A Coarse Taxonomy of Artificial Immune Systems

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1 Introduction

This work provides a high-level taxonomy of the field of Artificial Immune Systems (AIS). Specifically, the taxonomy presented is not application focused as is the case in de Castro and Timmis' seminal reference on the field [212], rather the field is presented firstly by *computational paradigm*, and secondary by so-called *thrust of research*. This secondary aggregation involves the subjective organisation of work based on authors involved and the theme of the presented research. The intent of this work is to provide both a high-level overview of the principle computational paradigms of the field and provide some indication of the major works and their relationships within each paradigm. This work is not a complete bibliography, rather it contains seminal and influencial works from each selected paradigm. Section 2 considers the general field of Artificial Immune Systems, and provides references regarding defintinios, overview of the field and conceptual frameworks. Section 3 considers those works inspired by the self-nonself principle refered to as the *Negative Selection Paradigm*. Section 4 considers those works inspired by Burnet's clonal selection theory refered to as the *Clonal Selection Paradigm*. Section 5 considers those works inspired by Jerne's immune network theory refered to as the *Immune Network Paradigm*. Section 6 considers those works inspired by Matzinger's danger theory refered to as the *Danger Signal Paradigm*. Section 7 considers those works that do not fit neatly into the selected organisation of the field. Finally, Section 8 considers works that focus on the *distributed* concerns of the immune system.

2 Artificial Immune System

2.1 Definitions

The field of Artificial Immune Systems (AIS) is primarily concerned with the development, demonstration, and implementation of computational tools inspired by principles and processes of the vertebrate immune system. The field of artificial immune systems is not concerned with the theoretical or computational modelling of the biological system. Standard definitions of both the field of AIS and what comprises an artificial immune system follow.

The authors de Castro and Von Zuben [210] define an AIS as

> "*… a computational system based upon metaphors of the biological immune system*".

They go on to define Immune Engineering (IE) as

> "*… a meta-synthesis process that uses the information contained in the problem itself to define the solution tool to a given problem, and then apply it to obtain the problem solution*".

The distinction is the IE is the engineering process, differentiated as to the conventional engineering process that uses ideas from biology, in this case an artificial immune system. Immune Engineering was later formalised by de Castro and Timmis [212]. A set of three principles was introduced that a framework for developing artificial immune system algorithms should contain, as follows:

1. A representation for the components of the system
2. A set of mechanisms to evaluate the interaction of individuals with the environment and each other
3. Procedures of adaptation that govern the dynamics of the system

A further, more concise definition of AIS is provided in [212] as

> "*… adaptive systems, inspired by theoretical immunology and observed immunological functions, principles and models, which are applied to problem solving*".

This definition clearly highlights the role of theoretical immunology and immunological observations as an inspiration and not the pursuit of research in AIS. Another perspective of AIS is provided by one of the pioneers in the field Ishida [353], who defines an Immunity-Based System (IMBS) as a:

> *"… self-maintenance systems learned from and inspired by the immune system*"

His IMBS is described to posses the following three properties:

1. a ***self-maintenance system*** with monitoring not only of the nonself but also of the self
2. a ***distributed system*** with autonomous components capable of mutual evaluation
3. an ***adaptive system*** with diversity and selection

Finally, Tarakanov et al. [15] introduce yet another interpretation on the field; Immunocomputing (IC) as

> "*... a new computing approach that replicates the principles of the information processing by proteins and immune networks*".

Immunocomputing is a protein and immune network approach that attempts to address the shortcomings in AIS, specifically the lack of a proper mathematical basis and a lack of an analogous hardware platform.

2.2 Overviews of the field

This section lists works that provide an introductory reference to the field of AIS. References are listed in no particular order.

Summary	**References**
AIS as a soft computing paradigm	[215]
Popular and generally useful (in nature)	[83]
Usefulness of AIS as a computational intelligence paradigm	[277]
Tech reports by de castro	Introduction [209], Applications [210]
AIS in the last 5 years	[72]
Review paper – a survey	[44]
Overview of AIS – chapter	[168]
General overview of AIS's usefulness as a learning paradigm	[349]
Intro to the field of AIS	[71]
AIS for optimization, a survey	[344]
An overview of AIS as intrusion detection (natural application)	[328]
Application of AIS	[78]
AIS as a new learning paradigm	[349]
AIS as a pattern recognition paradigm	[213]
The usefulness of the paradigm	[277]
The importance of AIS in the next 10-15 years	[308]
Why computer scientists and immunologists should work together	[257]

2.3 Conceptual Frameworks for AIS

This section lists some references that provide conceptual frameworks for considering AIS. Refernces are provided in no particular order.

Summary	**References**
Conceptual framework for AIS	Framework [310] Application of framework [153] Seeking a more complete model [241] More on the theme [309]

Immune Engineering (conceptual model for engineering with AIS)	[212], Claimed to be incomplete [310], More on immune engineering [202]
Related to AIS's place in optimisation	[20]
Next generation AIS	[256]
Revisiting the foundations of AIS	[14]
AIS as a soft computing paradigm	[215]
Related to problems – the need to go back and look at the roots of the field	[166]
Immunocomputing	[16]
Innate immunity (a framework)	[134]

3 Negative Selection Paradigm

This section summarises seminal works on the negative selection paradigm. References are listed in no particular order.

Approach	**Description**	**References / Application**
(Forrest, Smith, et al.)	Early pattern recognition work using GA's (prelude to NSA)	GA to evolve cooperative antigen-antibody model or coverage [266,267] Confirmatory work [290] Related (?) [288]
Change Detection (Negative Selection Algorithm) (**NSA**) (Forrest, D'haeseleer, et al.)	The original change detection algorithm, now commonly referred to as the negative selection algorithm.	Random binary strings, disassembled SPARC binaries (the instructions of which were mapped to an ASCII alphabet), and binary strings from DOS (.com) binary files [289] Formalisation, modelling and improvements [252,253]. // D'haeseleer has a few tech reports and unpublished works Overview of application to computer security [295]
Process Homeostasis (**pH**) (Forrest, Somayaji, et al.)	Anomaly detection in sequences of system calls known as deviation from process homeostasis (an intrusion detection system as a patch to the Linux kernel)	Sequences of system calls in privileged (root) UNIX processes [293], [301] process monitoring with intervention embedded in the Linux kernel [32] overview [33], [220] The need for diversity in computer security (related) [287] Culminating work [31] Hybridising pH and Cfengine [197]
Lightweight Intrusion Detection System (**LISYS**) (Forrest, Hofmeyr, et al.)	Anomaly detection in TCP/IP connections, an implementation of ARTIS for computer security	Host-based and network based intrusion detection (anomaly detection) [303], [299], [294] , [292] Related (?) [304] Culminating work [302] Overview of LISYS [291] Renamed to LISYS, an implementation of ARTIS [300]
(Balthrop, Forrest, et al.)	Simplified LISYS	Confirmation and extension of a simplified LISYS [126], [196]
Artificial Immune System (**ARTIS**) (Hofmeyr, Forrest)	The previous work on change detection, process homeostasis, and Hofmeyr's AIS were unified (retrospectively) by Hofmeyr under the ARTIS framework.	Definition of ARTIS [300]
Computer Virus Immune System (**CVIS**) (Harmer)	Computational immune system for virus detection	Proposal and culminating work [255] Summary and analysis of algorithm [105]
Computer Defense Immune System (**CDIS**) (Williams, Gunsch, Lamont et al)	A multi-agent, hierarchical, distributed computational immune system for intrusion detection An extension of CVIS with network-based intrusion detection Uses negative selection, affinity maturation and co-stimulation	Proposal and development [254], [251], [199], [198]
Online Negative Database (Esponda, Forrest, et al.)	The concept of a negative database, which stores records that represent the complement of the data	Introduction to the concept, and demonstration of the computational complexity of the database (feasibility) [97,100] Extension of early work, again highlighting the difficulty of deriving the original data from a negative representation [98] Theoretical model (crossover closure) [99]

		Culminating work [96] A formal framework for positive and negative selection [101] // there are a few technical reports as well
Immunological Electronics (**Immunotronics**) (Bradley, Tyrrell, et al.)	Fault detection system for state machine (FSM) hardware systems	Introduction to idea [21], [55] Combining immunological and embryonic ideas [54] Hardware immune system [56], [57], [58], [50] Related (?) [51], [262] Perhaps related thesis (?) [200] Related (?) [263] Perhaps an innate immunity related (?) [345]
Dynamic Clonal Selection (**DynamiCS**) (Kim, Bentley, et al.)	Dynamic clonal selection (actually a T-cell inspired negative selection approach) algorithm for anomaly detection of real-time network traffic	Negative selection shows scaling problems, should be used as a filter for invalid detectors and not generation of useful detectors [185] Negative selection with niching for intrusion detection [184] An investigation of static clonal selection with a negative selection operator [186] (their IDS, but not NS (?) [183], [181]) Proposal of the approach (DynamiCS) [189] Extension to the original approach [187], [182], [188] Culminating work [190]
Real-Valued Negative Selection (**RNS**, **RRNS**) (Gonzalez, Dasgupta, et al.)	Anomaly detection and classification with a real-valued negative selection algorithm	Experimentation and limitations of with binary matching rules [93] Combining negative selection with a neural network (Self-Organising Map) [92] Introduced RNS on classification datasets [91] Real-valued negative selection for anomaly detection, using a GA for detector generation [67], [90] Extension of work [129] Randomised RNS [94] Real-valued anomaly detection [88] Culminating work [89]
Variable-sized Real-valued Negative Selection (Ji, Dasgupta)	Extension of real-valued negative selection with variable radius detectors	Variable sized real-valued detectors [358], [357]
(Dasgupta, Forrest)	Anomaly detection in time series data	Application to tool breakage detection [46] Application to cutting dynamics of a milling operation and a synthetic signal [70] Similar, but different authors (?) [227], [229]
(Wierzchon, et al.)	Models and improvements to the binary negative selection algorithm	Generating an optimal non-redundant pool of detectors [281], [282], [280]
Information immune system (Chao, Forrest, et al.)	Information filtering (collaborative filtering) using negative selection to censor undesirable data (Is this an application of ARTIS?)	Introduction to the idea of information filtering with negative selection [61], [63] Information filtering of art (biomorphs) [62] Use of negative preferences applied to radio for a group of users [60] // I think there is a tech report for adaptive radio
(Stibor, Timmis, et al.)	Negative selection models are too simplistic (naive)	Generation of all possible r-chunk detectors not in the self set [322] Negative selection is too naïve (binary model), not appropriate for network-based IDS [320] Comparison of variable sized RNS with SVM [323] Further comparisons of real-valued negative selection to statistical techniques [321] Stibor's Phd Thesis [319]

The following lists additional uncategorised negative selection works:

- Hightower's work on gene libraries [269]
- Maths of the matching model (change detection) [265]
- Maths and introduction of r-contiguous bits [130], [131]
- Some random classification approach with positive and negative selection [102]
- On the usefulness of the NS paradigm [277]
- Extension of LISYS (synapse) [48]
- Fault detection of temperature data in a refrigeration system [53]
- Investigation into different means of generating detectors (de castro and timmis) [230]

- Image classification of pictures of wooden kitchen components with negative selection [285]
- On the use of negative selection in an AIS (unable to get…) [232]
- Application of NSA to multi-dimensional sensitive personal data (data integrity) [45]
- Application of NSA to files, system calls and time series [274]
- Image segmentation application of a negative selection approach [49]
- There may be some related work on combining pH with cfengine (Burgess)
- Negative selection application to steganography (writing a cipher) [132]
- Aircraft fault detection using negative selection (real-valued negative selection) (MILD) [43]
    - Negative selection for aircraft fault detection (ultimately real-valued negative selection…) [69]

4 Clonal Selection Paradigm

This section lists seminal works in the clonal selection paraidm. Works a listed in no particular order.

Approach	Description	References / Application
Clonal Selection Algorithm (**CLONALG**) (de Castro, Von Zuben) (Watkins, et al.)	Implementation of the clonal selection principle and affinity maturation	Introduction (CSA) and application to binary character recognition, TSP and function optimisation [204], [209] Renamed to CLONALG [208] Parallel implementation of CLONALG [30]
Adaptive Clonal Selection (**ACS**) (Walker, White, Garrett)	Extensions and simplifications to CLONALG	Comparison of clonal selection and ES on dynamic function optimisation [146] Improvement and application of CLONALG to binary character recognition [143] Introduction of real-valued, parameter-free adaptive clonal selection (ACS) for optimisation [276]
Artificial Immune Recognition System (**AIRS**) (Watkins, Boggess, Goodman, Timmis, et al.) (Greensmith)	A supervised learning clonal selection algorithm for classification, derived from RLAIS/AINE	Introduction to the technique, application to classification [19], [17], [29], [28] Simplification of the approach (AIRS2), and applied to classification [26] Applied to multi-class data, compared to LVQ [74] Issues that affect the performance of AIRS [106] Investigation into the source of power of the AIRS algorithm (maintenance of memory cells) [75] Comparison between AIRS and LVQ on datasets with irrelevant features [228] Investigation of the memory cells [73] Parallel version of AIRS [27] The use of non-Euclidean distance measures [136] Culminating work [18] Application of AIRS to hierarchical multi-class document classification [174], [172]
B-cell Algorithm (**BCA**) (Kelsey, Timmis, et al.)	Clonal selection approach to multimodal function optimisation	Seminal (?) [157] Related (?) [20] Application to dynamic multimodal function optimisation [156] Culminating work (?) [155] Related culminating work (?) [35] Comparison of opt-aiNET, BCA, and a GA [160] Markov chain model of BCA [76] Theretical convergence proof – empirical [250]
Multi-objective immune system algorithm (**MISA**) (Cruz Cortes, Coello Coello, et al.)	A clonal selection approach for multi-objective optimisation	Introduction to approach [36] Extension (more relaxed) to approach compared to other genetic approaches [243] Proof of convergence of MISA [233] Culminating work (?) [244]
Simple Immune Algorithm (**SIA**) (Cutello, Nicosia)	Binary approach for combinatorial optimisation	Introduced and applied to combinatorial optimisation (?) [338] Summary [340]
Cloning, Information Gain, Aging (**CLIGA, CLIGA+, READI-Alg**)	Hybridised approach of clonal selection and information gain.	Introduction (?) [339] Application to the graph colouring problem (?) [341] Summary and extension (CLIGA+) and introduction of a diffuse version – Reaction Diffuse Immune

(Cutello, Nicosia)		Algorithm (READI-Alg) [340]
Immune Algorithm (**IA**) (Cutello, Nicosia, Pavone, et al.)	Clonal selection approach with hyper-macro-mutations	Application to the HP protein folding problem [343], Introduction (?) [335] Evaluation of different hypermutation operators (?) [342] Perhaps a culminating work (?) [108]
Optimised Immune Algorithm (**opt-IA**) (Cutello, Nicosia, Pavone, et al.)	Hard to see the difference… (extension of IA?)	Introduction to the approach and comparison to CLONALG [336] A more detailed comparison of opt-IA and CLONALG (?) [337] Comparison to other approaches on function optimisation [333]
Optimised Immune Algorithm (**opt-IMMALG**) (Cutello, Nicosia, Pavone, et al.)	An extension of opt-IA	Introduction to approach [334]

The following lists additiona unclassified clonal selection works:

- Early work by Fukuda using GA's
  - Using a GA as the clonal selection bit (?) [326]
  - Application to resource allocation problem (?) [201]
  - Function optimization (?) [327]
- In evolving gene libraries for antibodies, Hightower drew a similarity between clonal selection and the Baldwin effect of life-time learning [270]
- Early work (?) [264]

5 Immune Network Paradigm

This section lists seminal works in the immune network paradigm. References are listed in no particular order.

Approach	**Description**	**References / Application**
(Farmer, Packard, Perelson)	Claimed to be a continuous immune network model	A dynamic model of the immune system based on the immune network theory, and similarity to classifier systems [127]

(**JISYS**)
(Hunt, Cooke, et al.)
	Learning system inspired by the immune network theory.
	// refers to work as content-addressable memory
	// similar to CBR systems
		Related (?) used to classify DNA sequences [59], [149]
		Extension and application to the game of tic-tac-toe [148]
		Related (?) on the matching algorithm (?) [150]
		Perhaps related (?) Immunizing against fraud [147]
		Renamed to JISYS (?) [152]
		Augmented JISYS and application to learn trends in loan application data [154]

Artificial Immune Network (**AIN**) (Timmis, Neal, Hunt)	An extension of Hunt, Cooke's work (JISYS) with the major addition being ARB's. Immune network approach for data analysis, unsupervised clustering and visualisation	Proposal of approach for unsupervised clustering and visualisation [165] Extension and comparison with SOM [164] // related (?) [151]
Resource Limited Artificial Immune System (**RLAIS**) (Timmis, Neal)	An extension and rename of AIN, AIN refers to the model constructed by the approach	Application to unsupervised clustering and visualisation [163], [162] Culminating work [169]
Artificial Immune Network (**AINE**) (Knight, Timmis)	An extension and rename of RLAIS // proposed to be a discrete immune network model	Summary of work [167] Improvement and corroboration of results and additional testing on larger datasets [315] Investigation into parameters of AINE [158] (tech report) Assessing the performance of AINE [316] (tech report) Proposal of approach as a redesigned multilayered version of AINE (parallel to SSAIS) [317], [318] Thomas' thesis???
Self-Stabilising Artificial Immune System (**SSAIS**) (Neal)	An extension of RLAIS that is capable of finding stable clusters (parallel work to AINE and multi-layered redesign of AINE)	Proposed and applied to data analysis [239] Simplification of the approach [240]

Artificial Immune Network Visualisation (**aiVIS**) (Timmis)	A tool for visualising models prepared by AIN, RLAIS, AINE and SSAIS	Visualisation approach for unsupervised cluster models (AIN) [159]
Enhanced/Fuzzy Artificial Immune Network (**Enhanced/Fuzzy AINE**) (Nasraoui, Gonzalez, Dasgupta, et al.)	Extension of AINE that incorporates fuzzy sets in the ARB's	Proposal of Enhanced AINE and application to web-profile learning [247] Proposal and application of fuzzy AINE to learning user web-profiles [249] Application to synthetic data and web profiles [246] Extension that includes a dynamically weighted B-cell (D-W-B-cell) mechanism [248]
Artificial Immune Network Algorithm (**aiNet**) (de Castro, Von Zuben, Timmis, et al.)	Combines clonal selection and immune network properties. The aiNet is proposed as an immune network extension to CLONALG. // proposed to be a discrete immune network model	Proposal for unsupervised learning (clustering) [205] Presentation and investigation for unsupervised data clustering, compared to SOM, parameter sensitivity [206] Applied to machine learning and data compressing applications & comparison to neural networks [207] Summary of aiNet (and CLONALG) [213] Extracting classes and class hierarchies as well as convergence properties of the approach [214] Application of aiNet to bioinformatics [107]
Optimised Artificial Immune Network Algorithm (**opt-aiNet**) (de Castro, Von Zuben, Timmis, et al.)	An extension of aiNet for function optimisation	Proposed extension (opt-aiNet) for multimodal function optimisation [211] Summary of aiNet and opt-aiNet [203] Verification of results of opt-aiNet, minor fixes [161] Comparison of opt-aiNET, BCA and a GA [160] Extension of opt-aiNet (dopt-aiNet) for dynamic function optimisation [95]
Antibody Network (**ABNET**) (de Castro, Von Zuben, et al.)	A neural network approach inspired by the immune system (?)	Use of CLONALG to explain how the model is activated [216]
(Wierzchon, Kuzelewska)	AIN as a unification of ideas from AINE and aiNet	Proposed as a unified AIN from AINE and aiNet [283]
Simple Artificial Immune System (**SAIS, YSAIS**) (Gaspar, Collard, et al.)	Immune network approach for time-dependant optimisation. Makes use of clonal selection principles as well.	Proposal for time-dependant optimisation (TDO) [12] Renamed (YSAIS) more robust approach for TDO with niching-like properties [13], [11]
Recommender System (Cayzer, Aickelin) (Morrison, Aickelin) (Aickelin, Chen)	Immune network inspired (unsupervised) recommender system – collaborative filtering (given a film, make a prediction for other like films)	Proposed approach and applied to film user profiles [297] Extension of the recommender system to better understand the idiotypic effect [296] Improved version of the approach [298] Extension of (inspired by) approach user profiling of web data [325], [324] Extension of previous work, the effects of many different similarity measures, applied to movie recommendations [331], [330]
Genetic Immune Recruitment Mechanism (**GIRM**) (Bersini, et al.)	Recruitment strategies to improve the local search capabilities of a genetic algorithm	Related (?) [124] Related (?) [118] Immune recruitment mechanism (GIRM) (?) [122] Related to recruitment learning (?) [120] Related (?) [119] Related (?) [122] Adaptive distributed control and the recruitment mechanism applied to so control problems [123] Related book chapter (?) [121]
Distributed diagnosis model (Ishida, Mizessyn, et al.)	A distributed diagnosis model inspired by the immune network Self organisation (?) A complex systems and knowledge processing perspective using the immune network model	Related – sensor diagnosis (?) [354] Related – process diagnosis (?) [347] Distributed diagnosis application of faulty sensors in a cement plant [85] Extension including the use of an agent-based architecture based on local memory applied to an adaptive disturbance neutraliser [355] Sensor-based diagnosis using self organisation [348], [352] Related (self organisation) (?) [350]

The following lists additional uncategorised works from the immne network paradigm:

- An overview (taxonomy) of AIN approaches [171]
- Immunity-Based Genetic Algorithm: early application to VLSI clonal selection and GA [125] (IGA)
- Combining immune network with LVQ (distributed diagnosis system) [231]

- Relation to ANN
    - Immune network as parallel-distributed processing (PDP) [86]
    - Proposal of the immune network as a PDP model (Ishida) [346]
    - Immune network as a neural network (?) [87]
    - A neural network analogy of the neural network [104]
- A confirmation and extension of Farmer's model [103]
- An extension of Farmer's model as a probablistic model [170]
- Immune network models are too simple (epitope and paratope) (Garrett) [275]

6 Danger Signal Paradigm

This section lists works from the danger signal paradigm. References are listed in no particular order.

Approach	Description	References / Application
(Aickelin, Cayzer, et al.)	Proposal of Danger theory in AIS, adoption in intrusion detection – an alternative perspective to self/nonself discrimination	Proposal of Danger Theory as a useful process in AIS [332] Extension of previous work, proposal as an IDS [329], [176], [133] The use of sage and danger signals applied to anomaly detection in system calls [180]
(Secker, Freitas, Timmis)	A danger area is defined as an area (document) of interest (interesting signal)	Introduction and proposed application as an adaptive mailbox filter (email filter) [24] Proposed as an extension to AISEC [25]

7 Other Works

This section lists works that do not neatly fit into the prevous computational paradigm categories. References are listed in no particular order.

Approach	Description	References / Application
Co-evolutionary Sparse Distributed Memories (**COSDM**) Self-Organising Sparse Distributed Memory (**SOSDM**) (Hart, Ross)	Combining ideas from immunology and Sparse Distributed Memories (SDM), an extension of the argument that immunological memory is associative presented in [64]	Proposal of COSDM, evolved using a co-evolutionary GA, applied to data clustering in time series data [79] Extension called (SOSDM) applied to clustering benchmark data as well as non-stationary datasets [81], [80] Culminating work [77]
(Oda, White)	Spam email filter Involved creating a library of regular expressions (lymphocytes)	Proposed approach [312] Improving the accuracy [313] Summary and comparison [314] Culminating work [311]
Artificial Immune System for Email Classification (**AISEC**) (Secker, Freitas, Timmis)	Spam email classification system	Proposal of AISEC as an email classification system [23] A danger theory inspired extension to AISEC [25] Perhaps a related thesis (?) [144] Secker's thesus [22]
IBM AntiVirus (Kephart, et al.)	Classical work by IBM on an AIS as an anti-virus system	Proposal of an immune system for computers [139], [142] An immune system to protect computers from the internet [140] An immune system for computers [141]
Computer Immune System for Fraud Detection (**CIFD**) (Kim, Ong, Overill)	Application of both positive and negative selection for retail fraud	Proposal of the approach applied to detecting financial fraud [179]
Multilevel Immune Learning Algorithm (**MILA**) (Dasgupta, Yu, Majumdar)	Pattern recognition (anomaly detection) with multiple detection schema, clonal expansion, and dynamic detector generation	Proposal of the approach [65], [47]
(**Immunos-81**) (Carter)	Supervised classification system inspired by populations of T and B cells (clonal selection)	Proposal of the approach [145]
Site Configuration Engine (**Cfengine**) (Burgess, et al.)	The work is on network computer security, although there is an immunological inspiration influencing	Proposal of Cfengine (not immunological) [234], [238] Using ideas of immunology for reliable software

	the work	systems [235] A review of the immunity model used in Cfengine [236] On hybridising pH with Cfengine [197] Immunological properties as they relate to lazy evaluation and probabilistic models [237] // many other unrelated references on Cfengine
(Hajela, Yoo, et al.)	Immune network to handle constraints within a genetic algorithm	Related (?) [260] Application of embedded immune network in a GA to multi-objective design and optimisation [261], [178]
(Hightower, Forrest, et al.)	Evolution of gene libraries	Use of a genetic algorithm to evolve immune system genes for a binary immune system model (secondary effect is organisation within the genes) [269], [272] Extension of the previous model to include Baldwin learning [270] Culminating work [271]
Tissue / Dendric Cell Algorithm (**libtissue**, **DCA**) (Greensmith, Aickelin, et al.)	Tissue models inspired by the innate immune system, dendric cells and toll-like receptors	Algorithm inspired by dendritic cells (between innate and acquired systems) applied to classification [177] Proposal for using tissue in AIS (two tissue growing algorithms are introduced) for classification [258] Tissue models for feature extraction and clustering (based on SOM and toll-like receptors) [128] DC Algorithm (DCA) applied to classification data and an anomaly detection problem in real-time [173] DC Algorithm (DCA) applied to a real-time port scan problem [175] Introduction to the libtissue framework [135]

Some additional uncategorised works are listed as follows.

- Associative memory (CBR, instancse-based, content-addressable memory, etc)
  - Early work on associative memory in the immune system (?) [34]
  - Early work on associative memory in an immune network [84]
  - The relation between AIS and CBR is discussed in Chao and Forrest's work [63]
  - Also discussed in Hunt and Cooke's work

8 Distributed Artificial Immune Systems

This section considers distributed artificial immune systems, irrespective of their base computational paradigm. References are listed in no particular order.

Approach	**Description**	**References / Application**

(**iNexus**, **iNet**)
(Suzuki, Yamamoto)
(Lee, Suzuki, et al.)
	Decentralised policy negotiation – allowing applications to adapt their configurations to meet their needs
	// Decentralised and autonomous policy negotiation between applications within an application server?
	// immune network
	// inet can interact with inexus
	// extension of inet as a netsphere plugin
		iNet application framework/architecture [194]
		Summary of iNexus [193], [195]
		Related (?) [192]
		Culminating work [191]
		An extension of iNet for adaptive network applications (NetSphere plug-in) [39], [41], [40]

(Segel)	The immune system as a decentralised/distributed autonomous system	Immune system as a prototype autonomous decentralised system (a feedback model) [217] Related (?) (Segal's chapter in Dasgupta's book) [225] Related (?) (Segal's book) [224] Related (?) (Segal's chapter in his book) [220] Diffuse feedback system [220], [218] Further related diffuse feedback system – diffuse information network [219] Models of an adaptive immune system based on

		feedback (good differential equations) [226] All about the role of feedback in the immune system [222], [221] Review of spatio-temporal models of immunology [223]
(Ishida)	The immune system (immune network theory) as a model for Autonomous Decentralised Systems (ADS) // very likely to have links to his distributed sensor immune network research	Proposal of the immune network as a model for autonomous distributed systems, and the internet as an example [351]
(Le Boudec, Sarafijanovic)	Misbehaviour detection in mobile ad hoc networks (message routing). Uses ideas of negative selection and danger signals // uses danger signals	Proposal of the approach applied to dynamic source routing (tech report) [137], [138] An extension that introduces a virtual thymus, clustering and danger signals [278] Extension with the use of a secondary response [279] // more technical reports
Immunology-derived Distributed Autonomous Robotics Architecture (**IDARA, Kilorobot**) (Singh, Thayer)	Coordinate and control large scale distributed robot teams	Proposal of the architecture applied to a robot mine field [305] Introduction of IDARA for the manipulation of kilorobots (large multi-robot colonies) applied to mapping scenarios [273], [307] Extension applied to large colonies of kilorobot's for a search and rescue application[306]

(**Immunobot**, **Immunoid**)
(Ishiguro, Kondo, Watanabe, Uchikawa, et al.)
	Autonomous robot control inspired by the immune network theory (consensus making system)
	// action selection mechanism
	// originator of the term meta-dynamics in AIS???
		Autonomous robot control applied to robot navigation [8]
		Proposed decentralised consensus making system (Immunobot) [2]
		An extension applied to garbage collection with self sufficiency (Immunoid) [6], [4], [5]
		Related (?) (seminal Immunoid?) [3]
		Application to goal seeking and obstacle avoidance [7]
		Extension and inclusion of meta-dynamics, applied to a predator-prey simulation [1]
		Related (?) (book chapter) [356]

General Suppression Framework (Lau, Wong, et al.) (Ko, Lau, Lau)	Distributed control framework	Related (?) (Control system for warehouse vehicle control) [109] Related (?) [113] Related (?) [9] Automated transport system [111] Related (?) (distributed multi-agent system) [110] Distributed control framework for a modular self-reconfigurable robot arm [10] Autonomous distributed vehicle control system for an automated warehouse [114] Mathematical model of the control framework for automated warehouses, distribution centres, and automated material handling systems [112]
Distributed Autonomous Robotics System (**DARS**) (Meshref, VanLandingham)	Distributed autonomous system (multi-agent system)	Application of DARS to the dog and sheep problem (classic agent problem) [117] Related thesis (?) [116]
Artificial Immune System based Intelligent Multi Agent Model (**AISIMAM**) (Sathyanath, Shin)	Multi-agent system model	Proposal of the agent model, application to a mine detection and diffusion problem [286]
(Dasgupta)	Collaborative multi-agent decision support system // comments on the recirculation of lymphocytes	Proposal of a collaborative multi-agent decision support system as an OO platform with visualisation tools [42]

The following lists some additional uncategorised distributed AIS works.

- Use of negative selection for constraint handling in a GA island population model [38]
    - There may be more work that exists on this (defiantly on the use of NSA within a GA for constraint handling) (culminating [37])
- Immunity based learning for distributed search and constraint relaxation (?) [115]

- AIS as a context aware ubiquitous distributed system (immune network) [259]
- A distributed framework for multiple search algorithms (applied to FPGA) [153]
- Distributed algorithm for searching P2P networks (ImmuneSearch) [245]
- Multi-agent system for breaking up a problem (distributed problem solving) (immune network and MHC) applied to TSP (n-TSP) [242]
- An agent-based intrusion detection system (Dasgupta, Gonzalez) [66]
    - A very similar piece of work on agent-based intrusion detection by the same author [68]
- Robot control (autonomous, distributed, etc…)
    - Realisation of cooperative strategies in group behaviour (?) [52]
    - Immune network robot architecture for robot learning (?) [82]
    - Autonomous robot control for garbage collection (immune network) [268]
    - Immune system and fault tolerant computing (?) [284]

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