_\lambda L_{bb}(5900K)\rho_o\epsilon_s\tau_s\tau_a \mathcal{S} d\lambda}^{\text{reflected sunshine}} \\
& \overbrace{+\cos\theta_a\int_\lambda L_{\text{sky}}\rho_o\epsilon_h\tau_a \mathcal{S} d\lambda}^{\text{reflected sky ambient}} \qquad (1)
\end{aligned}
$$

TABLE I
TERMINOLOGY DEFINITION FOR OBJECT SIGNATURE EQUATION (1)

Symbol	Meaning
$\alpha_s L_{bb}(5900K)$	approximation of reflected solar radiance
ϵ_a	the ambient environment's spectral emissivity
ϵ_b	the background spectral emissivity
ϵ_h	sky radiance spectral emissivity
ϵ_o	object surface spectral emissivity
ϵ_s	solar surface's spectral emissivity
$L_{bb}(T_a)$	black body radiance, environment at temperature T_a
$L_{bb}(T_b)$	black body radiance, background at temperature T_b
$L_{bb}(T_o)$	black body radiance, object at temperature T_o
L_p	atmospheric path radiance: emitted plus scattered
L_{sky}	sky radiance: emitted plus scattered
ρ_o	object surface spectral reflectance
$\mathcal{S}$	camera spectral response
τ_a	object to sensor spectral atmospheric transmittance
τ_{abo}	background to object atmospheric transmittance
τ_{ao}	ambient to object spectral atmospheric transmittance
τ_o	object surface spectral transmittance
τ_{so}	sun to object spectral atmospheric transmittance
θ_a	angle between the surface normal and the vertical
θ_s	angle between the surface normal and solar incidence

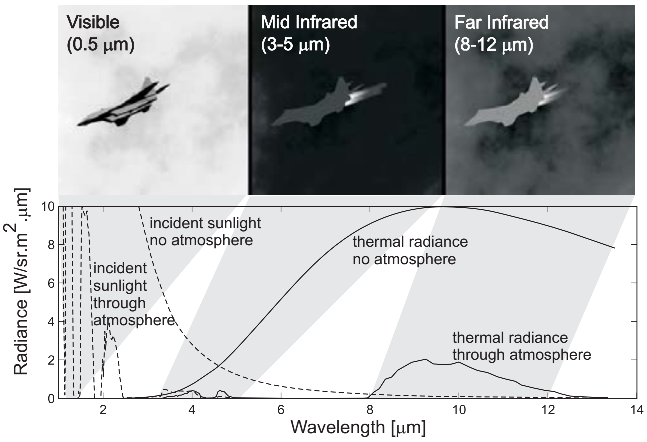

Fig. 3. Optical signature in several spectral bands: the solid line is self-emittance and the broken line is reflected sunlight. The target has 80% emissivity. The images show rendering of an object in three different bands.

Objects with spectrally varying radiance, such as illustrated in Fig. 4, require that calculations account for the spectral variations *within* a spectral band. It is also important that atmospheric transmittance be considered as a spectral variable within a band. The integrals in (1) indicate spectral calculations.

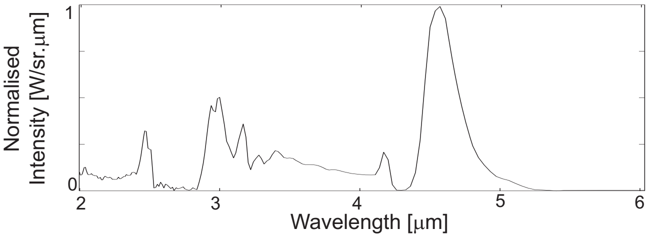

Fig. 4. Normalised spectral radiant intensity of a gaseous radiator.

C. Thermal Modelling

1) Thermodynamic Modelling: Object thermodynamic behaviour is modelled with a heat balance equation [3], accounting for the net energy flow from absorbed energy (Q_a), radiated energy (Q_t), convection (Q_k), evaporation (Q_v) and conduction from internal heat sources (Q_d). Incoming flux flow is positive and flux leaving the surface is negative. Then

$$Q_a + Q_t + Q_k + Q_v + Q_d = Q_{net} \rightarrow 0 \qquad (2)$$

is the residual flux, approaching zero. In this model, the object's surface radiative temperature (T_o) adjusts, minimising the net residual flux.

The use of the heat balance equation (2) in conjunction with the thermal material properties, enables the simulation to calculate objects' radiative temperature (T_o) at any time of the day. Fig. 5 shows measured temperatures for grass, glass and sheet metal, during a 24-hour diurnal cycle. Note how the object temperatures increase and decrease with time of day, as affected by the net energy flow (solar influx, radiated heat loss, etc.). If two objects have the same radiance signature,

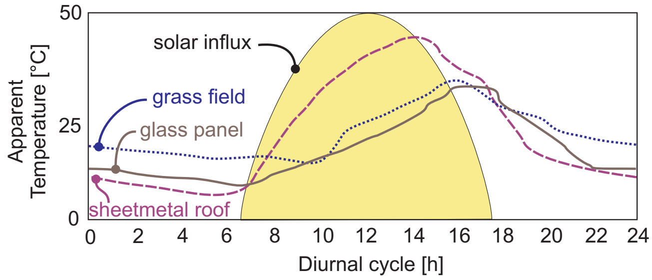

Fig. 5. Diurnal temperature variation of terrain objects, demonstrating thermal crossover.

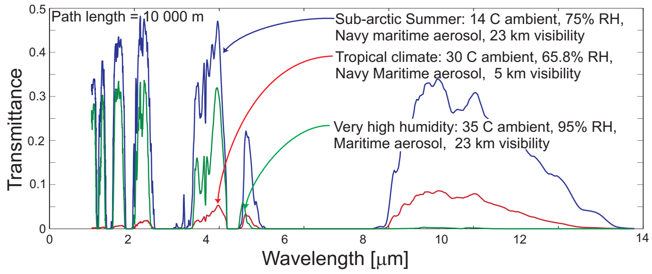

Fig. 6. Atmospheric transmittance at sea level, calculated with MODTRAN.

thermal crossover occurs — under these conditions the contrast between the two objects disappears.

2) Internal Heat Source Modelling: In addition to diurnal temperature variations, objects' thermal properties are further affected by internal and external heat sources. Internal heat sources include vehicle engines, heated buildings and similar objects.

3) Aerodynamic Modelling: Flying objects' skin temperature is affected by aerodynamic heating, using the well known stagnation temperature equation

$$T_{\text{aero}} = T_{\text{amb}} \left(1 + r\frac{\gamma - 1}{2} M^2\right) \tag{3}$$

where T_{amb} is the ambient air temperature in [K], r is the recovery factor, $\gamma = 1.4$ for air, and M is the mach number.

D. Atmospheric Modelling

Atmospheric conditions have a significant effect on the radiometric presentation of an object's signature. To allow for the subtleties and full scope of variability in atmospheric attenuation, the simulation employs all capabilities of the MODTRAN [4] code. This design choice provides all facilities of MODTRAN to the simulation user — a considerably powerful enabler for the modelling of arbitrary scenarios.

MODTRAN is a state-of-the-art computer code that calculates atmospheric transmittance and path radiance for frequencies from 0 to 50,000 cm^{-1} at moderate spectral resolution. MODTRAN defines six internal standard atmospheric models, but allows the user to define new atmospheric conditions. The simulation sets up MODTRAN with information such as path geometry, aerosol conditions (fog, particulate matter), visibility, radiosonde profiles, solar and lunar locations. After completion of the run, the simulation incorporates the MODTRAN results in its internal spectral radiometric calculations. Fig. 6 shows a sample spectral atmospheric transmittance curve, adjusted to low spectral resolution for the plot.

III. MODEL BUILDING

The simulation must be supported by a strong theoretical base and a signature measurement programme in order to ensure accurate radiometry. Initially, theoretical models are developed to gain a basic understanding. The measurement programme provides additional information to complement, validate and improve the theoretical models. The signature modelling cycle is shown in Fig. 7: theoretical modelling, field measurements, data reduction, model building and model validation. The scope of validity of the model is continually improved by repeating this measurements and modelling cycle.

The field of signature model building is a highly specialised science, requiring expensive equipment, expensive field trials and highly trained personnel. Measurements are typically performed with calibrated imaging and spectral radiometers. Imaging radiometers provide spatial information such as texture (local variations) and shape of the object. Spectral radiometers provide spectral information, such as emissivity and atmospheric transmittance — particularly important for gaseous radiators.

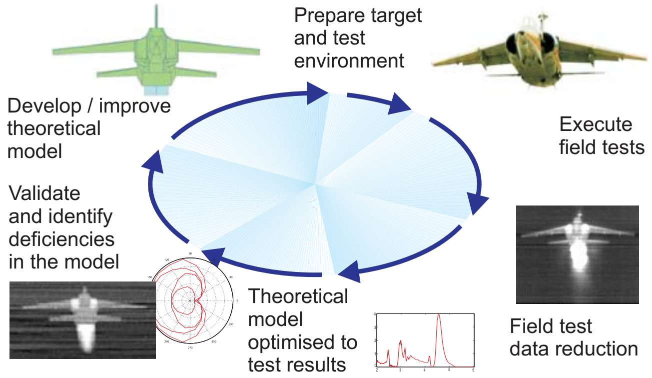

Fig. 7. The signature modelling and development cycle.

IV. SOFTWARE IMPLEMENTATION

The simulation is written in the C++ object oriented language, resulting in a modular and extendable software code base. The architecture provides a strong decoupling between 'user code' and simulation library code. Strict software engineering discipline is applied to ensure low life cycle cost and long term maintainability. Fig. 8 shows four main groups of software functions: physics calculators, scene objects, the scene graph and renderers.

The current renderer provides physics-based, high radiometric accuracy, albeit at non-realtime execution speeds. The physics calculators perform specialist tasks such as atmospheric transmittance calculations (MODTRAN), radiometry calculations, kinematics calculations and object temperature calculations.

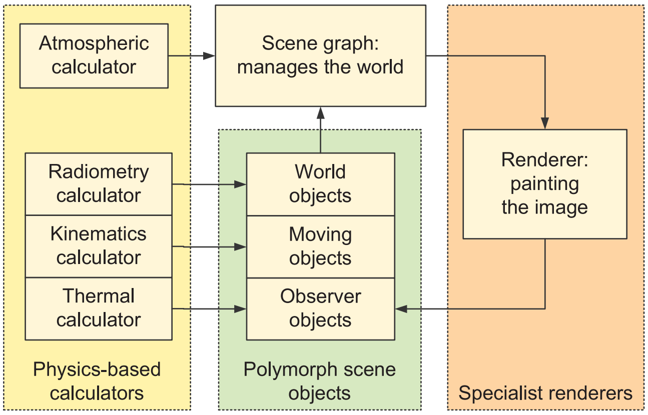

Fig. 8. Primary software functions in the simulation.

Objects in the scene all fit in a class hierarchy of increasingly more specialised objects. The base class is ’World Objects’ which represent all objects in the world. Some objects have the additional property of movement (’Moving Objects’), while some objects have more specialised properties of observation (’Observer Objects’). This hierarchy ensures that all objects are visible in the world, and hence that all observer objects can observe any and all other objects in the world. The simulation supports an arbitrary number of observers. For example, an optical missile warning sensor and an approaching missile can observe each other throughout the engagement.

V. SIMULATION VALIDATION

The simulation models provide the link between the real world and the simulation and must therefore be validated prior to use.

The model generally used for verification and validation, as formally defined by the Society for Modelling and Simulation International (SCS) [5], recognises three distinct elements of the item under investigation: (1) the physical reality, (2) the conceptual model and (3) the simulation implementation. Fig. 9 shows the relationships between the three elements.

The infrared simulation verification and validation are done by a combination of objective (statistical or mathematical procedures) and subjective evaluations [6]. These include (1) animation and operational graphics, (2) comparison with other models, (3) degenerative stress testing, (4) extreme condition testing, (5) expert opinion and Turing tests[1], (6) regression testing, (7) comparison with historical evidence, (8) confirming internal consistency, (9) analysing parameter sensitivity, (10) validating of predictions versus reality. Ideally, every model characteristic should be validated with a number of orthogonal and independent tests.

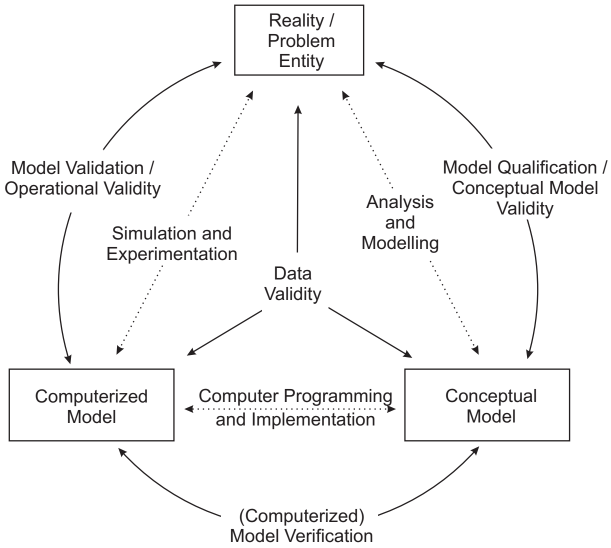

Fig. 9. Simplified Version of the Verification and Validation Process [5], [6].

VI. APPLICATIONS

The simulation has been applied in a number of diverse applications, for sensors operating in various infrared spectral bands. In these applications the simulation was used in different modes: (1) creation of single frame static images, (2) creation of image sequences and (3) closed loop simulation of missile flights. In the closed loop mode, the moving objects are implemented in six-degree-of-freedom (6-dof) flight and aerodynamic models of arbitrary complexity.

A. Thermal Imager Development

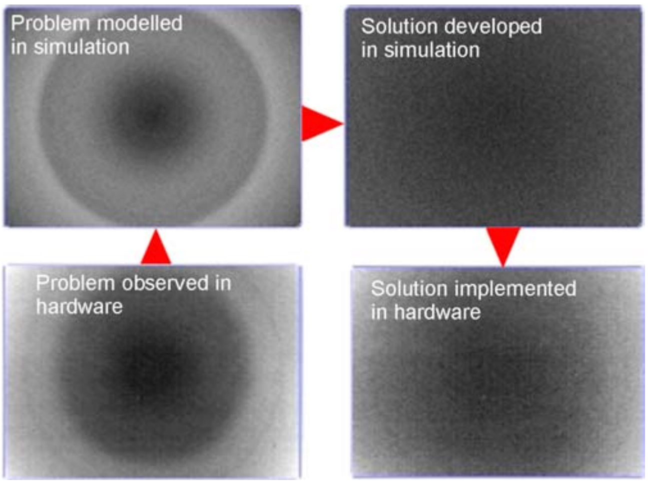

Fig. 10. Solving a narcissism problem in simulation.

The simulation is used in sensor optimisation and embedded software algorithm development. In one case, a thermal imager was troubled by narcissism: the cold detector is re-imaged onto itself after a minuscule reflection from an optical surface. The optimal solution is to redesign the optics. In this case, optical

---

[1] The Turing test was originally defined to test whether a non-interactive human operator can distinguish between a computer performing a task versus a human performing the same task. We extend that notion to the test as to whether a user or other application can discriminate between the output of the simulation and reality.

redesign was not an option and the effect had to be removed by image processing. The bottom left image in Fig. 10 shows the image observed in the imager. A model of this specific narcissism effect was built in the simulation, yielding the top left image. A correction algorithm was developed in simulation, resulting in the top right image. The solution developed in the simulation was then implemented in the imager embedded software, yielding the image in the bottom right. It is evident that not all narcissism is removed, but its effect is much reduced, especially under adverse environmental conditions.

B. *Reticle Seeker Development*

For a reticle-based missile seeker, the design of the reticle pattern, its associated signal processing and tracking loop, were conceptualised, developed and optimised using the imaging simulation. The sensor model forms an image of the scene and spins the reticle across the image, thereby creating the reticle signal, as shown in Fig. 11. The image in the top left shows the original simulation image. The image on the top right shows the reticle spinning across the image. Several different reticle designs were evaluated and the signal processing optimised for the finally selected reticle.

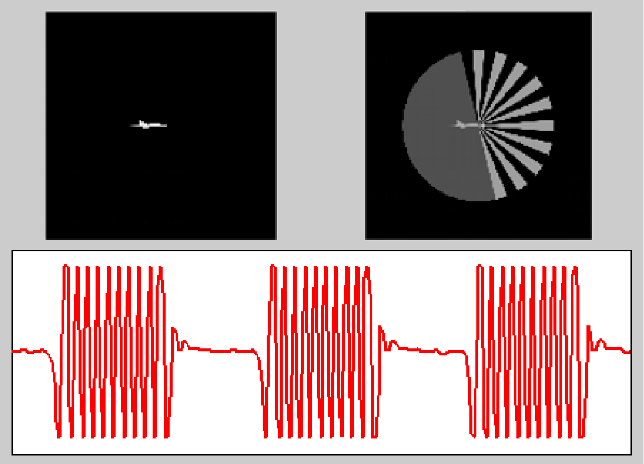

Fig. 11. Reticle design and optimisation. The reticle shown here is only for illustrative purposes, it is not the final design!.

C. *Image Processing Algorithm Development*

The most comprehensive application of the simulation was in the development of image processing and tracking algorithms for an imaging air-to-air missile. A very comprehensive sensor model was built, accounting for all known artefacts in the image. This sensor model was used to create images that closely represent the actual hardware sensor images. The target detection, tracking and countermeasure algorithms were developed in a closed loop 6-dof simulation, where thousands of missile flights were simulated. The algorithms were evaluated under widely varied scenarios, background clutter conditions, flight conditions and target manoeuvres.

Subsequent flight testing, against real-world targets indicated that the algorithms performed as expected from simulation experience. The algorithm developers expressed surprise at the high degree of repeatability of algorithm behaviour from simulation evaluation to flight test evaluation — thereby satisfying the Turing test, described earlier.

The left hand image in Fig. 12 shows one frame from a closed loop tracking test, where the target flies against a cloud background. The right hand side shows the detection and handling of false detections in the image, during the target track.

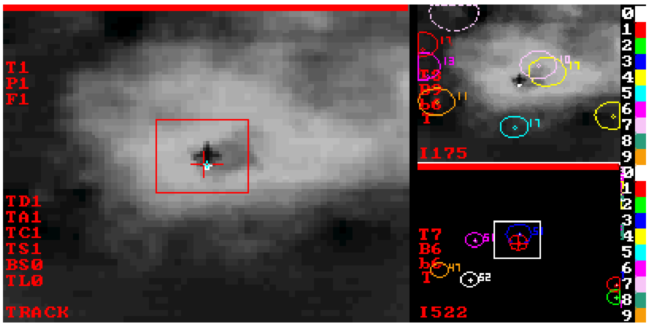

Fig. 12. Image processing and target tracking algorithm development.

D. *Development of Automatic Target Recognition Algorithms*

The image simulation is also used in the development of non-cooperative Automatic Target Recognition (ATR) algorithms for stand-off weapons. These weapon systems focus specifically on high value ground targets such as runways and buildings. Image simulation provided the development environment for the algorithm development, testing and evaluation, as well as flight test preparation.

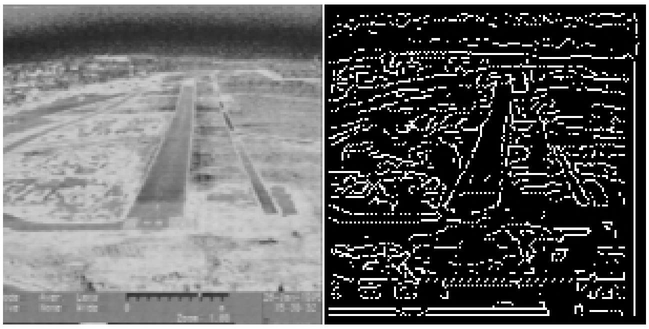

Fig. 13. Development of ground target automatic target recognition algorithms.

E. *Electronic Warfare Countermeasure Development*

The simulation is used extensively in the development of Electronic Warfare (EW) aircraft protection measures. The effects of flare spectral emittance, intensity and flare sequence timings are evaluated by Monte Carlo techniques; simulating thousands of missile firings, throughout missile missile attack envelope. An example result is shown on the right-hand side of Fig. 14. In this graph the red areas indicate aircraft vulnerability zones. In preparation for countermeasure effectiveness field trials, the intended test points are run in the simulation to verify test set-ups and predict outcomes.

F. *Thermal Camouflage and Signature Management*

The simulation is not yet used in the development of thermal camouflage and signature management techniques, but this is an intended application area. Models of the equipment are constructed and the effect of various camouflage and signature management techniques can be evaluated.

G. *Surveillance Evaluation*

The simulation is not yet used in the prediction of detection, recognition and identification (DRI) ranges, but it is an intended application area. The DRI range predictions were traditionally done using the Johnson criteria. The new NVESD model requires that images and image sequences be used in a new technique, called the Targeting Task Performance (TTP) metric [7]. The simulation can be used to create images of carefully modelled objects in cluttered surroundings, for use in TTP DRI range prediction.

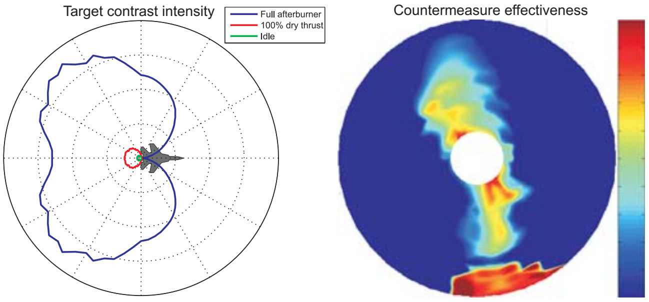

Fig. 14. Performance prediction examples: polar target intensity plot and countermeasure effectiveness evaluation (unrelated graphs).

H. *Performance Prediction*

The image simulation is used on various projects for performance prediction. In this application, the seeker is modelled in very high detail in order to predict detection range, countermeasure performance and to assist in flight test preparation. Fig. 14 shows two unrelated applications of performance prediction. The left-hand side plot shows the intensity of a target in the mid-IR band, while the right-hand side plot shows countermeasure effectiveness prediction.

I. *Flight Test Preparation*

Prior to stand-off weapon ATR evaluation flight tests, the algorithms were evaluated and test points optimised in simulation. Image sequences were generated for all the planned flights, covering various atmospheric conditions as well as time of day or night. After a very successful flight test, feedback from the developers were very positive – the simulations were remarkably similar to what were recorded in flight with the thermal imager.

The simulation was also used extensively for flight test preparation for a number of infrared missile products and countermeasure effectiveness evaluations. In all cases did the simulation contribute significantly to flight test optimisation and risk reduction.

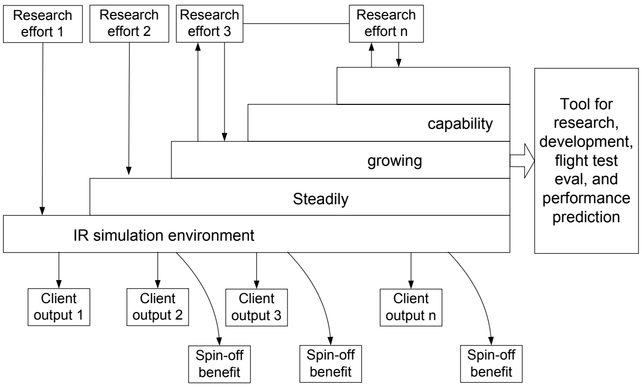

Fig. 15. Simulation as knowledge management tool.

VII. SIMULATION AS KNOWLEDGE MANAGEMENT TOOL

Through the years, the simulation environment has proved to be an excellent knowledge management tool. The knowledge gained through infrared measurements and other related studies are captured in models and data in the image simulation environment. Initially, all work was focussed towards building the core IR simulation environment. In later years, activities were focused towards satisfying the client need at hand, growing the simulation — often providing unexpected spin-off benefits (Fig. 15). Today, the simulation environment is a living repository, serving as a tool for future research and development work.

VIII. CONCLUSION

The scene simulator developed over the past 17 years has proved to be invaluable in the development of advanced optronic systems. The complexities of modern imaging systems necessitate the use of a comprehensive simulation environment where the interplay between sensor, environment and target can be modelled, studied and evaluated. The simulation is the *only* means to evaluate performance for test points that cannot be executed in field trails, due to safety or cost considerations. Extensive use of this simulation, in many projects, has consistently resulted in reduced risk, lower cost, and shorter development time scales. A new version of the simulation is currently under development to meet future challenges.

REFERENCES

[1] *Digital Imaging and Remote Sensing Image Generation (DIRSIG)*, http://dirsig.cis.rit.edu/ [Web site accessed on 2007-07-26].
[2] C. J. Willers, *Electro-Optics Systems Design*, unpublished.
[3] P. A. Jacobs, *Thermal Infrared Characterization of Ground Targets and Backgrounds*, SPIE Tutorial Texts in Optical Engineering, Vol TT26, 1996.
[4] *MODTRAN 4 SOFTWARE*, [Web site accessed on 2007-07-26], http://www.kirtland.af.mil/library/factsheets/factsheet.asp?id=7915.
[5] S. Schlesinger, *et.al.*, *SCS Technical Committee on Model Credibility: Terminology for Model Credibility*, Simulation, Vol. 32, No. 3, pp. 103104, 1979.
[6] R. G. Sargent, *Verification and Validation of Simulation Models*, Proc 1998 Winter Simulation Conference Vol 1, D. J. Medeiros et.al. Ed., pp. 121130, 1998.
[7] R. H. Vollmerhausen & E. Jacobs, *The Targeting Task Performance (TTP) Metric A New Model for Predicting Target Acquisition Performance*, AMSEL-NV-TR-230, NVESD, U.S. Army CERDEC, Fort Belvoir, VA 22060.