Military Technical Academy

HABILITATION THESIS

Advanced Signal Processing Techniques in the Field of Electronic Warfare

Scientific Domain:
Electronic Engineering and Telecommunications

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This habilitation thesis is dedicated to my family:
Claudia and Alexandru

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Chapter 1

Abstract

1.1 Abstract

The present habilitation thesis is a cumulative synthesis of my relevant professional and research results achieved in the period 2004-2015, following the public presentation of my doctoral thesis in 2003.

In this period, my research activity covered *four* important research areas: *Automatic target recognition* (ATR) *systems*, *High-resolution radar* (HRR) *signal processing*, *Hybrid artificial intelligence* (AI) *paradigms* and *Electronic warfare* (EW), respectively. These are the core domains of my professional training and education.

The present habilitation thesis is structured into three parts. The first part overviews concisely my teaching and research activities. The second part presents the most important achievements related to the four major research fields mentioned above, each interesting research direction being fully-described in a dedicated section. The third part draws the future objectives and directions of scientific research in the fields presented before. Also, two comprehensive annexes present the general references and the list of my scientific publications.

The main core of this habilitation thesis is geared on my scientific research directions and achievements which are synthetically described hereinafter.

In *ATR systems* research field, my work was mainly focused on identifying and testing more efficient and performing classification/PR chains for different spectral input information flows (belonging to video, thermal and HRR imageries). Consequently, there were investigated some improved techniques of feature extraction (i.e., a new set of invariants related to Flusser moments family) and selection (i.e., a generalized (neural) version of the standard Sammon mapping algorithm) for a pattern of interest. To increase the recognition accuracy of an ATR system, an advanced decision fusion technique based on Sugeno's fuzzy integral was proposed. Furthermore, another approach to assure the highest classification rate was centered on the development of new customized PR chains. Finally, there were also discussed some improved design solutions in the field of automatic license plate and speech recognition, respectively.

My research activity in the ATR systems area was materialized in a national grant conducted by me as a project manager and five national projects, all following competitions, in which I was involved as a research team member. The experience accumulated working for these projects was put to use both to improve the scientific level of the courses I taught and to upgrade some of the facilities in the department's laboratories (e.g., a modern anechoic chamber into audio spectrum, some dedicated PR/data fusion processing tools etc.). Moreover, I published more than 25 papers on this topic, among which 15 (10 as first author) in various prestigious ISI ranked journals and conferences with ISI CPCI proceedings. In addition, I co-authored a book in the field of EM image processing.

In the field of *HRR signal processing*, my work was mainly focused on designing new robust algorithms (concerning the level of the sidelobes) for the synthesis of NLFM signals and on studying some advanced superresolution methods in order to improve the quality of the available HRR imagery database. Consequently, the proposed NLFM synthesis techniques were based on both temporal predistortioning of LFM signals and stationary phase concept. In point of novelty, the proposed approach provides an effective modality to optimize (using the

sidelobe reduction criterion) the specific parameters of the investigated NLFM synthesis methods. Moreover, by applying such advanced algorithms alongside with minute simulations, a significant sidelobe suppression (more than -40 dB, on average) was obtained. Finally, my research activity was also focused on both the theoretical and experimental investigation of some superresolution techniques used to generate the target HRRPs and the design of suitable reconstruction algorithms of the target radar images for different PR tasks, respectively.

It is worth noticing that the main results achieved in the *HRR signal processing* area were supported by two national projects following competition in which I was involved as a research team member. In addition, I published more than 10 papers, among which 7 (5 as first author) in various well-known ISI ranked journals and conferences with ISI CPCI proceedings.

The fusion between the standard connexionist models and some relatively recent mathematical theories had as effect an explosive theoretical and experimental development of new powerful *hybrid AI* (also known as neuro-fuzzy-genetic) architectures. In this still promising research area, my activity was mainly targeted at investigating, theoretically and experimentally, some hybrid AI paradigms, focusing directly on both GANN systems theory and their hardware implementations. Consequently, there were proposed two improved algorithms used to ensure a full-training genetic procedure for both RBF (i.e, a GARBF system) and MLP (i.e., a GAMLP system) networks. Within this framework it was also carried out a comparative study between the current approaches based on FPGA technology and some of the standard neurohardware solutions.

The relevant results of my research in the *hybrid AI paradigms* domain were the outcome of my work as a research team member in four national projects following competition. In this context, I published more than 15 papers, among which 10 (8 as first author) in various prestigious ISI ranked journals and conferences with ISI CPCI proceedings. Moreover, it is worth mentioning that I was the single author of three books introducing important approaches in the field of hybrid AI models and the co-author of a book in the GANN systems theory domain.

Generally, my research activity in the *EW* domain can be divided into two important directions, i.e. the publishing activity and the actual research activity, respectively. I think that it is very important to start by mentioning that Romanian literature faces a major lack of current information in the *technical* field of EW. Taking that into account, my publishing activity is significant coming as a result of many years of scientific documentation in this area. Consequently, it is worth mentioning that I was the single author of two reference books in this field (very importantly, a *unique endeavor* in Romanian EW literature, so far). In addition, I published two more books as single author and co-authored another book, all extremely useful for understanding some theoretical and practical aspects of EW.

The actual research activity in the EW field was carried out as a project manager of three projects of the Defense Ministry's research program or as a research team member in two projects of the same program. It is also important to mention that I was involved in more than twelve national research projects following competition, acting as a research team member.

An additional direction of interest in the EW field appeared from the necessity to understand the complex connections between EW and other modern concepts of the current military battlefield (e.g., the NCW concept). In this area, I published more than 25 papers, among which 15 (10 as first author) in some prestigious ISI ranked journals and conferences with ISI CPCI proceedings.

The consistent research experience and expertise achieved in the EW domain allowed me to participate in specific standardization and military acquisition activities. Consequently, I was involved as a member of the working team (2004-2008), either in the development or the acceptance of four MIL/STANAG standards. In addition, in 2010, I participated as a technical expert, in an acquisition group of some dedicated military products for the aviation EW area.

1.2 Rezumat

În cadrul acestei teze de abilitare sunt prezentate cele mai importante rezultate obținute în perioada 2004-2015, atât în plan profesional, cât și în activitatea de cercetare științifică. Această perioada este cea care a urmat anului 2003, an în care am susținut teza de doctorat.

În perioada mai sus menționată, activitatea mea de cercetare a cuprins *patru* direcții majore de cercetare științifică: *Sisteme de recunoaștere automată a țintelor* (ATR), *Procesarea semnalelor radar de înaltă rezoluție* (HRR), *Paradigme hibride ale inteligenței artificiale* (AI) și respectiv, *Războiul electronic* (EW). Practic, aceste patru domenii de interes au reprezentat și baza întregii mele pregătiri profesionale.

Teza de abilitare este structurată în *trei* părți distincte. Astfel, prima parte este un rezumat sintetic al activității mele didactice și de cercetare științifică. În partea a doua sunt prezentate cele mai importante realizări în domeniile de interes amintite anterior, fiecare direcție de interes fiind descrisă în detaliu, într-o secțiune separată. Partea a treia a tezei de abilitare trasează direcțiile de dezvoltare și obiectivele de lucru în domeniile de cercetare prezentate anterior. De asemenea, această lucrare conține și două anexe comprehensive care prezintă bibliografia generală și lista publicațiilor mele științifice.

În domeniul *sistemelor ATR*, activitatea mea de cercetare științifică a fost focalizată în principal, pe identificarea și testarea unor lanțuri de clasificare eficiente din perspectiva unor fluxuri informaționale de intrare diferite (aparținând imageriilor de tip video, termal și HRR). Prin urmare, au fost investigate unele tehnici îmbunătățite de extragere (un nou set de invarianți aparținând familiei momentelor Flusser) și respectiv, selecție (o versiune (neuronală) generalizată a algoritmului standard de proiecție Sammon) a caracteristicilor unei forme de interes. Pentru creșterea acurateții de recunoaștere a unui sistem ATR, a fost propusă o tehnică avansată de fuziune decizională bazată pe integrala fuzzy Sugeno. Suplimentar, tot în contextul creșterii ratei de clasificare, o altă direcție vizată a fost și cea axată pe dezvoltarea unor lanțuri de recunoaștere a formelor personalizate pentru fiecare tip de aplicație. De asemenea, au fost discutate și o serie de soluții îmbunătățite de proiectare în contextul sistemelor de recunoaștere automată a plăcuțelor de înmatriculare și respectiv, a vorbirii.

Activitatea mea de cercetare științifică în domeniul sistemelor ATR s-a concretizat într-un proiect național pe care l-am condus în calitate de director de proiect și respectiv, cinci proiecte naționale, toate prin competiție, în care am fost implicat ca și membru în echipa de lucru. Experiența acumulată prin aceste proiecte de cercetare științifică a fost utilizată atât în îmbunătățirea cursurilor predate, cât și în dezvoltarea unor facilități moderne în laboratoarele departamentului (spre exemplu, o cameră anecoidă în spectrul audio, unele instrumente de procesare dedicate în domeniul recunoașterii formelor/fuziunii de date etc.). De asemenea, am publicat peste 25 de articole în acest sens, dintre care 15 (10 ca autor principal) în diferite reviste indexate ISI sau proceedings-urile unor conferințe ISI CPCI. Nu în ultimul rând, am fost co-autor la o carte în domeniul procesării imaginilor electromagnetice.

În domeniul *procesării semnalelor HRR*, activitatea mea de cercetare științifică a fost focalizată în principal, pe proiectarea unor algoritmi robuști (ca și nivel al lobilor secundari) de sinteză a semnalelor de tip NLFM și respectiv, pe studiul unor metode avansate de înaltă rezoluție, totul în ideea creșterii calității bazei de date HRR avută la dispoziție. În consecință, tehnicile de sinteză propuse au fost axate atât pe utilizarea predistorsionării temporale a semnalelor de tip LFM, cât și a conceptului de fază staționară. Ca noutate, abordările propuse au oferit și posibilitatea efectivă a optimizării (utilizând ca și criteriu, nivelul lobilor secundari) unor parametri specifici ai metodelor de sinteză NLFM investigate. Suplimentar, prin aplicarea acestor algoritmi avansați și simulări amănunțite, a fost obținută o suprimare semnificativă a nivelului lobilor secundari, în medie, mai mare de -40 dB. Și în sfârșit, legat de imageria HRR,

activitatea mea de cercetare ştiinţifică a presupus şi investigarea atât la nivel teoretic, cât şi experimental, a unor tehnici de înaltă rezoluţie pentru a genera profilele sintetice de distanţă ale unor ţinte, precum şi proiectarea unor algoritmi eficienţi de reconstrucţie a imaginii radar a unei ţinte, totul în ideea implementării unor aplicaţii complexe de recunoaştere a formelor.

Trebuie amintit şi faptul că, rezultatele ştiinţifice majore obţinute în contextul procesării semnalelor HRR au fost fundamentate şi pe cele două proiecte de cercetare naţionale câştigate prin competiţie, în care am fost implicat ca şi membru în echipa de lucru. De asemenea, am publicat peste 10 articole în acest sens, dintre care 7 (5 ca autor principal) în diferite reviste indexate ISI sau proceedings-urile unor conferinţe ISI CPCI.

Fuziunea modelelor conexioniste standard cu unele teorii matematice relativ recente a avut ca prim efect, o dezvoltare explozivă atât la nivel teoretic, cât şi experimental, a unor *arhitecturi* robuste *de tip neuro-fuzzy-genetice*. În acest domeniu de cercetare încă promiţător, activitatea mea a fost focalizată în principal, pe investigarea unor noi tipuri de modele AI hibride, cu o atenţie sporită acordată teoriei sistemelor de tip GANN şi respectiv, implementării hardware a acestora. Prin urmare, în cadrul lucrării de faţă au fost propuşi şi descrişi în detaliu doi algoritmi genetici dedicaţi asigurării unui proces de instruire complet pentru o reţea neuronală RBF (un sistem de tip GARBF) şi respectiv, feedforward/MLP (un sistem de tip GAMLP). De asemenea, a fost realizat un studiu comparativ între abordările curente bazate pe utilizarea tehnologiei FPGA şi unele soluţii neuro-hardware standard.

Rezultatele ştiinţifice relevante obţinute în investigarea modelelor AI hibride au fost generate în cadrul a patru proiecte de cercetare naţionale, toate câştigate prin competiţie, în care am fost implicat ca membru în echipa de lucru. În acest context, am publicat peste 15 articole, dintre care 10 (8 ca autor principal) în diferite reviste indexate ISI sau proceedings-urile unor conferinţe ISI CPCI. În plus, am fost autor unic pentru trei cărţi, importante ca deschidere, în domeniul arhitecturilor neuro-fuzzy-genetice, dar şi co-autor pentru o carte în domeniul teoriei sistemelor GANN.

În general, activitatea mea de cercetare ştiinţifică în *domeniul EW* ar putea fi împărţită în două direcţii majore, şi anume: activitatea publicistică şi respectiv, cea de cercetare propriu-zisă. Pentru început este foarte important de ştiut faptul că, în literatura de limbă română există o lipsă acută de informaţii curente în domeniul *tehnic* asociat EW. Din acest punct de vedere, activitatea mea publicistică obţinută în urma unui proces îndelungat de documentare ştiinţifică în acest domeniu este una, în opinia mea, semnificativă. Astfel, trebuie amintit faptul că în calitate de unic autor, am elaborat două cărţi de referinţă în domeniu (foarte important, un demers, cel puţin până în momentul de faţă, *unic in literatura română* în domeniul EW). De asemenea, tot în calitate de unic autor, am publicat două cărţi, iar în calitate de co-autor, o carte, toate extrem de utile în înţelegerea unor aspecte teoretice şi practice esenţiale ale EW.

Cercetarea ştiinţifică propriu-zisă în domeniul EW a fost concretizată atât în calitate de director de proiect pentru trei proiecte derulate în programul de cercetare al Ministerului Apărării Naţionale, cât şi ca membru în echipa de lucru a două proiecte, în cadrul aceluiaşi program. De asemenea, este important de menţionat că am fost implicat în peste douăsprezece proiecte naţionale câştigate prin competiţie, ca membru în echipa de lucru.

O altă direcţie de interes în domeniul EW a fost legată de necesitatea înţelegerii conexiunilor complexe între acesta şi alte concepte moderne ale câmpului de luptă actual (spre exemplu, conceptul NCW). În acest domeniu de cercetare am publicat peste 25 de articole, dintre care 15 (10 ca autor principal) în diferite reviste indexate ISI sau proceedings-urile unor conferinţe ISI CPCI.

Experienţa consistentă şi expertiza acumulată în aria EW mi-au permis să particip la activităţi specifice de standardizare şi respectiv, achiziţii pe linie militară. Prin urmare, am fost implicat, ca membru în echipa de lucru (2004-2008), în dezvoltarea sau acceptarea a patru standarde de tip MIL/STANAG. De asemenea, în anul 2010, am participat, în calitate de expert tehnic, într-un proces specific de achiziţii de produse militare din domeniul EW în aviaţie.

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List of acronyms

AEW	A*viation* EW
AI	A*rtificial* I*ntelligence*
ALPR system	A*utomatic* L*icense* P*late* R*ecognition* system
AOA	A*ngle* O*f* A*rrival*
ARM	A*ntiradiation* M*issile*
ART	A*daptive* R*esonance* T*heory*
ASR system	A*utomatic* S*peech* R*ecognition* system
ATR system	A*utomatic* T*arget* R*ecognition* system
ATTR system	A*utomatic* T*arget* T*racking and* R*ecognition* system
BP rule	B*ack*-P*ropagation* rule
CAD	C*omputer*-A*ided* D*esign*
C2 concept	C*ommand*-C*ontrol* concept
C4I2SR system	C*ommand*-C*ontrol*-C*ommunications*-C*omputer*-I*nformation*-I*nteroperability*-S*urveillance*-R*econnaissance* system
CCD technology	C*harge* C*oupled* D*evice* technology
CD model	C*ontext*-D*ependent* model
CEW	C*ommunications* EW
CMN	C*epstral* M*ean* N*ormalization*
CNN	C*onvolutional* NN
COMINT	COMM*unications* INT*elligence*
COMSEC	COMM*unications* SEC*urity*
CR	C*lassification* R*ate*
CSR	C*ontinuous* S*peech* R*ecognition*
CybW	Cyb*er* W*ar*
DA technique	D*ual* A*podization* technique
DEW	D*irected* E*nergy* W*eapons*
DF	D*ata* F*usion* D*irection* Finding
DIP	D*igital* I*mage* P*rocessing*
DSP	D*igital* S*ignal* P*rocessor*
EA	E*lectronic* A*ttack*
ECCM	E*lectronic* C*ounter*-C*ounter*M*easures*
ECM	E*lectronic* C*ounter*M*easures*
ED	E*lectronic* D*eception*
EFuNN	E*volving* Fu*zzy* N*eural* N*etworks*
ELINT	EL*ectronic* INT*elligence*
EM	E*lectro*M*agnetic*
EMC	EM C*ompatibility*
EMCON	EM*ission* CON*trol*
EP	E*lectronic* P*rotection*
ES data fusion	E*xpert* S*election* data fusion

ES	E*lectronic* S*upport*
ESM	E*lectronic* S*upport* M*easures*
ESPRIT algorithm	E*stimation of* S*ignal* P*arameters by* R*otational* I*nvariance* T*echnique* algorithm
EW	E*lectronic* W*arfare*
FE	F*eature* E*xtraction*
FFLN	F*uzzy* F*unctional* L*ink* N*ets*
FLD analysis	F*isher* L*inear* D*iscriminant* analysis
FLIR	F*orward* L*ooking* IR
FM	F*requency* M*odulation*
FOSART neural network	F*ully self*-O*rganizing* S*implified* ART neural network
FoV	F*ield of* V*iew*
FPGA technology	F*ield*-P*rogrammable* G*ate* A*rray* technology
FS	F*eature* S*election*
FuNN	Fu*zzy* NN
FUZZSAMM	FUZZ*y* SAMM*on*
GA	G*enetic* A*lgorithm*
GANN system	G*enetic* A*lgorithm* N*eural* N*etwork* system
GPR	G*round* P*enetrating* R*adar*
HD camera	H*igh*-D*efinition* camera
HH polarization	H*orizontal polarization at emission and receiving*
HMM	H*idden* M*arkov* M*odels*
HNN	H*ardware* NN
HRR	H*igh* R*esolution* R*adar*
HRRP	H*igh* R*esolution* R*ange* P*rofile*
HV polarization	H*orizontal polarization at emission and* V*ertical at receiving*
ICA	I*ndependent* C*omponent* A*nalysis*
IFFT	I*nverse* F*ast* F*ourier* T*ransform*
INFOSEC	INFO*rmation* SEC*urity*
IR	I*nfra*R*ed*
ISAR	I*nverse* SAR
ISODATA	I*terative* S*elf*-O*rganizing* D*ata* A*nalysis* T*echnique*
ISR system	I*ntelligence,* S*urveillance* and R*econnaissance* system
LDHD	L*ow*-D*ensity* H*igh*-D*emand*
LEM technique	L*eakage* E*nergy* M*inimization* technique
LFM signal	L*inear* F*requency* M*odulation* signal
LIDAR	LI*ght* D*etection* A*nd* R*anging*
LoS	L*ine of* S*ight*
LP	L*icense* P*late*
LPR	L*icense* P*late* R*eader*
LVQ neural network	L*earning* V*ector* Q*uantization* neural network
MD data fusion	M*edian* V*oting* data fusion
MDL technique	M*inimum* D*escription* L*ength* technique
MFCC	M*el*-F*requency* C*epstral* C*oefficients*
MFR	M*atched* F*ilter* R*esponse*
MJ data fusion	M*ajority* V*oting* data fusion
MLP	M*ulti*L*ayer* P*erceptron*
MSE	M*ean Squared* E*rror*

MT algorithm	M*ultistyle* T*raining* algorithm
MUSIC algorithm	MU*ltiple* SI*gnal* C*lassification* algorithm
NCW	N*etwork* C*entric* W*arfare*
NFN	N*eo*-F*uzzy* N*euron*
NN	N*eural* N*etwork*
OCR system	O*ptical* C*haracter* R*ecognition* system
OPINT	OP*tical* INT*elligence*
PCA	P*rincipal* C*omponent* A*nalysis*
PR	P*attern* R*ecognition*
PSAR	P*olarimetric* SAR
PSD function	P*ower* S*pectral* D*ensity* function
PST function	P*ower* T*emporal* D*ensity* function
RCS	R*adar* C*ross* S*ection*
RBF neural network	R*adial* B*asis* F*unction* neural network
REW	R*adar* EW
SAMMANN	SAMM*on* A*rtificial* NN
SAR	S*ynthetic* A*perture* R*adar*
SART neural network	S*upervised* ART neural network
SIGINT	SIG*nal* INT*elligence*
SNR	S*ignal to* N*oise* R*atio*
SOM neural network	S*elf*-O*rganizing* M*ap* neural network
SP principle	S*tationary* P*hase* principle
SSE	S*um*-S*quared* E*rror*
SVA technique	S*patially* V*ariant* A*podization* technique
TEMPEST technology	T*elecommunications* E*lectronics* M*aterial* P*rotected from* E*manating* S*purious* T*ransmissions* technology
TOA	T*ime* O*f* A*rrival*
UWB technology	U*ltra*-W*ide*B*and* technology
VAD	V*oice* A*ctivity* D*etector*
V-ATR system	V*ideo*-ATR system
VH polarization	V*ertical polarization at emission and* H*orizontal at receiving*
VLSI technology	V*ery* L*arge* S*cale* I*ntegration* technology
VV polarization	V*ertical polarization at emission and receiving*
WARM	WAR*time reserve* M*odes*
WER	W*ord* E*rror* R*ate*
WM data fusion	W*eighted* M*eans* data fusion

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