Development of Integrated Biomimetic Framework with Intelligent Monitoring, Cognition, and Decision Capabilities for Control of Advanced Energy Plants

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Goals and Objectives

Task 2.0 Development of Algorithms for Biomimetic, Self-Organizing Control Structure Selection
- Establish connectivity relationship amongst various measured variables in process plant
- Exploit connectivity matrix to develop controlled variable selection

Task 3.0 Development and Implementation of Biomimetic Controller Design Method
- Implement biomimetic controller for DYNSIM plant representing AVESTAR-WVU Center
- Integrate multi-agent optimization framework with biomimetic controller design

Task 4.0 Development of Biomimetic Adaptive Controllers with Intelligent Monitoring, Cognition, and Decision Capabilities
- Detect, identify, evaluate, and accommodate abnormal conditions
- Optimize baseline/adaptive controller parameters using EA

Task 5.0 Development of a Multi-Agent Optimization Framework for Control Structure Design, and State and Parameter Estimation
- A novel and efficient multi-agent optimization framework
- Integration to biomimetic framework and applications

Milestones

Subtask	Project Milestone Description	Planned Completion Date	Actual Completion Date
2.1	M1: Complete the input-state-output data collection for the DCM	8/15/2014	8/29/2014
2.1	M5: Successful development of the DCM	10/14/2015	10/14/2015
2.2	M10: Development of Multi-agent optimization for self-organizing controlled variable selection	10/14/2016	10/14/2016
3.1	M4: Complete the Development of Deterministic Biomimetic Controller Design	7/14/2015	7/14/2015
3.2	M6: Incorporate Adaptive Component into Biomimetic Controller	1/14/2016	1/14/2016
3.3	M11: Implement Biomimetic Controller Design in AVESTAR-WVU	1/14/2017	1/14/2017
3.4	M12: Integrate Biomimetic Controller with Multi-Agent Optimization Framework	1/14/2017	1/14/2017
4.3	M2: Completed design of the intelligent AIS system	1/14/2015	1/14/2015
4.2	M7: Successful implementation and testing of the evolutionary optimization	1/14/2016	1/14/2016
4.4	M9: Successful implementation and testing of the adaptive control laws	1/14/2016	1/14/2016
4.3	M13: Successful implementation and testing of the intelligent monitoring system	10/14/2016	10/10/2016
5.2	M8: Development of MP, EGA, and ESA agents	1/14/2016	1/14/2016
5.3	M14: Development of optimal control agents	2/14/2016	2/7/2016
5.4	M3: Development of Ant Colony Optimization New Algorithm and Agent	9/28/2016	9/30/2016

Outline

- **Introduction**
  - Challenges
  - Approach

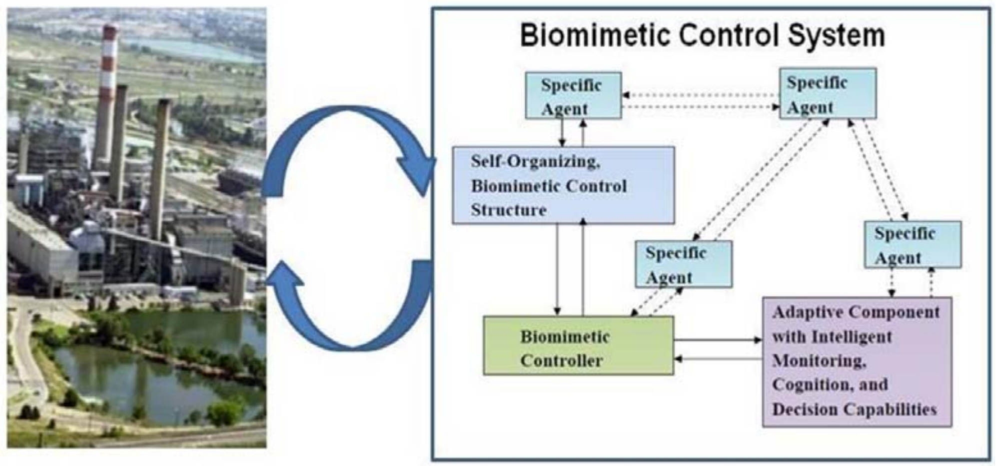
- **Task 2.0: Development of Algorithms for Biomimetic, Self-Organizing Control Structure Selection (Task Lead: Prof. Debangsu Bhattacharyya, WVU)**
  - Dynamic casual model
  - Methodology
  - Acid gas removal unit

- **Task 3.0 Development and Implementation of Biomimetic Controller Design Method (Task Lead: Prof. Fernando Lima, WVU)**
  - BIO-CS implementation for IGCC-AGR sub-system
  - BIO-CS with multi-agent optimization framework

- **Task 4. Development of Biomimetic Adaptive Controllers with Intelligent Monitoring, Cognition, and Decision Capabilities (Task Lead: Prof. Mario Perhinschi)**
  - Artificial immune system (AIS) paradigm
  - Artificial immune system for IGCC-AGR sub-system
  - Example results

- **Task 5: Development of Multi-agent Optimization Framework for Integration with Biomimetic Control (Task Lead: Prof. Urmila Diwekar)**
  - A novel and efficient agent based optimization system
  - Real world case studies
  - Integration with biomimetic framework and applications

Our Approach



- Self-organization of the control structure that mimics the function of the cortical areas of human brain
- Distributed and adaptive controllers that mimic the rule of pursuit present in ants
- Intelligent monitoring, cognition, and decision capabilities that mimic the immune system
- Seamless integration and coordination in the entire framework that includes both the control structures and the controllers by mimicking the central nervous system

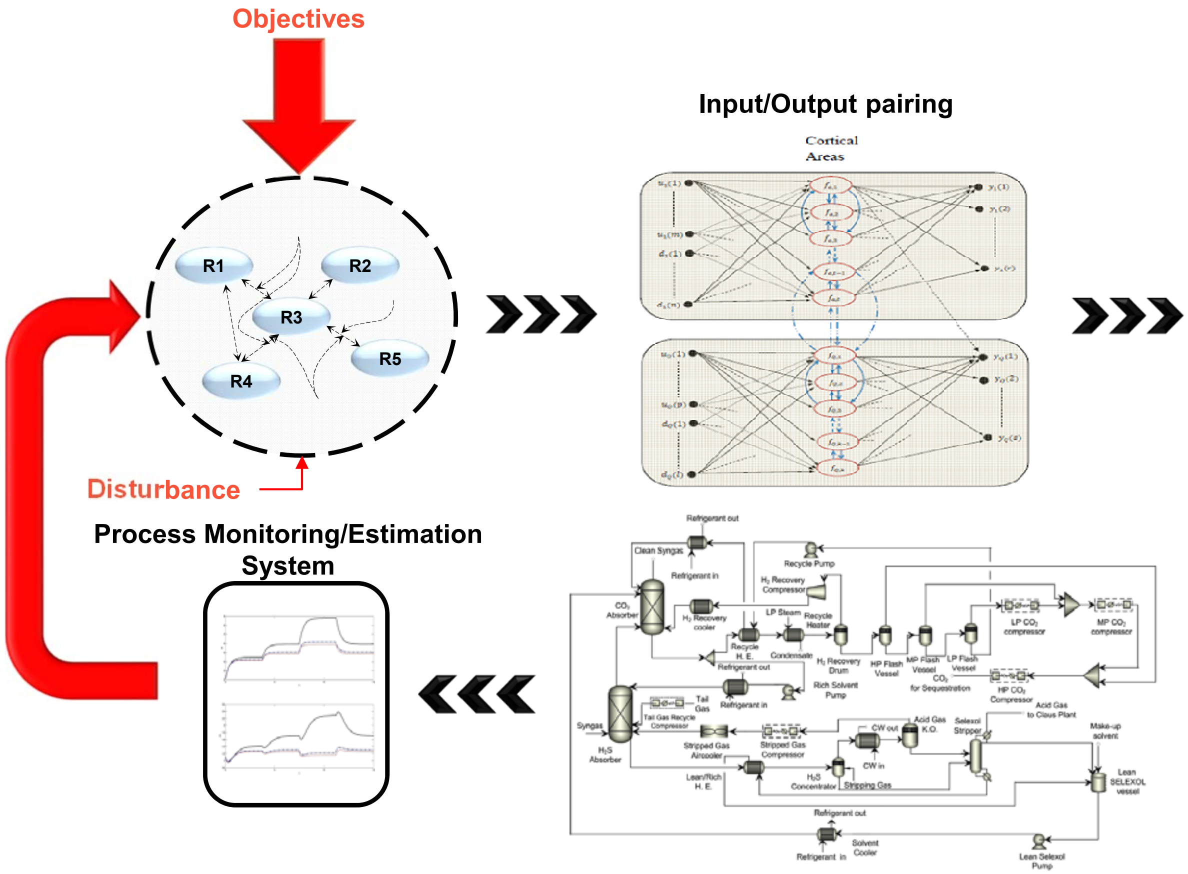
Task 2.0 Development of Algorithms for Biomimetic, Self-Organizing Control Structure Selection

Traditional	Biomimetic
• Selection of controlled variable typically based on heuristics/process knowledge	• Algorithmic approach uses biologically inspired methods
• Systematic approach involves computationally expensive branch and bound algorithm	• Efficient multi-agent optimization methods and coordination of tasks lower computation time significantly
• Computes controlled variable selection for the entire system making the approach intractable for large-scale systems	• Connectivity information is exploited for optimal decomposition of the plant into multiple islands
• Can only be deployed **offline** due to computational limitations	• Can be deployed **online** due to optimal decomposition of the plant, multi-agent optimization, and parallelization

Task 2.0 Development of Algorithms for Biomimetic, Self-Organizing Control Structure Selection

Task 2.1 Development of Dynamic Causal Model (Q1-Q8)

- Exploits the functional specialization and integration that characterizes the cortical/sub-cortical areas of human brain

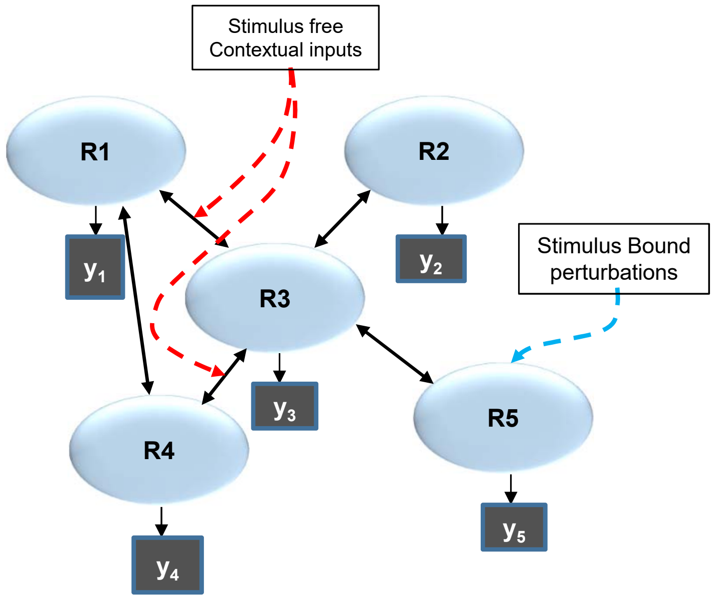


Dynamic Causal Modeling

- **Latent Connectivity**
- **Induced Connectivity**
- **Extrinsic Influence of Inputs**

$$\dot{z} = \left(A + \sum_j u_j B^j\right) z + Cu$$

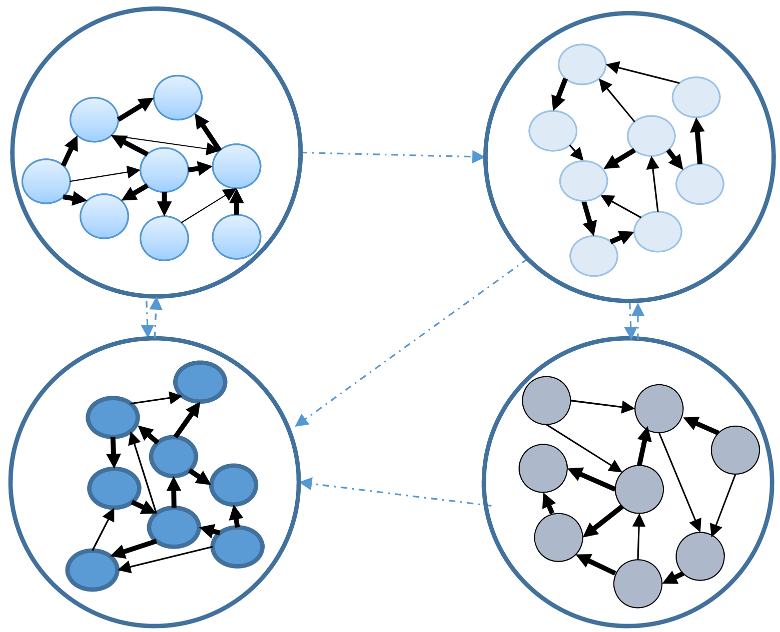
$$\hat{\theta} = \{A, B^j, C\}$$



Friston, K J., Lee H., and Will P., "Dynamic causal modelling."Neuroimage 19.4 (2003): 1273-1302.

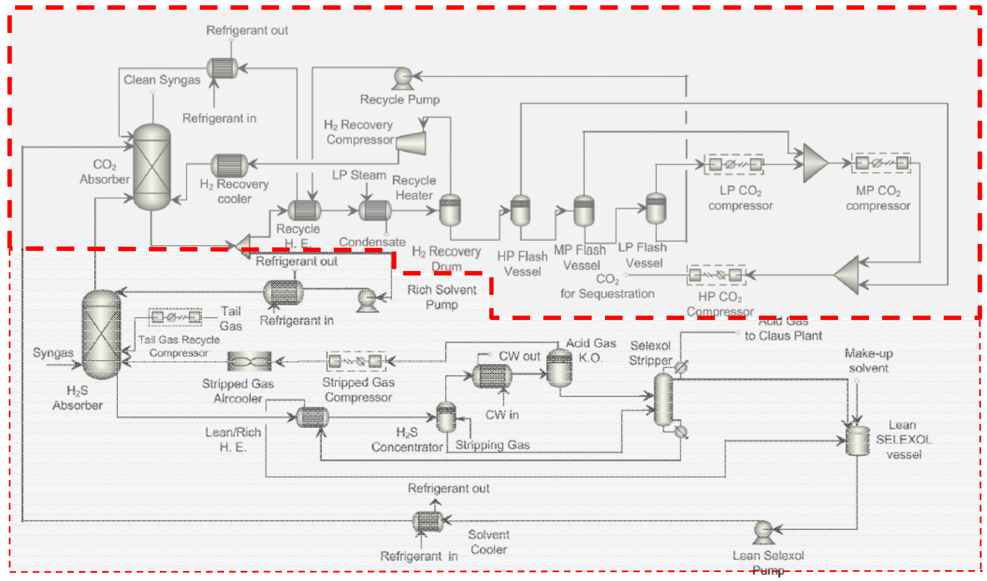
Dynamic Selection of Controlled Variables

- Establish levels of connectivity between plant sections (islands)
- Separate islands based on connectivity
- Parallelize controlled variable selection
- Reduction of combinatorial problem of controlled variable selection
- Controlled/manipulated variable selection



Acid Gas Removal Unit

- **CO_2 Absorber section**
  - ➢ CO_2 absorption
  - ➢ H_2 recovery
  - ➢ CO_2 recovery
  - ➢ Lean solvent recycle
  - ➢ CO_2 sequestration



- **H_2S Absorber/Selexol stripper section**
  - ➢ H_2S absorption
  - ➢ H_2S recovery
  - ➢ Selexol stripping/recovery

- 32 independent input variables
- 38 independent output variables

Results: CO_2 Absorber section

Strong connectivity from:

- CO_2 absorber to H_2S absorber
- H_2 recovery drum to CO_2 absorber
- LP flash drum to CO_2 absorber

Weak connectivity from:

- CO_2 absorber to HP flash

Strong connectivity from:

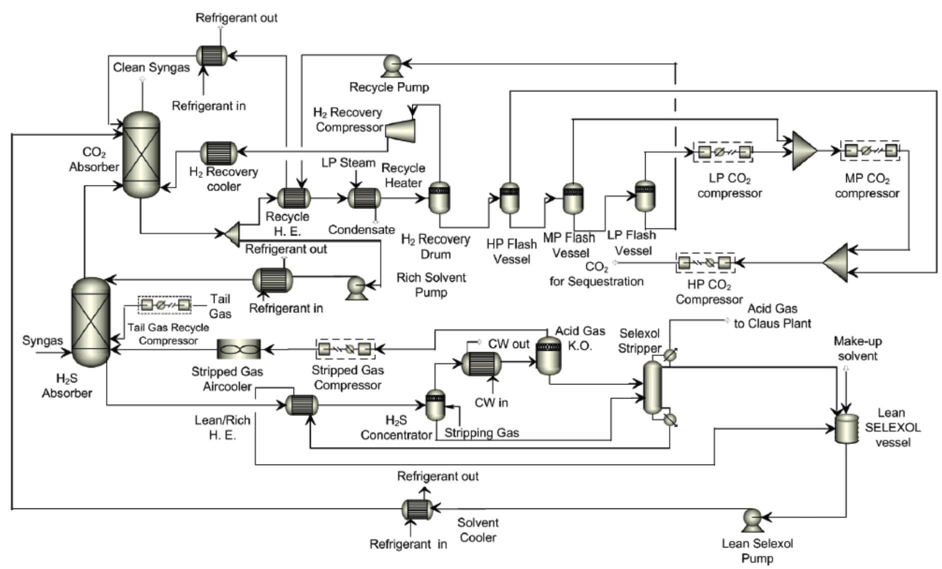
- HP flash to MP flash
- MP flash to LP flash
  - ➢ Due to *H_2 vapor only*

			CO_2 Absorber	HP flash	MP flash	LP flash	H_2S absorber
CO_2 Absorber	H_2S	Vapor					
		Liquid					
	CO_2	Vapor					
		Liquid					
	T						
H_2 recovery drum	H_2S	Vapor					
		Liquid					
	CO_2	Vapor					
		Liquid					
	T						
HP flash	H_2	Vapor					
		Liquid					
	CO_2	Vapor					
		Liquid					
	T						
MP flash	H_2	Vapor					
		Liquid					
	CO_2	Vapor					
		Liquid					
	T						
LP flash	H_2	Vapor					
		Liquid					
	CO_2	Vapor					
		Liquid					

Strong Weak

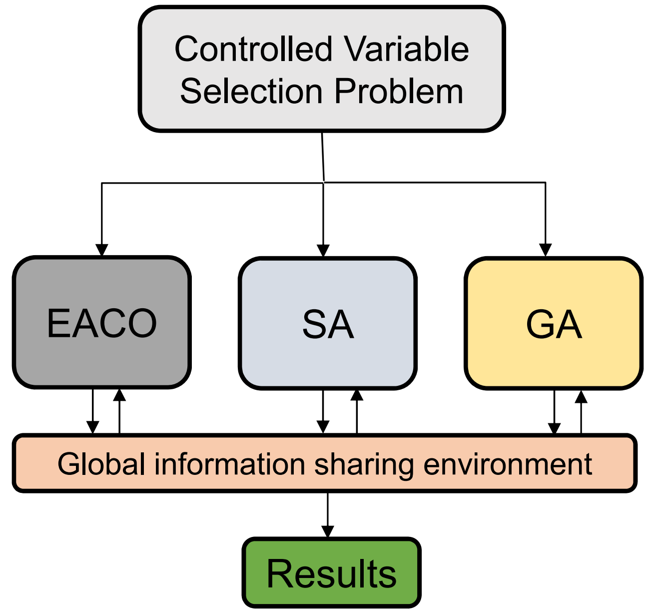
Biomimetic Controlled Variable Selection

- Acid gas removal unit modeled in DYNSIM® environment
- **Goal**: Selectively choose outputs to control which *minimize* drift from optimal cost function
- Objective: Maximize economic cost as well as controllability
- $\binom{230}{5} = 5.1339 \times 10^9$ possible combinations
- Recent approaches:
  - Heuristic methods:
  - Branch and Bound
  - Multi-agent methods:
    - Efficient Ant Colony (EACO)
    - Simulated Annealing(SA)
    - Genetic algorithm(GA)



Biomimetic Controlled Variable Selection

- Mixed integer non linear problem is passed into the multi-agent framework.
- Each solver represents a meta heuristic biological agent.
- Each agent is initialized with required parameters.
- After every iteration, communication and sharing of information ensues.
- Solution is compared and stored.
- Best solutions are retained for post-processing.



Sets	Controlled variables					J
C0	7	116	197	204	207	0.20224
C1	8	116	197	204	207	0.20306

Optimal controlled variable sets

7 : $(x_{CO2})_{06}$ CO_{2Abs}; **116**: $(x_{H2S})_{12}$ H_2S Abs; **197**: (y_{CO2}) H_2flash; **204:** (H_2) MP flash; **207**: $(x_{CO2})_{01}$ H2S conc.

Contributions and Novelty

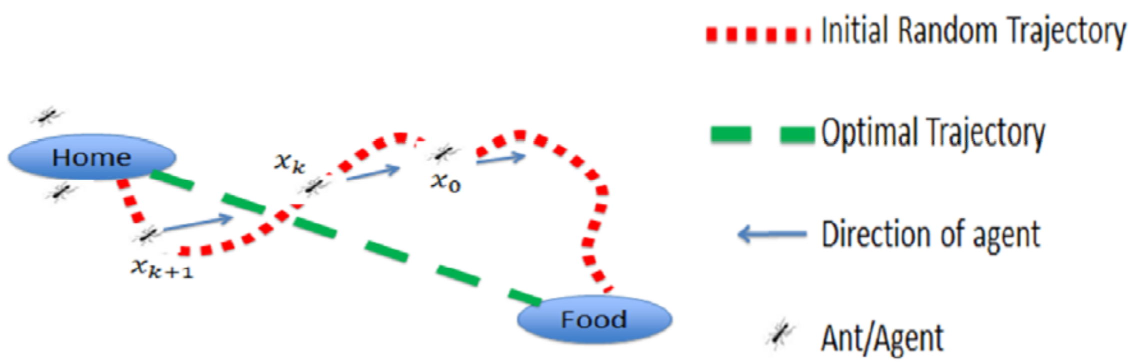
Unique features of Biomimetic controlled variable selection:

- ✓ Development of a novel algorithm that can be applied for online optimal adaptation of control structure
- ✓ Biomimetic algorithm developed for extracting connectivity information from operational data
- ✓ Connectivity information is exploited for controlled variable selection
- ✓ Multi-agent optimization leads to faster, parallelized approach that is significantly faster than the traditional methods

Task 3.0 Development and Implementation of Biomimetic Controller Design Method

Task 3.1 Development of Deterministic Biomimetic Controller Design (Q1-Q6)

- Biologically-Inspired Optimal Control Strategy (BIO-CS) has been designed (Milestone#4 report)
- Proposed strategy has been implemented to address chemical and power systems (e.g., fermentation process, IGCC-AGR sub-system, HYPER transfer function model)
- Unique features of BIO-CS for improved computational performance:
  - ✓ Algorithm termination at a suboptimal solution corresponding to a specific agent
  - ✓ Possibility of parallelizing optimal control problems associated with different agents



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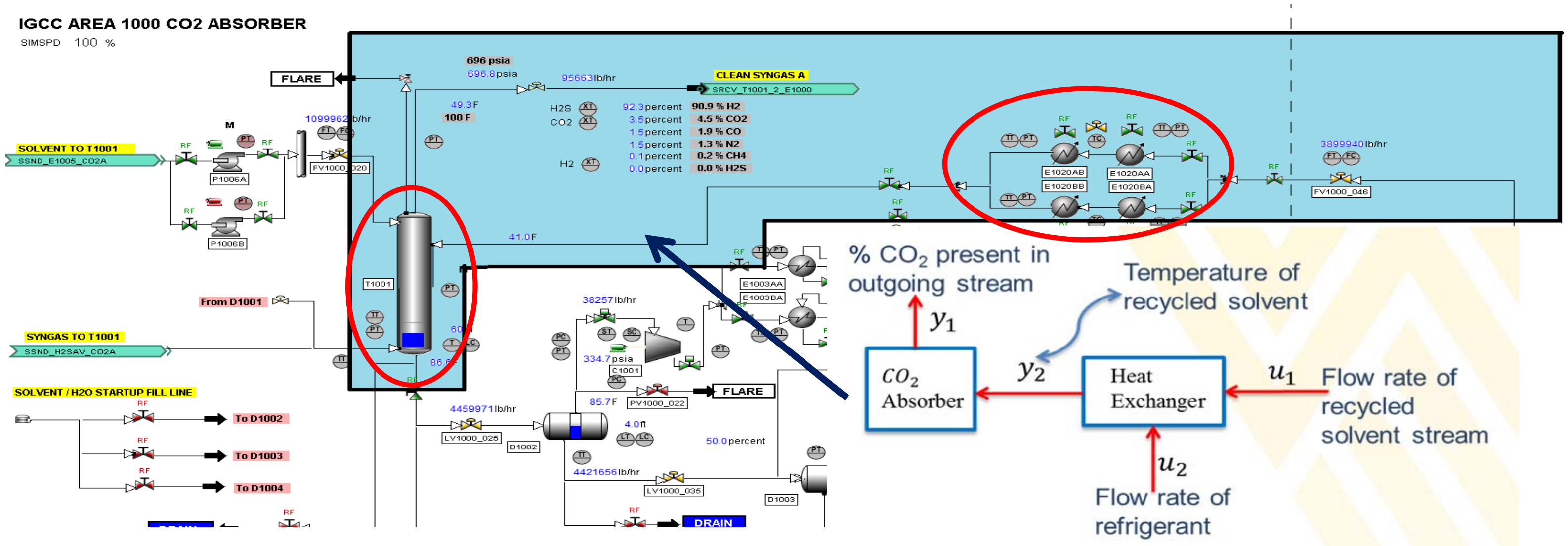
Task 3.2 Incorporation of Adaptive Component into Biomimetic Controller Design (Q5-Q9)

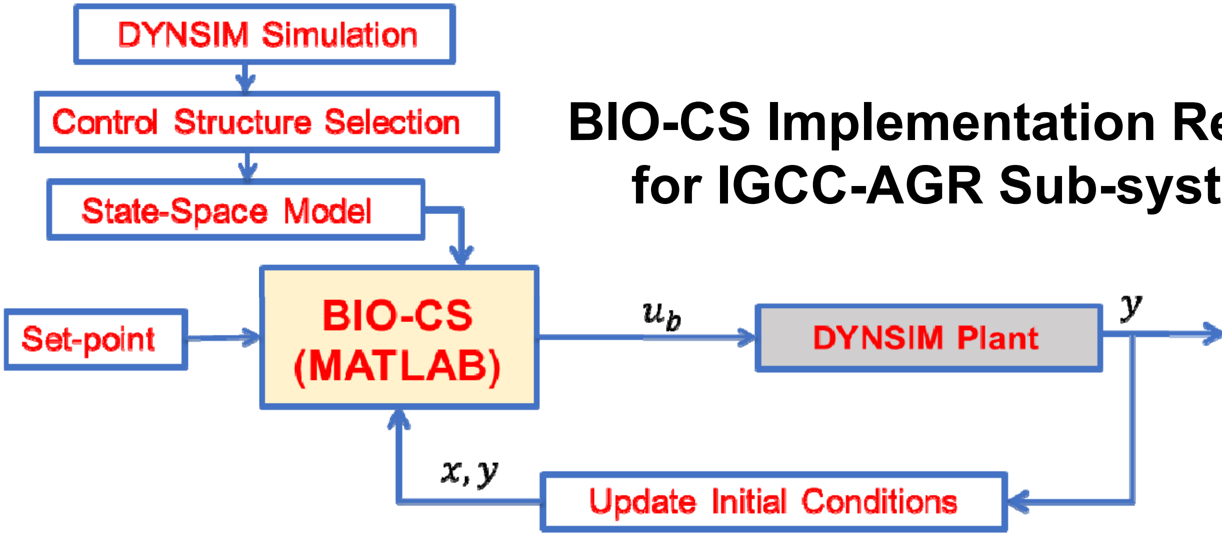
- Adaptive component has been incorporated into BIO-CS in collaboration with Dr. Perhinschi's group (Milestone#6 report)
- Proposed framework has been applied to IGCC-AGR sub-system

Task 3.3 Implementation of Biomimetic-based Method in AVESTAR-WVU Center (Q6-Q12)



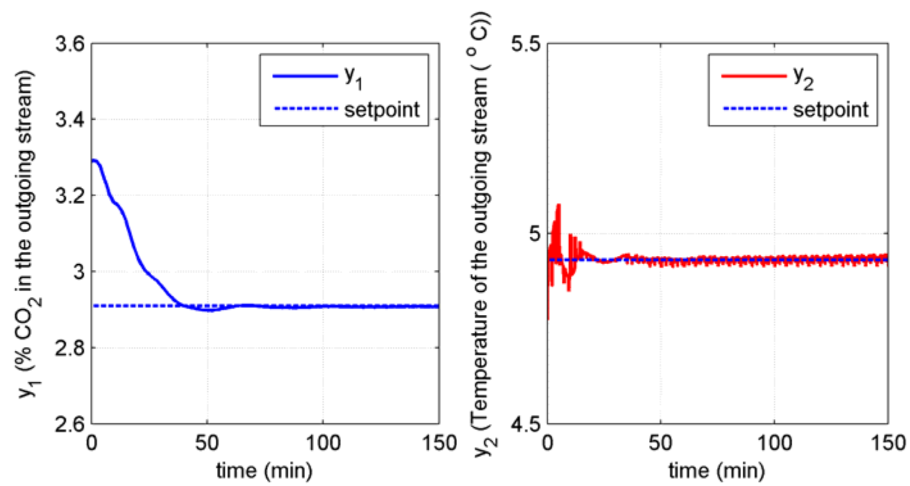
DYNSIM simulation of IGCC-AGR (Integrated Gasification Combined Cycle – Acid Gas Removal):

- Selective removal of CO_2 using solvent absorption process
- Multivariable (2×2) control structure is selected for BIO-CS implementation
- Data-driven model is developed for controller design purpose
- Goal: setpoint tracking of y_1 while keeping the other output y_2 at a steady setpoint



BIO-CS Implementation Results for IGCC-AGR Sub-system

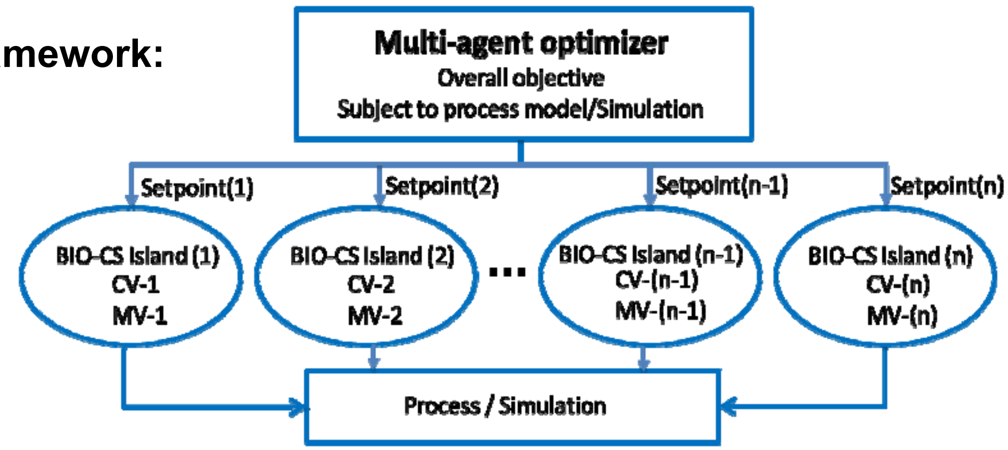
- Implementation of BIO-CS as supervisory controller
- MATLAB-DYNSIM link employed for implementation of control laws
- Current focus is on online application with adaptive component to different scenarios (e.g., plant-model mismatch)*



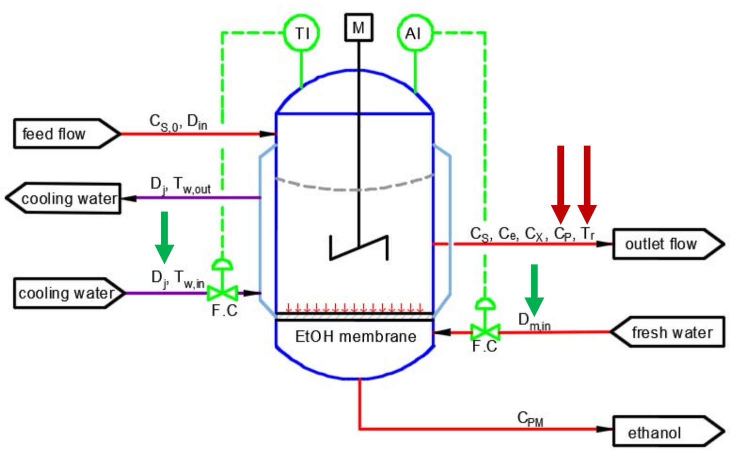
*In collaboration with Dr. Perhinschi's group

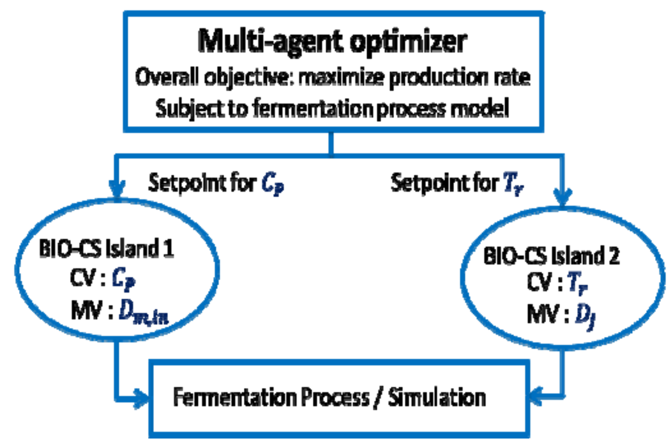
Task 3.4 Integration of Controller Design Method with Multi-agent Optimization Framework (Q9-Q12)

Overall framework:



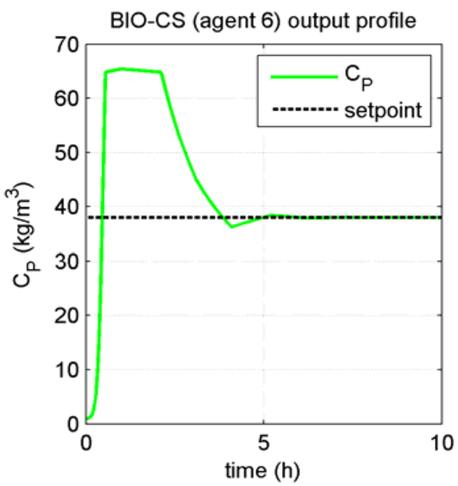
Fermentation process implementation case study:

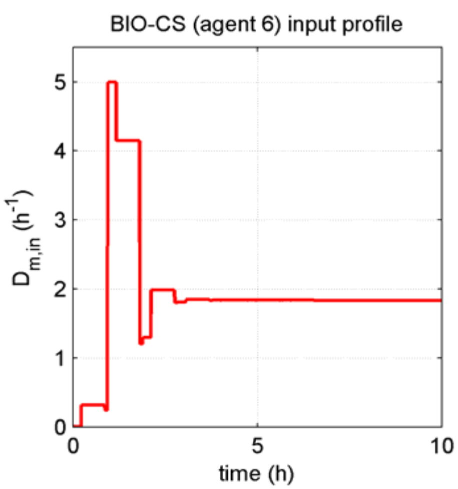




BIO-CS with Multi-agent Optimization Results*

BIO-CS Island-1





Multi-agent optimization results:

Max. production rate: $0.93\ kg/h$

Optimal setpoints:

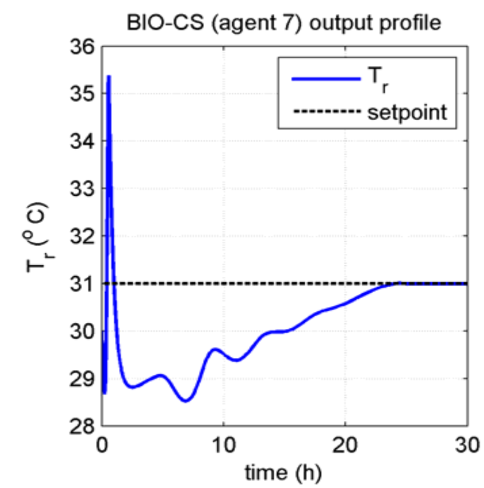
$$C_{P,sp} = 38\ kg/\text{m}^3$$

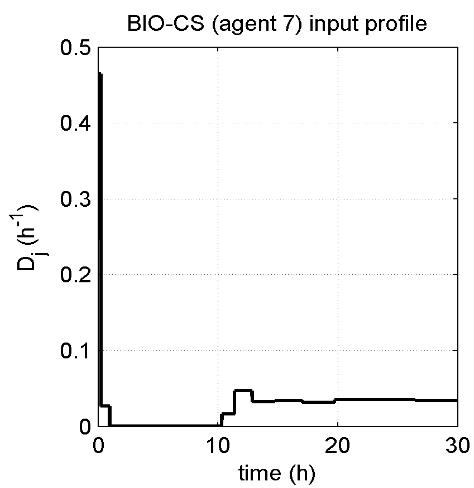
$$T_{r,sp} = 31°\text{C}$$

- Current focus is on addressing the IGCC-AGR DYNSIM plant
- Future work will consider use of ant-colony-based solver (EACO) towards model-free control

*In collaboration with Dr. Diwekar's group

BIO-CS Island-2

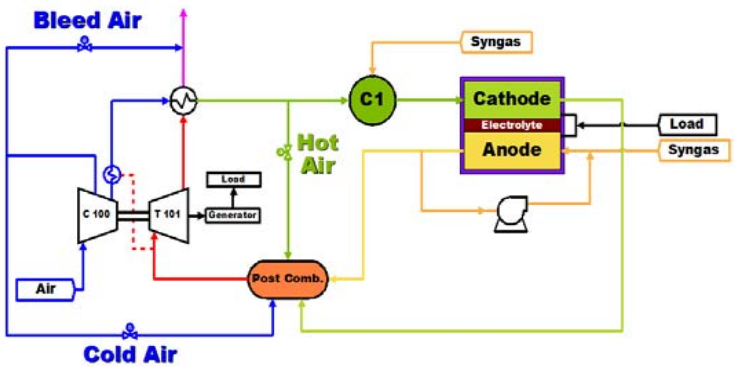


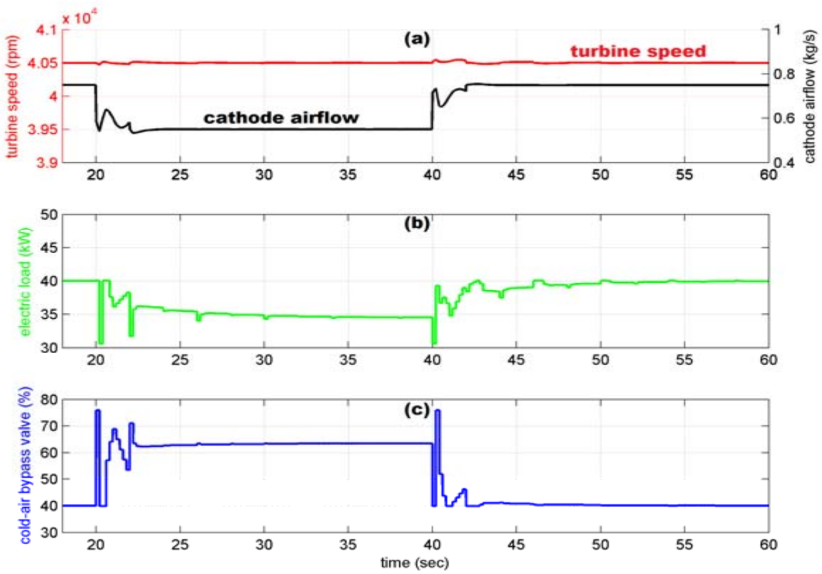


Ongoing Collaboration

Application to HYPER process*:

- Implement BIO-CS for MIMO (2×2) transfer function sub-system
- Simultaneously control multiple outputs at desired setpoints





BIO-CS implementation results:

- Effect on turbine speed due to coupling was limited to 0.2%
- Future plans include potential implementation of BIO-CS for HYPER process at NETL (in collaboration with Ames Lab)

*Mirlekar G. V., Pezzini P., Bryden M., Tucker D. and Lima F. V., “A Biologically-Inspired Optimal Control Strategy (BIO-CS) for Hybrid Energy Systems”. To appear in Proceedings of the 2017 American Control Conference (ACC).

Contributions and Novelty

Unique features of BIO-CS for online implementation:

✓Algorithm termination at a suboptimal solution corresponding to a specific agent

✓Possibility of parallelizing optimal control problems associated with different agents

✓Future work will consider use of ant-colony-based solver (EACO) towards model simplification or model-free control

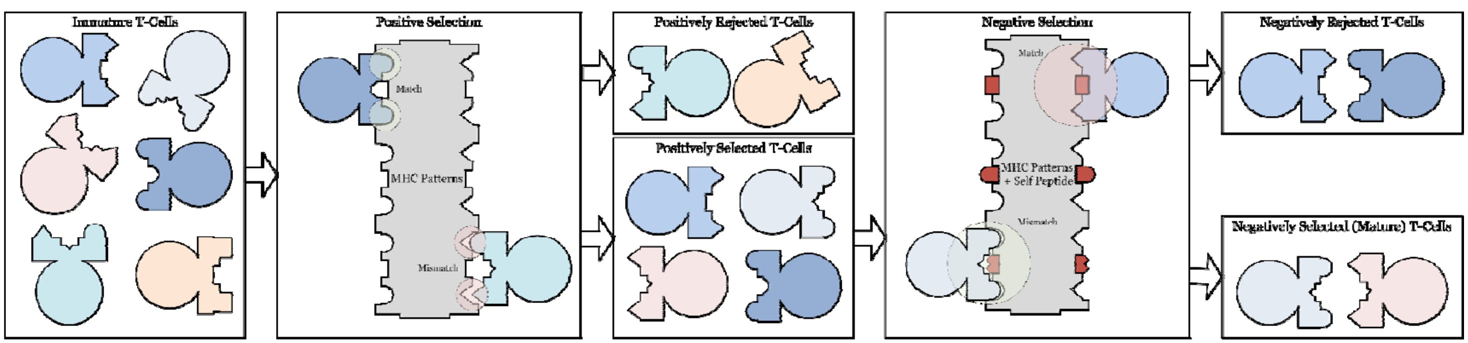
Task 4. Development of Biomimetic Adaptive Controllers with Intelligent Monitoring, Cognition, and Decision Capabilities

- **Objective:** Development of an intelligent, comprehensive, and integrated framework for advanced power plant monitoring and control. Development and testing of specific methodologies, techniques, and algorithms.
- **Approach:** The artificial immune system (AIS) paradigm is inspired by mechanisms of the biological immune system, which exhibit all the valuable characteristics needed to solve the problem of monitoring and controlling complex multi-dimensional technical systems in comprehensive and integrated manner.

AIS Paradigm for abnormal condition detection, identification, evaluation, and accommodation (ACDIEA) relies on mechanisms that distinguish between elements of the "self" and "non-self".

The immunity based AC accommodation is approached based on the biological feedback that establishes a balance between the activation and suppression of the antibodies generation.

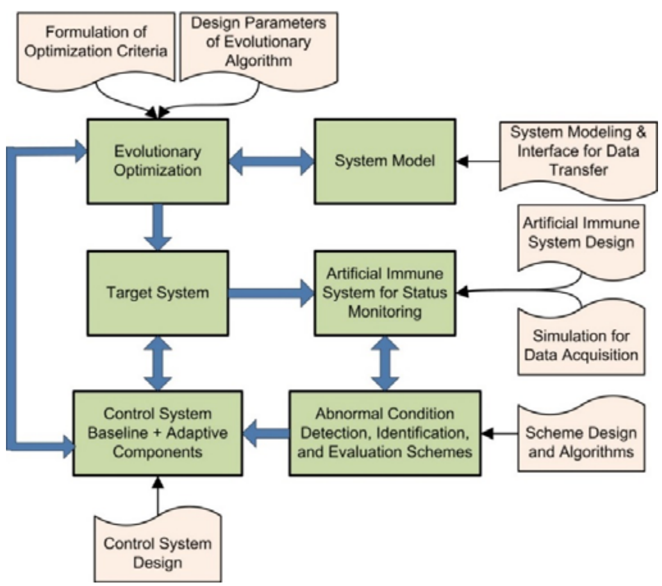
The immunity evolutionary optimization relies on the general concept of genetic optimization augmented with mechanisms inspired by the generation of highly specific and effective antibodies.

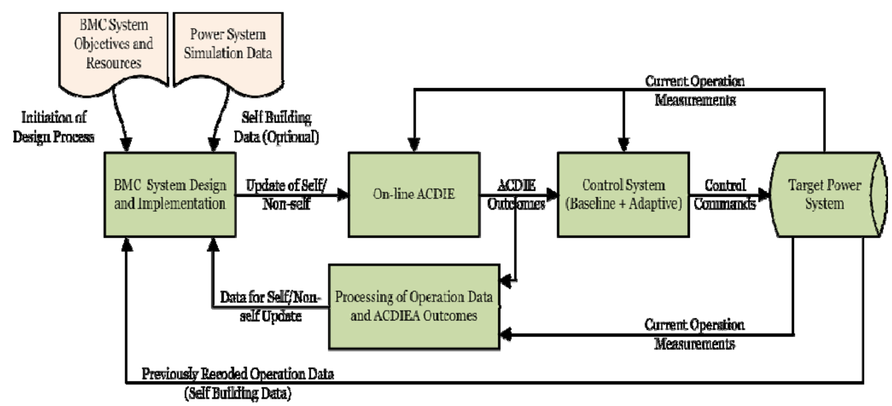


AIS-based Framework for ACDIEA

The ACDIEA monitoring and control framework has an integrated structure and provides comprehensive outcomes in order to address the complexity and multi-dimensionality of chemical processes in a coherent and consistent manner and the variety of all scenarios involving all relevant subsystems and the possible, known and unknown ACs.

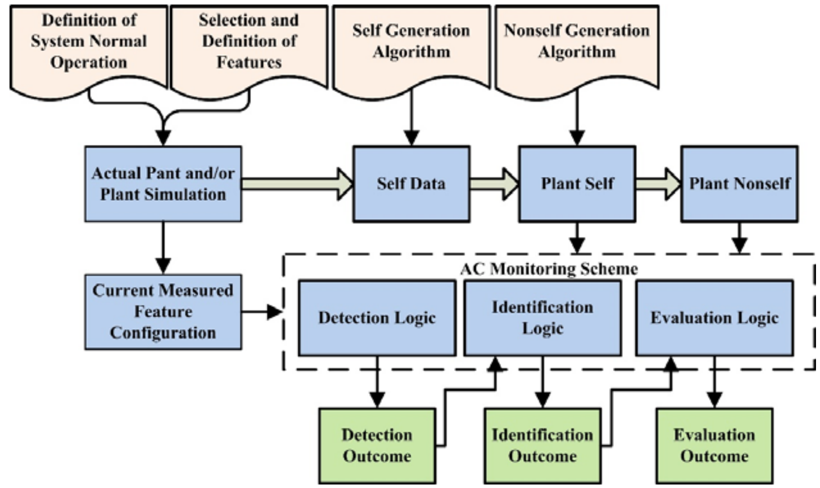
ACDIE algorithms must be fast enough to detect, identify, and evaluate the AC before reading the next online data .
The control framework should be fast enough to provide adequate AC accommodation.
The system should have online-learning capability to adapt to new conditions.
The development and use of all tools and mechanisms within the framework must be straightforward, simple, and affordable.





Artificial Immune System for ACDIE

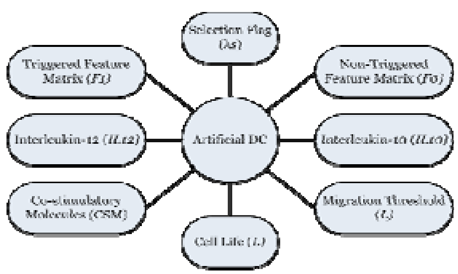
Building the AIS may be regarded as a data-driven modeling methodology that relies on exhaustive collections of system feature measurements and derived variables.

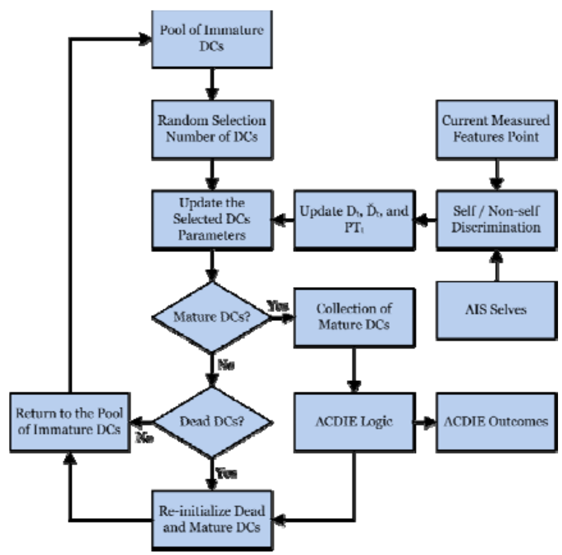


A novel approach to generate the technical system self called the partition of the universe approach (PUA) was developed to facilitate the use of full-dimensional self for system abnormal condition detection .

A novel dendritic cell mechanism has been proposed for ACDIE.

Self Partition Cluster # 1	p_{11}	p_{12}	· · ·	p_{1i}	· · ·	p_{1N}
Self Partition Cluster # 2	p_{21}	p_{22}	· · ·	p_{2i}	· · ·	p_{2N}
⋮				⋮		
Self Partition Cluster # j	p_{j1}	p_{j2}	· · ·	p_{ji}	· · ·	p_{jN}
⋮				⋮		
Self Partition Cluster # Nc	p_{Nc1}	p_{Nc2}	· · ·	p_{Nci}	· · ·	p_{NcN}





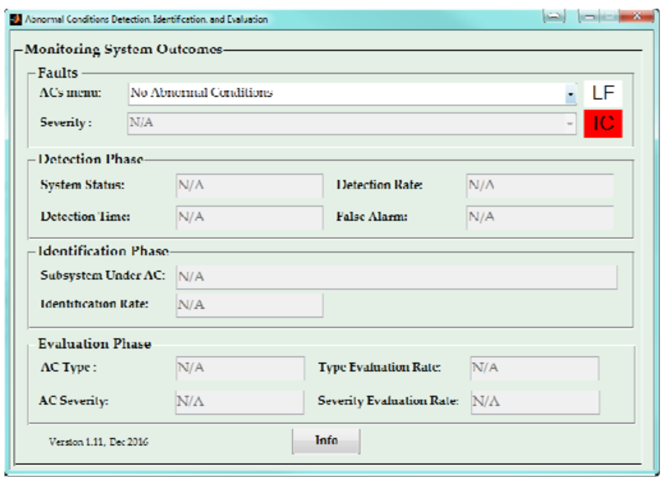
Example Results

The acid gas removal (AGR) unit is part of an integrated gasification combined cycle power plant.

A total of 77 features were selected to build the self of the AGR unit, including pressure, temperature, flow rate, and composition measurements across the unit.

Over 700 tests each lasted 270 minutes by varying 6 most significant inputs were used. Normal versus abnormal operation is determined based on system constraints

For the purpose of demonstrating the operation of the proposed ACDIE scheme, a number of 14 AC that include deposit of solids, such as flyash, and leakages in the pipes or equipment items are presented.



#	AC
1	Reduction in the area of the 13^{th} tray of the CO_2 absorber
2	Reduction in the area of the 15^{th} tray of the CO_2 absorber
3	Reduction in the area of the 23^{rd} tray of the H_2S absorber
4	Reduction in the area of the 26^{th} tray of the H_2S absorber
5	Reduction in the area of the 4^{th} tray of the H_2S concentrator
6	Reduction in the area of the 6^{th} tray of the H_2S concentrator
7	Reduction in the heat transfer coefficient of lean/rich H.E
8	Leakage in the H_2 recovery compressor suction line
9	Leakage in the H_2 recovery flash drum liquid phase
10	Leakage in the H_2S acid gas knock-out drum liquid phase
11	Leakage in the CO_2 low pressure flash drum vapor phase
12	Leakage in the CO_2 medium pressure flash drum vapor phase
13	Reduction in the area of the 8^{th} tray of the SELEXOL stripper
14	Reduction in the area of the 11^{th} tray of the SELEXOL stripper

Example Results

The Performance of the ACDIE is evaluated using detection time (DT), detection rate (DR), identification rate (IR), type evaluation rate (TER), and severity evaluation rate (SER). No false alarms were recorded in all cases.

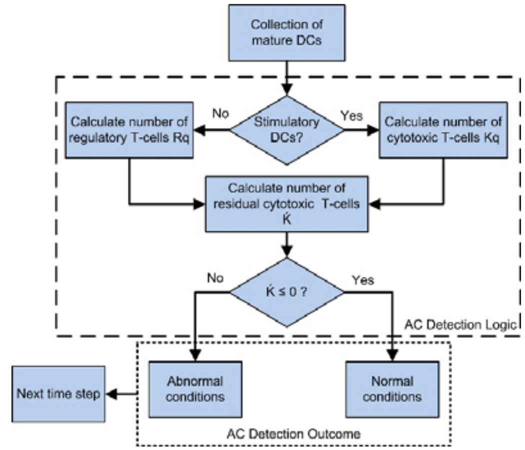
The average of the detection time is 122 seconds.

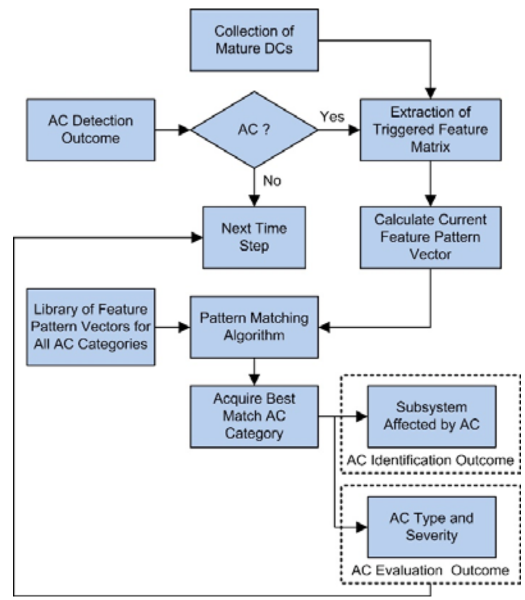
The monitoring scheme achieves 100% DR for almost all ACs.

The monitoring scheme achieves excellent IR and TER indices. In only 8 cases IR is less than 100%, but not less than 92%.

The average SER for low severity ACs is 96%. The performance of the monitoring scheme in terms of AC severity evaluation may appear lower due to a typical underestimation of higher severity levels.

#	Severity	DT (sec)	DR (%)	IR (%)	TER (%)	SER (%)
1	15%	220.75	100	100	100	100
	20%	225.75	100	100	100	90.76
	25%	130.75	100	100	100	94.83
2	15%	226.5	100	100	100	87.17
	20%	216	100	100	100	98.35
	25%	125.75	100	100	100	82.24
6	1%	670.75	100	100	100	91.43
	2%	484.08	100	100	100	40.05
	3%	402.42	100	100	100	54.62
7	1%	65.75	100	100	100	100.00
	2%	62.50	100	100	100	94.84
	3%	59.08	100	100	100	83.72





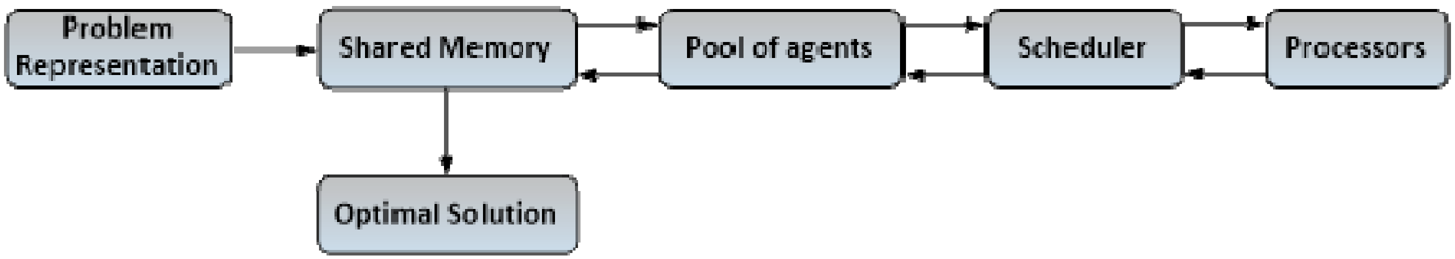
Contributions and Novelty

- ✓ The proposed methodology provides the tools for addressing the complexity and multi-dimensionality of the modern power plants in a comprehensive and integrated manner that classical approaches cannot achieve
- ✓ The methodology is comprehensive in the sense that it offers the framework for addressing all system components, all AC (including known and unknown ones), and all major components of the system monitoring and control process (detection, identification, evaluation, and accommodation).
- ✓ The proposed methodology is highly integrated because one single package relying on few shared concepts and mechanisms can solve all components of the system monitoring and control process.
- ✓ Conceptually, the methodology is data-driven, which makes it easy to develop, implement, and operate.
- ✓ The methodology provides robustness and adaptability because it allows for relatively simple updating, extension, and re-structuring of the self/non-self throughout the life cycle of the system.

Novel Multi-agent Optimization (MAOP) Framework

- MAOP is a nature-inspired optimization method, which supports cooperative search by group of algorithm agents coordinated in an environment with certain predefined sharing protocol.
- An agent in MAOP is an autonomous entity with personal declarative memory and behavioral components.
- Agents explore the search space of an optimization problem based on individual learning and indirectly interacting with other agents through sharing public information organized in sharing memory

Novel Multi-agent Optimization (MAOP) Framework

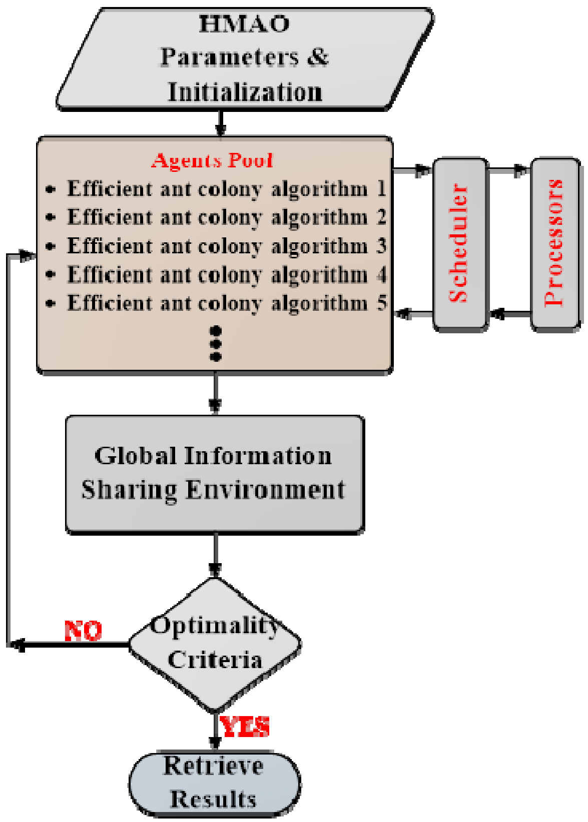


- The major emphasis of MAOP framework is enhancing the accommodation of different classes of optimization problems and increasing the computational efficiency
- MAOP focuses on the
  - ✓ Diversity of agents involved in the framework
  - ✓ Coordination between agents and global sharing memory
  - ✓ Parallelization of agents

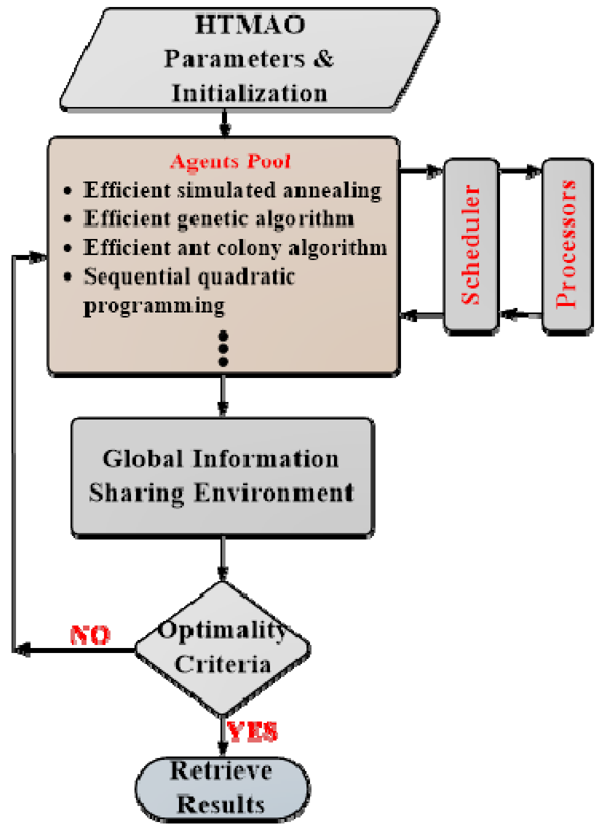
Diversity

- Homogenous Multi-Agent Optimization (HMAO)
  - ✓ same algorithms and differ in algorithmic parameters
  - ✓ run in parallel
  - ✓ cooperate through the sharing memory environment
- Heterogeneous Multi-Agent Optimization (HTMAO)
  - ✓ use diverse algorithms
  - ✓ run in parallel
  - ✓ cooperate through the sharing memory environment

Diversity

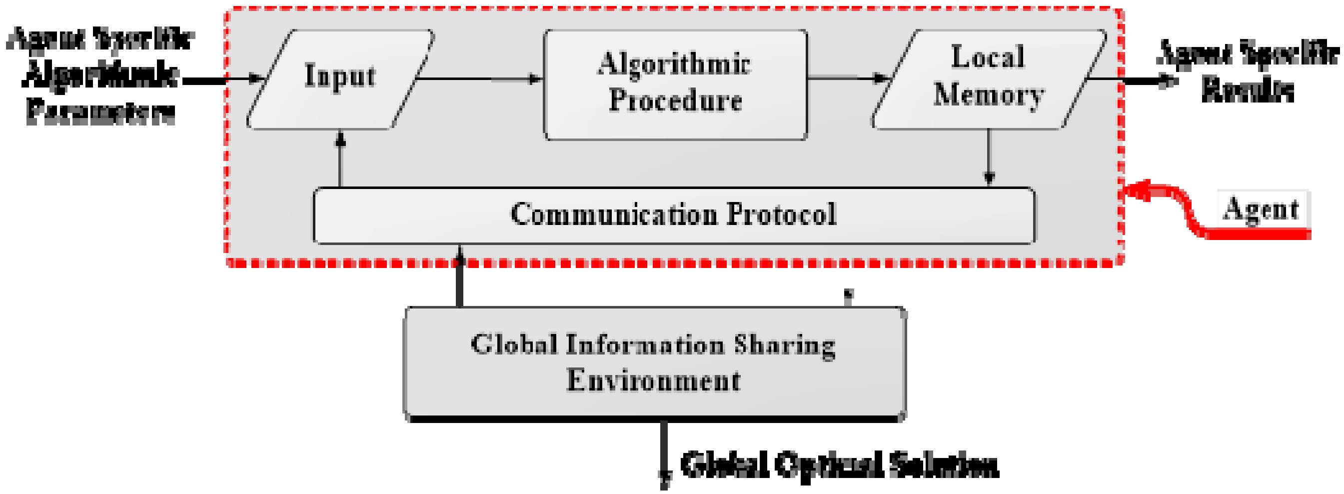


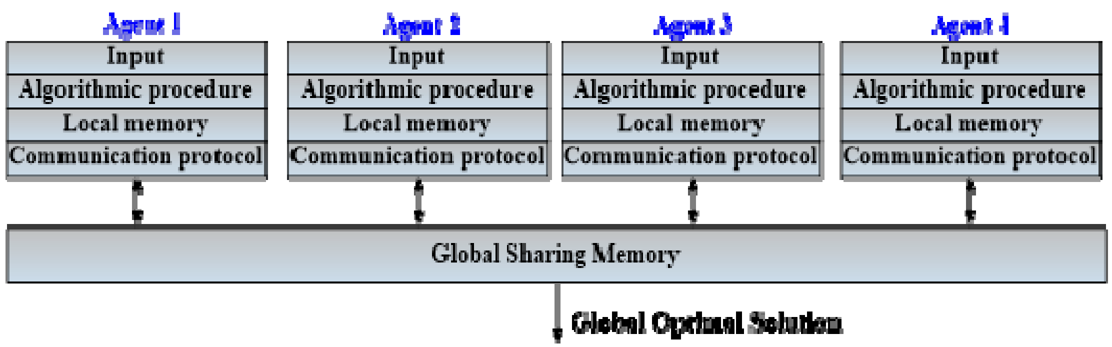
HMAO



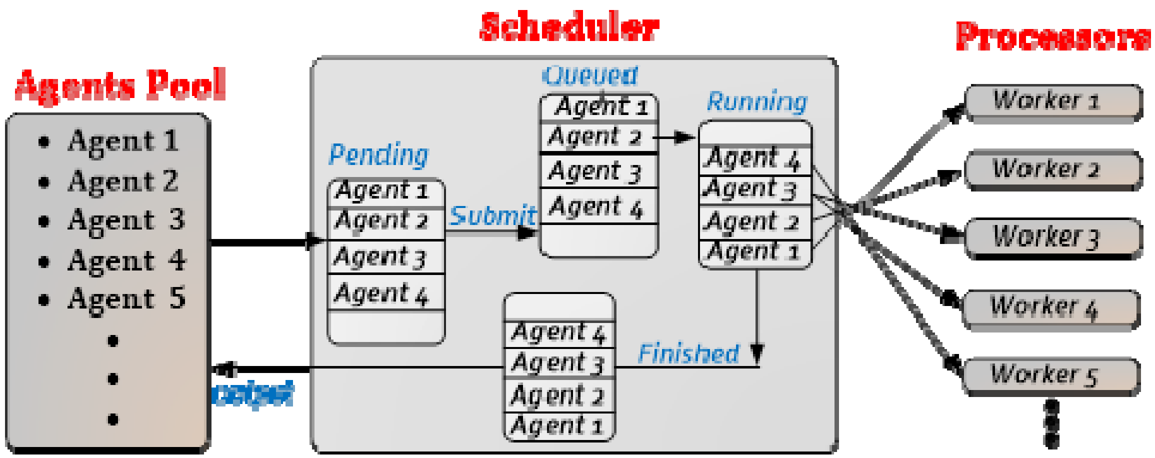
HTMAO

Coordination





Parallel Algorithm



Matlab job scheduler (MathWorks)

Results of the Blending Problem: A Real World Case Study

- ✓ The blending problem is solved using the individual agents at the parametric setting similar to the HTMAO framework.

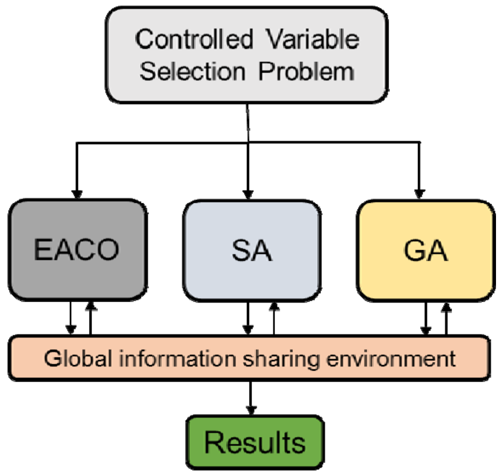
	ESA-SQP	EGA-SQP	EACO-SQP	EGA-EACO	HTMAO
totFrit (Kg)	11171	11690	Fails	11515	11023

- ✓ Comparison with results of the same problem solved using branch and bound and SA-NLP (Narayan and Urmila (1996), Chaudhuri and Diwekar (1999)

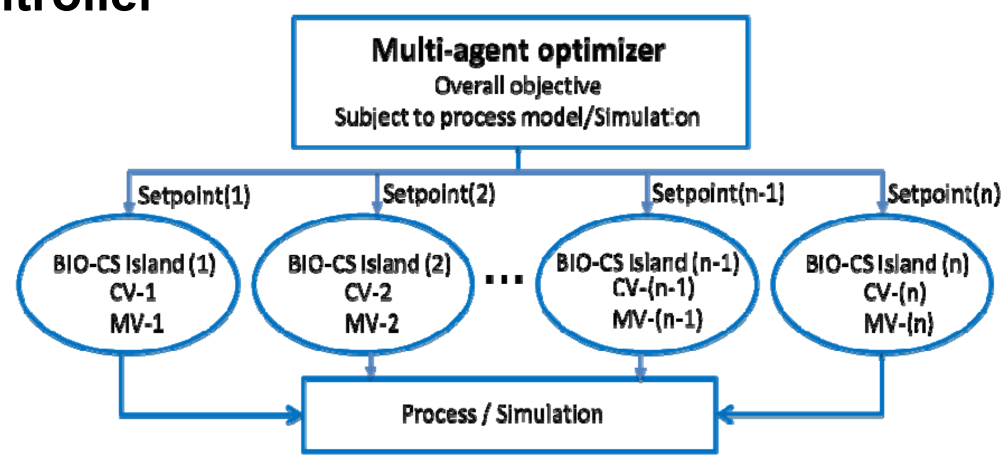
	SA-NLP	BB	HTMAO
totFrit (Kg)	11028	11028	11023
CPU time	45 min	3 days	6.5 min

Applications

✓ **Controlled Variable Selection Problem**



✓ **Bio-CS Controller**



Contributions and Novelty

- **A novel and efficient multi-agent optimization framework**
- **Real world case studies to illustrate the usefulness of framework**
- **Integration with biomimetic framework**

Presentations

1. Gebrelassie B. H., Diwekar U., “Efficient Ant Colony Optimization for Deterministic Optimization”, AIChE Annual Meeting, Atlanta, GA, November, 2014
2. Gebrelassie B. H., Diwekar U., “Efficient Ant Colony Optimization for Solvent Selection Using CAMD”, PSE/ESCAPE, Denamark, 2015
3. Mirlekar G. V., Gebreslassie B., Diwekar U., Lima, F. V. “Design and Implementation of a Biomimetic Control Strategy for Chemical Processes Based on Efficient Ant Colony Optimization”, AIChE Annual Meeting, Salt Lake City, UT, November 8-13, 2015
4. Gebreslassie B., Diwekar U. “Multi-Agent Optimization Framework (MAOP) for Large Scale Process System Engineering Optimization Problem”, AIChE Annual Meeting, Salt Lake City, UT, November 8-13, 2015
5. Gebreslassie B., Mirlekar G. V., Lima, F. V., Diwekar U. "Optimal Control based on Efficient Ant Colony (EACO) Algorithm. Case Study: Chemical Process Control", AIChE Midwest Regional Conference, Chicago, IL, March 3-4, 2016
6. Bankole T. S., Bhattacharyya D., “Algorithmic Development of Dynamic Causal Model for Process Plants”, American Control Conference, Boston, MA, July 6-8, 2016
7. Bankole T, Bhattacharyya D, “Exploiting Connectivity Structure for Online Selection of Primary Controlled Variables”, AIChE Annual Meeting, San Francisco, CA, November 13-18, 2016
8. Mirlekar G. V., Lima F. V., “Design and Implementation of a Biologically-Inspired Optimal Control Strategy (BIO-CS) for Advanced Energy Systems”. AIChE Annual Meeting, San Francisco, CA, November 13-18, 2016
9. Gebreslassie B. H., Mirlekar G. V., Lima F. V., Diwekar U. M. "Optimal Controller Design Based on Efficient Ant Colony Optimization Algorithm. Case Study: Chemical Process Control". AIChE Annual Meeting, San Francisco, CA, November 13-18, 2016
10. Al-Sinbol, G., Perhinschi, M., Bhattacharyya, D., Evolutionary Optimization Environment for Power Plant Control with Dynsim® Interface. Presented at AIChE 2016 Annual Meeting, San Francisco, CA
11. Al-Sinbol, G., Perhinschi, M., Bhattacharyya, D., Power Plant Abnormal Condition Detection Using the Artificial Immune System Paradigm. Poster Presented at AIChE 2016 Annual Meeting, San Francisco, CA
12. Gebreslassie B., and U. Diwekar, “Heterogeneous multi-agent optimization framework for synthesizing optimal nuclear waste blends”, AIChE Annual Meeting, Sanfrancisco, CA, November, 2016.
13. Gebreslassie B., and U. Diwekar, “Heterogeneous multi-agent optimization framework for synthesizing optimal nuclear waste blends”, AIChE Midwestern Meeting, Chicago, IL, March, 2017

Publications

1. Perhinschi M. G., Al-Sinbol G., Bhattacharyya D., Lima F., Mirlekar G., Turton R., “Development of an Immunity-based Framework for Power Plant Monitoring and Control”, *Advanced Chemical Engineering Research*, Vol. 4, Issue 1, pp. 15-28, September 2015
2. Gebrelassie B. H., Diwekar U., “Efficient Ant Colony Optimization for Computer-Aided Molecular Design: Case Study Solvent Selection Problem”, *Computers & Chemical Engineering*, Vol. 78, pp. 1-9, 2015
3. Gebrelassie B. H., Diwekar U., “Efficient Ant Colony Optimization for Solvent Selection Using CAMD”, Proceeding of PSE/ESCAPE, Denamark, 2015
4. Gebreslassie B., Diwekar U., “Homogenous Multi-Agent Optimization for Process Systems Engineering with Application to Computer Aided Molecular Design”, accepted, Chemical Engineering Science, 2016.
5. Gebreslassie B., Diwekar U., “Efficient Ant Colony Optimization (EACO) Algorithm for Deterministic Optimization”, International Journal of Swarm Intelligence and Evolutionary Computation, Vol. 5, pp. 1-10, 2016
6. Bankole T. S., Bhattacharyya D., “Algorithmic Development of Dynamic Causal Model for Process Plants”, Proceedings of the American Control Conference, Boston, MA, July 6-8, 2016
7. Bankole S, Bhattacharyya D, “Exploiting Connectivity Structures for Decomposing Process Plants”, To be Submitted, Chemical Engineering Science, 2016
8. Al-Sinbol, G., Perhinschi,M. Generation of power plant artificial immune system using the partition of the universe approach. International Review of Automatic Control (IREACO) 9(1), 2016.
9. Mirlekar G. V., Li S., Lima F.V. “Design and Implementation of a Biologically-inspired Optimal Control Strategy (BIO-CS) for Chemical Process Control. *Submitted for publication,* 2016
10. Mirlekar G. V., Pezzini P., Bryden M., Tucker D., Lima F. V., “A Biologically-Inspired Optimal Control Strategy (BIO-CS) for Hybrid Energy Systems”. To appear in *Proceedings of the American Control Conference (ACC)*, Seattle, WA, May 24-26, 2017
11. Perhinschi, M., Al-Sinbol, G. Artificial dendritic cell algorithm for advanced power system monitoring. International Review of Automatic Control (IREACO) 9(5), 2016
12. Al-Sinbol, G ., Perhinschi, M., Bhattacharyya, D., Evolutionary Optimization of Power Plant Control System Using Immunity-inspired Algorithms. International Review of Chemical Engineering (I.RE.CH.E.), Vol. 9, No. 1, 2017
13. Al-Sinbol, G., Perhinschi, M., Development of an Artificial Immune System for Power Plant Abnormal Condition Detection, Identification, and Evaluation, submitted to International Review of Automatic Control (I.RE.A.CO.), Feb. 2017

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Thank you