AI-Augmented MFR Radar Engineering with DIGITAL TWIN: towards PROACTIVITY

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***Abstract*— New generation Thales digital multi-missions radars, fully-digital and software-defined, like Sea Fire and Ground Fire radars, benefit from a considerable increase of accessible degrees of freedoms to optimally design their operational modes. To effectively leverage these design choices and turn them into additional operational performances, it is necessary to develop new, augmented by artificial intelligence, engineering tools. Innovative optimization algorithms in the discrete and continuous domains, coupled with Radar Digital Twin have allowed to elaborate a generic tool for "search" modes design (beam synthesis, waveform and search Search volume grid) compliant with the available radar time budget. High computation speeds of these algorithms suggest tool application in a "Proactive Radar" configuration, which would dynamically propose to the operator, operational modes better adapted to the environment, the threat and equipment failures.**

Keywords—Artificial Intelligence; Digital Twin

I. NEW GENERATION MFR RADAR, ARTIFICIAL INTELLIGENCE AND DIGITAL TWIN

Antenna digitalization will increasingly enable to design full software-defined radars with more degrees of freedom (scalable front-end, digital beamforming with diverse beam shapes…), enhanced with intelligent resource management and graceful degradation by reconfiguration. Radars will become proactive to achieve missions that are more complex. They will integrate digital assistants to interact with human operators through intuitive multimodal dialogue.

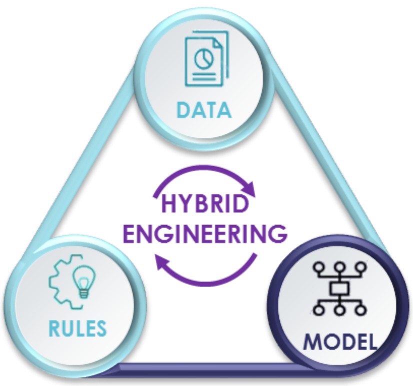

Fig. 1. Hybrid Engineering coupling Data, Rules and Model

Artificial Intelligence (AI) algorithms (optimization, learning, reasoning…) will foster the development of cognitive functions underlying innovative capabilities as self-adaptation, contextual inference and situation understanding. Coordinated in dense networks, radars will be able to optimize their resources in a collaborative way, potentially fully distributed, with advanced "what-if" capabilities to improve their agility and robustness to defeat new threats (hypersonic & hyper-maneuvering missiles, swarm of drones, stealth mobile objects, slow moving targets…). Such AI-based functions will help to improve operational capacity in tactical anticipation.

As a result of radar's full digital transformation, the radar's digital twin will enable to faster prototyping, algorithm design and AI-based augmented engineering. Thales TrUE AI (Transparent, Understandable and Ethical AI) strategy for a trustable and explainable AI will be also implemented in radar systems. Relying on a hybrid AI (combining model-based and data-driven approaches), it aims at paving the way to the design, the development, the validation and the certification of critical systems involving AI technologies.

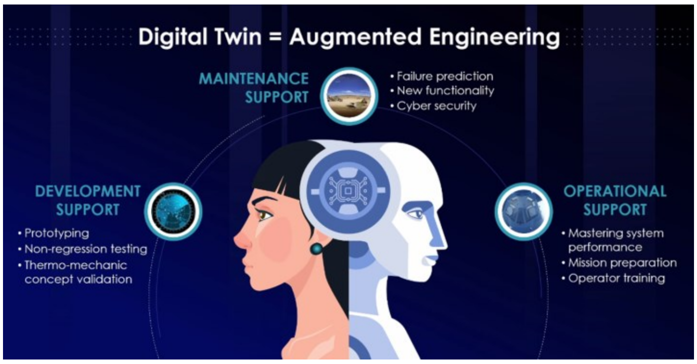

Fig. 2. Digital Twin & Development, Maintenance and Operational Supports

Compare to classical way of simulation, Digital Twin will evolve and will follow the Radar sensor development throughout the product life cycle. Digital twin will be used at the early stage for "Development Support" as prototyping, non-regression testing, hardware design (e.g. thermos-mechanic concept validation). After Radar development, Digital twin will be used for "Maintenance Support" as failure prediction, support for new functionality and cyber security. In operation, Digital twin will be used for "Operational Support" as mastering system performance, mission preparation and operator training.

A. *Artificial Intelligence for Engineering*

Digitalization implies new need of systems optimization. Numerical systems provide new agility capabilities with new degrees of freedom. Main challenge is how to use these new opportunities? Due to combinatorial complexity explosion, the classical engineering approaches fail. Experts need to be assisted, in the design, deployment and monitoring phases with an Augmented Design/Digital Assistant. In this context, Digital twins should be used to speed-up engineering processes to deal with functional, multi-engineering, multi-domains/multi-physics design optimization. At the right level of physic modelling (nor to simplified, nor to complex), coupling the modeling is a key challenge to optimize all engineering phases.

B. *AI- Augmented Engineering with Digital Twin*

Data-driven engineering design under uncertainty is emerging because probes and monitoring equipment are being increasingly employed in engineering applications (IoT/Internet of Things). The data being generated presents enormous opportunities to transform Engineering design, as used of "Surogate Model". This challenge area will address fundamental questions of optimal data collection and design optimization in uncertain environments (e.g. model calibration and tuning).

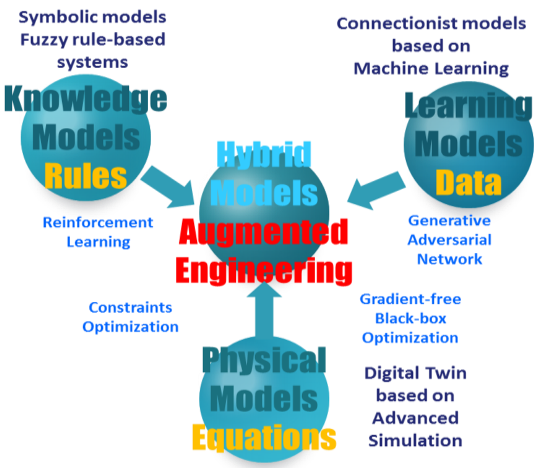

Fig. 3. Augmented Radar Engineering based on Hybrid Model

Model-based Engineering with revolutionize Design approach by intensive use of DIGITAL TWINS coupled with most advance optimization tools Digital twins offer new opportunities, and research is starting to develop new decision-support methods, identifying key connections from design product and process data. It could be also coupled with data in development of new methods to realize the benefit of the digital twin in data-driven design by providing engineering designers with leading indicators, helping them to trace and handle interdependencies and uncertainties in design.

C. *Digital Twin: main objectives and technical challenges*

Sensor design based on Digital Twin will benefit of multidisciplinary design optimization and automation of the design process. Main advantages will be Design time/cost decreasing while quality/performance improvement. It will ensure data continuum by solving Inefficient "manual" data exchange between tools. It will also help the design for constraints satisfaction and trade-off. For functional Design, parameter setting will increase robustness of processing chains based on sensitivity analysis and uncertainty quantification.

Some technical challenge should be addresses as curse of large dimensionality (combinatorial explosion of parameters), linear and nonlinear constraints between parameters and multi-criterion optimization.

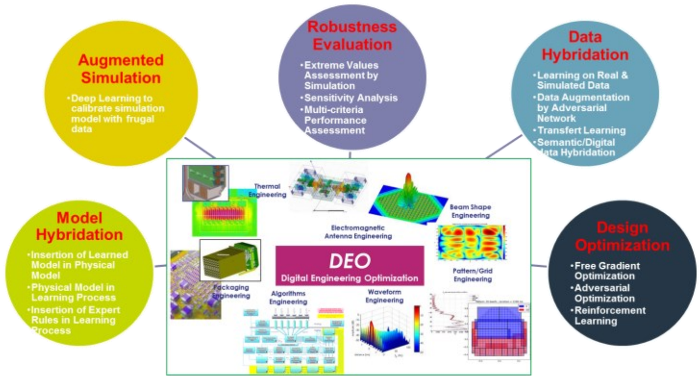

Fig. 4. Digital Engineering Optimization approaches

II. AI-AUGMENTED RADAR FUNCTIONAL ENGINEERING

Software-defined digital radar systems can dynamically and freely sweep their surroundings using AESA technology, and implement advanced radar algorithms through digital data processing. However, those new capabilities come at the cost of large increase in the system complexity, with thousands of design parameters across a broad spectrum of domains.

Integration of this evolution in the engineering methodology is a necessary step for harnessing the full potential of modern radar systems. AI now offers several tools to master this associated complexity while ensuring optimality of the results.

We present in this article an application of this approach on scanning radar modes definition at mission level: a new framework relying on optimization methods for optimized digital radar design regarding beam synthesis, waveform generation and scanning patterns.

A. *Functional Design Optimization challenges*

With full design antenna and software defined capability, Functional Radar Design should address best adaptation of these degrees of freedom. With modular AESA antenna, we have from hundreds to thousands of T/R channels based on GaN High Power Amplifier for high efficiency, compactness & reliability with Wide instantaneous RF bandwidth for high range resolution. We have laso a Full digital multibeam capability with (at element level) digital Beam Forming with more than 100 simultaneous beams, with dynamic beams managements adaptable to mission and operational environment and Long Time on Target for enhanced Doppler resolution and reduced reaction time.

Multi-function radars (MFR) usually perform multiple tasks simultaneously, such as scanning, target tracking and identification, clutter mapping, etc. [12, 16, 17]. Electronic scanning and numerical processing allow dynamical use of transmit beam steering, receive beam forming, dwell scheduling and waveform processing to adapt to operational requirements. As complex situations can result in system overload, multi-function radars must optimize resources allocation to ensure robust detection. Beam synthesis, waveform generation and scan pattern optimization can be used to minimize the required time-budget of radar scanning (search) modes, thus freeing resources for other tasks.

In the past, several works have explored various approaches for beam synthesis, waveform computation or optimization of the radar scan pattern (for a pencil-beam lattice over the surveillance space [13], adaptive activation strategies on a pre-designed radar scan pattern [11]). Those approaches however do not fully use active radars capabilities to dynamically perform beam-forming and are not integrated in a more global framework. In [15], radar scan pattern optimization was formulated as a set cover problem, which resulted in a flexible and powerful framework for this problem.

We present RadOpt (Radar Optimization) framework, developed for designing optimized scanning radar modes through beam synthesis, waveform generation and scan pattern optimization. This tool segments the generation of radar scanning modes into multiples steps, allowing for both modularity and complexity control.

B. *Functional Design Optimization Algorithms*

For these challenges to master complexity of these new degrees of freedom, we have used Digital Twin for Radar Functional Design addressing jointly Radar « Search » Design Decision Aid, Architecture Design based on performances assesment (e.g. Antenna size) and operational use of « Search » Mode Reconfiguration. For this purpose, we have developed most advanced optimization tools to solve these problems: RADOPT-T tool for Waveform Optimization based constraints programming solver, large-scale CMA-ES Tool based on Gradient Free Evolutionary Algorithms (developed with INRIA and Ecole Polytechnique) for Beamshape Synthesis, and RADOPT-S Tool based on Mixed-Integer solver for Search Grid Optimization.

Gradient Free Evolutionary Algorithms (Large Scale CMA-ES) is able to solve black-box optimization problem with more than 1000 parameters to tune. This tool is used for Waveform Phase code Optimization with a cost function defined by cross/auto-correlation constraints and for Antenna Phase Weight Optimization with a cost function given by beam shape template (Main/2nd lobes). Constraints Programming is used for multi-bursts waveform design to mitigate eclipses induced by multi-PRI/frequencies selection with respect to Doppler/Range ambiguities. Multi-Bursts binary integration is optimized to optimize homogeneous probability of detection. Mixed Integer Programming Solver are used for Search Grid Optimization on Discrete Spatial Grid for Combinatorial Coverage better selection (including Beam shape, Beam Position, Waveforms and update rate).

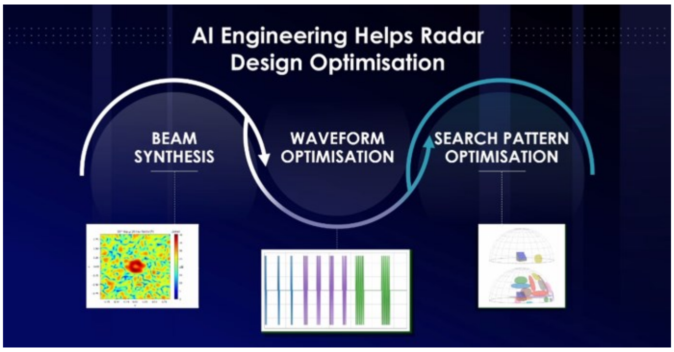

Fig. 5. Radar Functional Design Optimization for Beam Synthesis, Waveform Optimization and Search Pattern Optimization

C. *AI Algorithm for Beam Synthesis*

AESA offers capability to steer at transmission various beam pattern (focused beam, enlarged beam on one, two axes…). In association with the full (element-level) digital multi-beam at reception, such flexibility enables a quasi-infinite number of configurations to cover the angular domain. Nevertheless, this requires, for each transmission beam, to define the thousands of parameters associated to all antenna elements. The beam synthesis module synthetizes feasible radiation patterns from ideal radiation patterns through the use of continuous black-box optimization methods, such as evolutionary strategies or genetic algorithms.

D. *AI Algorithm for Waveform Generation*

Pulsed-Doppler radar models require a careful selection of pulse-repetition intervals, pulse widths, and signal integration techniques to ensure ambiguity detection removal, eclipses mitigation, and detection performances optimization (detection probability vs. false alarm probability). Discrete black-box optimization methods, such as branch-and-bound, combinatorial heuristics or genetic algorithms can be used on this type of problem.

E. *AI Algorithm for Scan Pattern Optimization*

Scan pattern (i.e. combination of beams and waveforms to answer to the operational mission) optimization can be formulated as a special case of set covering, a well-known problem in combinatorial optimization: among a collection of available sets, find the smallest subset of this collection whose union covers all elements. Both the general case and the specific case of bi-dimensional grid covering are NP-hard to solve [10, 14]. In practice, problems of reasonable size can be efficiently solved using branch-and-bound with linear relaxation for lower bound estimation.

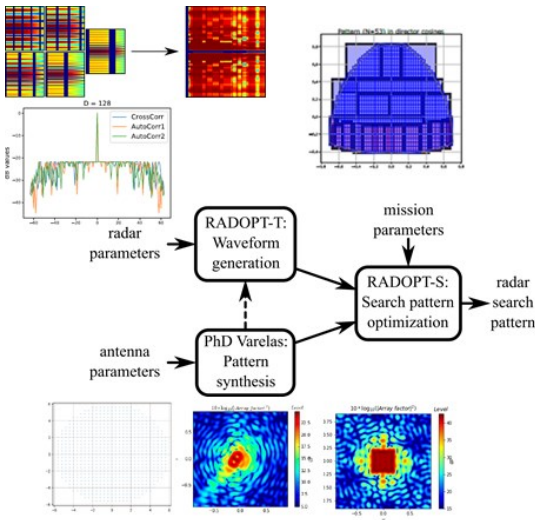

Fig. 6. Radar Functional Design Optimization based on most advanced Optimization Algorithms from AI (CMA-ES, Constraints Programming Solver, Mixed Integer Solver,…)

III. AI-AUGMENTED MFR RADAR HARDWARE DESIGN OPTIMIZATION WITH DIGITAL SENSOR TWIN

In addition to the operational part (Digital Platform , Real software, Simulation of part of antenna, Real or simulated targets & environment), the Digital twin will be made of an hardware part including Mechanic, Fluid, Thermic and Electro-magnetic models. Digital Twin also includes Harware Design Optimization to enable Multi-Disciplines design based on consistent and linked data, improve co-engineering with system team, and support Engineers and Managers in their daily tasks with no overhead for disciplines specialists. Expected benefit is to increase Design Process performances by multi-physic simulation and digital continuity. Digital Twin will facilitate practices during development: Management data, Traceability, Configuration management, Requirements management.

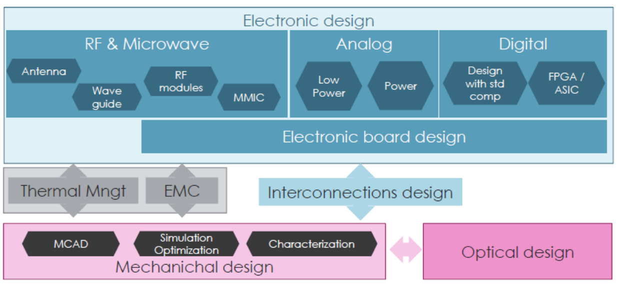

Fig. 7. Hardware design areas : a large diversity of skills

MBSE (Model Based System Engineering) approach has been developed based on use of integrated multiple models as illustrated in the following figure, to extrapolate behavior in different environment conditions. Models could be recalibrated with data after first real equipment tests.

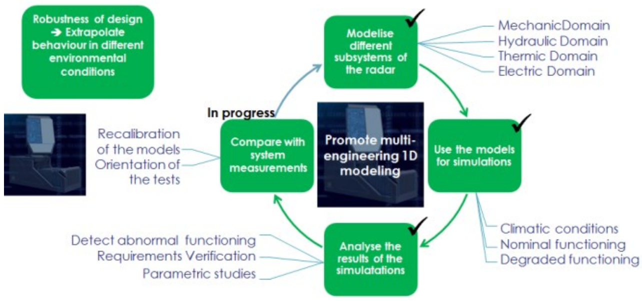

Fig. 8. Digital Twin Mechanical-Thermal

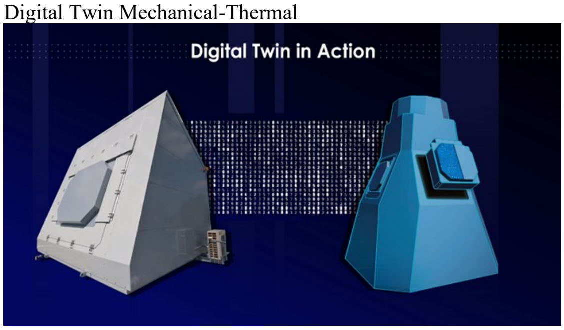

Fig. 9. Digital Twin Model Calibration with real equipment

IV. DIGITAL TWIN FOR NAVAL AND LAND-BASED MFR

Thales is integrating a new generation of Multi-Function Radars (MFR), both for naval (Sea Fire) and ground (Ground Fire) based upon a common architecture, new AESA technology and a new digital processing technology using an open architecture. This paper presents the breakthroughs brought by the use of a MFR Digital Twin (named Twin Fire) first for Thales development process and then for our customers and the end users. First part introduces the Twin Fire. Second part presents the use of the Twin Fire in development phase and the way it impacts this phase. Third part presents the benefits of using the Digital Twin for our customer(s). The new generation of Thales MFR is based on 3 main pillars:

- A new AESA technology: The full Element Digital Beam Forming (FEDBF), which allow a very high reactive and flexible management of radar resources
- A new digital processing technology with computational power 1000 times greater than the previous generation
- An Open radar architecture allowing to SW defined radar
    - Configure the radar for a given mission by simply adding SW plug in, without any HW modification (Software Defined Radar).
    - Handle new threats appearing during the radar life cycle either by upgrading algorithms within SW components or by adding new SW components in parallel.

This solid foundation removes previous limits and opens new fields of possibilities for this radar family. The Digital Twin of such SW radars is the key to make the possibilities happen.

Fig. 10. Naval MFR Radars

A. MFR DIGITAL TWIN

A Digital Twin is the replication of a process or a system for test purposes. For previous generation of MFR, with a high level of interactions between the analog and digital domains, a dedicated simulation model of the radar had to be built. Many issues regarding its representability and its maintainability rose. With the new generation of SW MFR, the effective radar processing itself is used and the simulated part is now limited to the generation of digital stimuli at radar processing input. Those stimuli simulate the radar environment seen through the antenna, as highlighted, for Sea Fire radar case. The Twin Fire consists then in the following functions as depicted in figure below: IHM to build operational scenarios and monitor their execution; Stimuli Generation; Effective radar processing; Replay monitoring; Radar data recorder; MMI for radar monitoring/data display; Radar performance assessment Tools

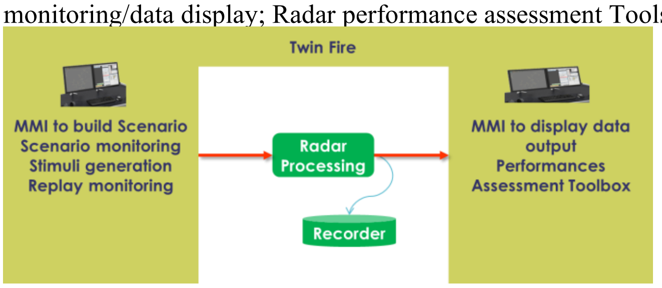

Fig. 11. Twin Fire functional breakdown

The Digital Twin can be implemented either on the same hardware as the radar itself (as illustrated in figure 4) or, as a "lab" configuration, on a PC (it can even be included in a PC farm). Furthermore, the stimuli generation part of the Digital Twin is also embedded within the radar itself and can be used while the radar is operating. Such a Digital Twin is used for three purposes:

- The first one consists in defining an operational scenario and then playing it on the Digital Twin to assess radar performances or to analyze radar behavior in that scenario
- The second one consists in replaying on Digital Twin real recordings at radar antenna output level to analyze radar behavior in trials or missions.
- The third one consists in defining an operational scenario and then playing on the radar itself (mixed with real clutter/background measures), to assess operational performance on specific targets in a given environment.

Beyond the radar itself, the Twin Fire is designed to be embedded in a Digital Twin at system of systems level, such as a Weapon Engagement System.

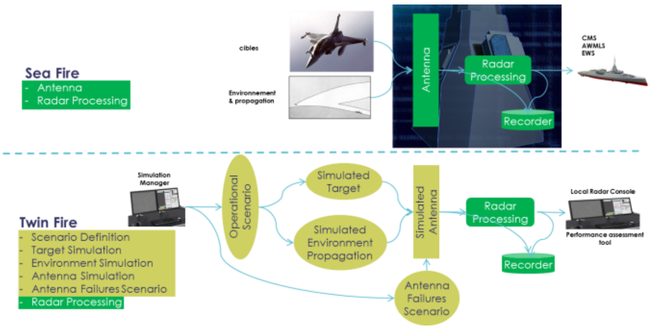

Fig. 12. Twin Fire & Sea Fire

B. Benefit for Development Phase of MFR

The Twin Fire speeds up dramatically the processing development time, in three different ways:

- The discovery of anomalies, both in specifications or in code at earlier stages, in order to correct them as soon as possible and, consequently, to avoid propagating disturbances in next steps of development
- To validate parameters tuning at each incremental step
- To perform automatic and exhaustive non regression tests at each incremental steps

Furthermore, the Twin Fire will be used to implement and validate new capabilities through SW upgrades along the life time of the system radar life cycle by testing these SW updates with recordings made in representative scenarios and environments. This will facilitate the cross fertilization between MFR radars, that is the implementation of a capability developed for one of the MFR on the others. This brings the SW defined radar concept to reality!

C. Benefit for Customer Validation Authority and End Users

For Customer Validation Authority, the first benefit is brought by the replay capability. As a matter of fact, data at antenna output can be recorded during validation trials, with various operational scenarios and environmental conditions, and can be analysis through replay to understand and check the radar behavior. If questions rise regarding radar behavior, the Validation Authority has the opportunity to inform Thales in a very efficient way as the records can be provided together with the analysis results. The second benefit is the evaluation of radar performances on specific scenarios: during trials, it is always difficult, if not impossible, to test specific scenarios, e.g. a sea skimmer fired from a shore with mountainous background, a synchronized attack with several sea skimmers together with divers, plus Anti-Ship Ballistic Missiles…. Using the radar embedded Digital Twin, superposing a simulated targets on the effective environment is simple and requires no specific equipment. The key point is the representativeness of the simulated target, which is ensured through comparison with real observed targets during other trials. For End Users, the first benefit is the evaluation of performances using the embedded Twin Fire while in operation: according to the current environmental conditions, what are the radar performances in front of such or such operational threat scenario? The second benefit is the mission preparation: as threats and missions evolve, the Twin Fire allows an End User to assess if the radar is fit for the mission or the new threats and, where appropriate, could ask Thales to propose an improvement. Along a radar life time, Thales envisages the opportunity to offer some tuning facilities at radar level (e.g. to provide a set of radar modes to fulfill several needs): the Twin fire will be of great help, if not mandatory, to select the most relevant mode and to be aware of its strengths and weaknesses. The third one is the usual operational training, enriched with the large scope of simulation capability.

V. CONCLUSION & SYNTHESIS

Radar Digital Twin coupled with most advanced Optimization could be used not only in the engineering phase but also in more operational ones for mission preparation of Radar Mode selection or reconfiguration according to the environment (clutter and jammer) and threats.

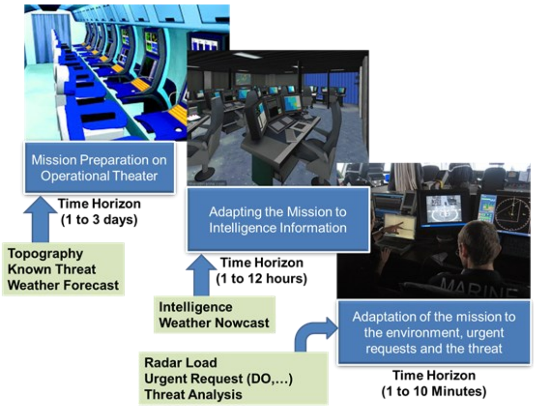

Fig. 13. Digital Twin Use for Mission Preparation and Reconfiguration

High computation speeds of these algorithms suggest tool application in a "Proactive Radar" configuration, which would dynamically propose to the operator, operational modes better adapted to the environment, the threat and equipment failures, only by software reconfiguration.

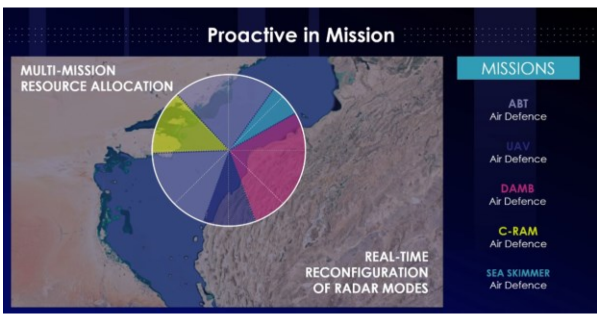

Fig. 14. PROACTIVE RADAR using Real-Time Modes Reconfiguration

We presented in this article a complete and modular framework for designing and optimizing radar scanning mode. It also proved to be a flexible tool, compatible with extensions for modelling complex situations with multiple mission requirements under localized constraints. This framework not only opens interesting research avenues for improving radar performances. It also offers various possible applications for aided-design of radar scan patterns, simulation of new radar architectures performances, and development of cognitive radar systems capable of adapting in real time to the operational environment. The Twin Fire is the answer to exploit the huge opportunity offered by the new generation of SW defined MFR.

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