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 biomimetic algorithms

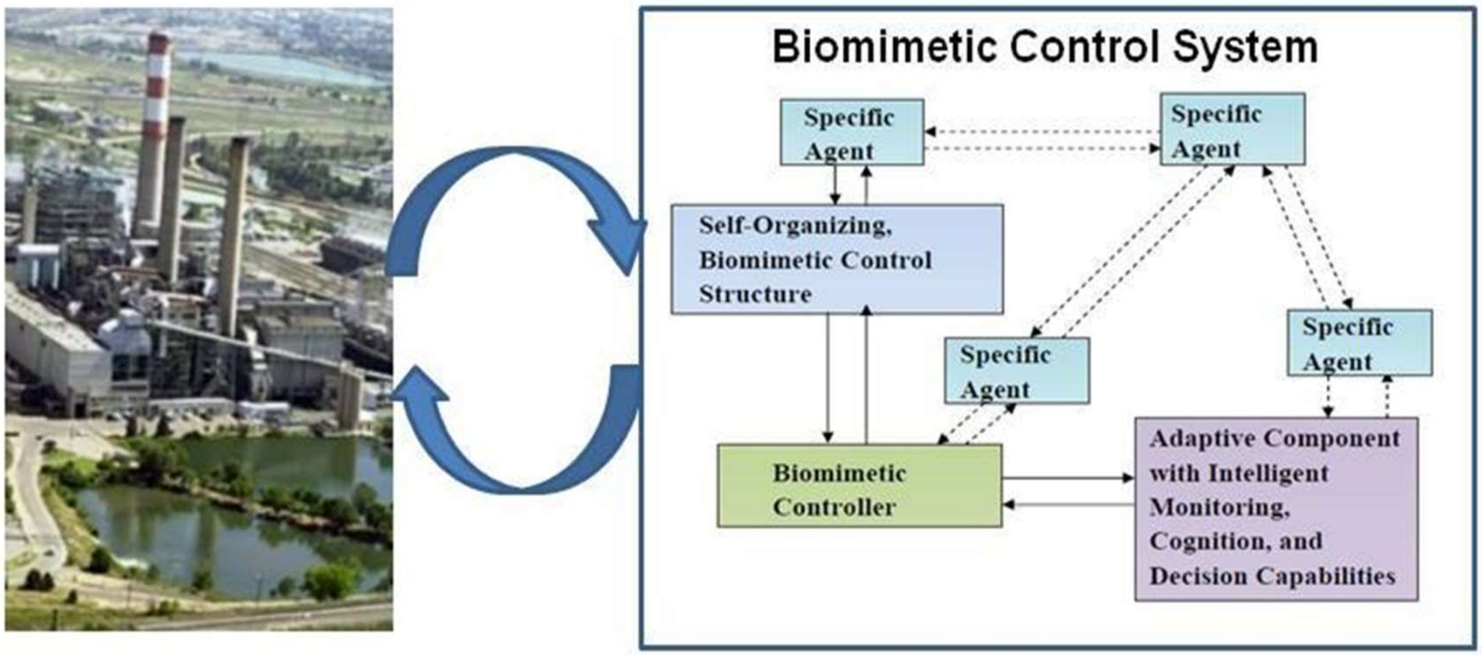
Task 5.0 Development of a Multi-Agent Optimization Framework for Control Structure Design, and State and Parameter Estimation

- 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

Our Approach

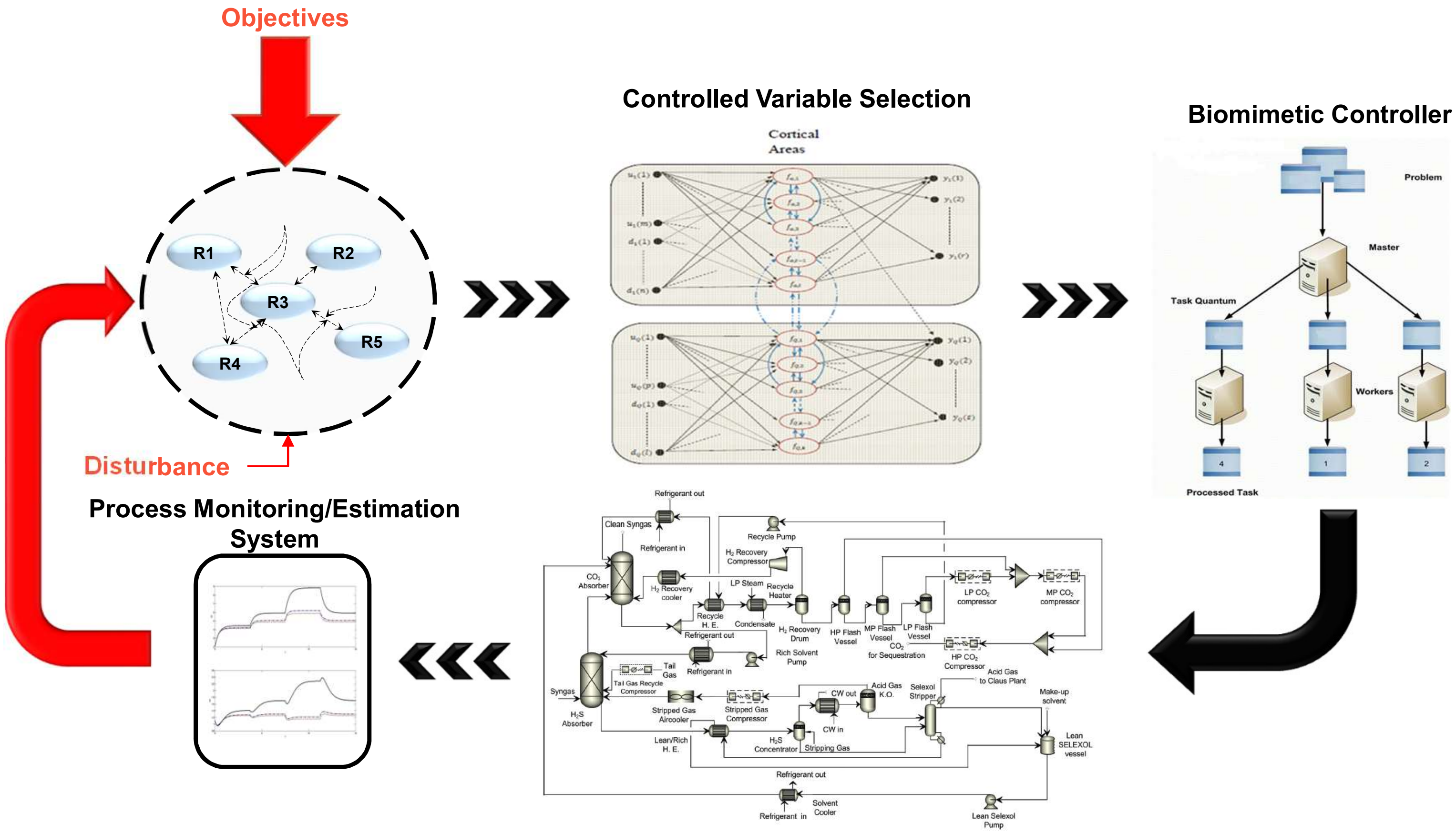


- Self-organization of the control structure that mimics the function of the cortical areas of human brain
- Distributed and adaptive controllers that mimic the rule of pursuit present in ants
- Intelligent monitoring, cognition, and decision capabilities that mimic the immune system
- Seamless integration 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

Development of Dynamic Causal Model (Q1-Q8)

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

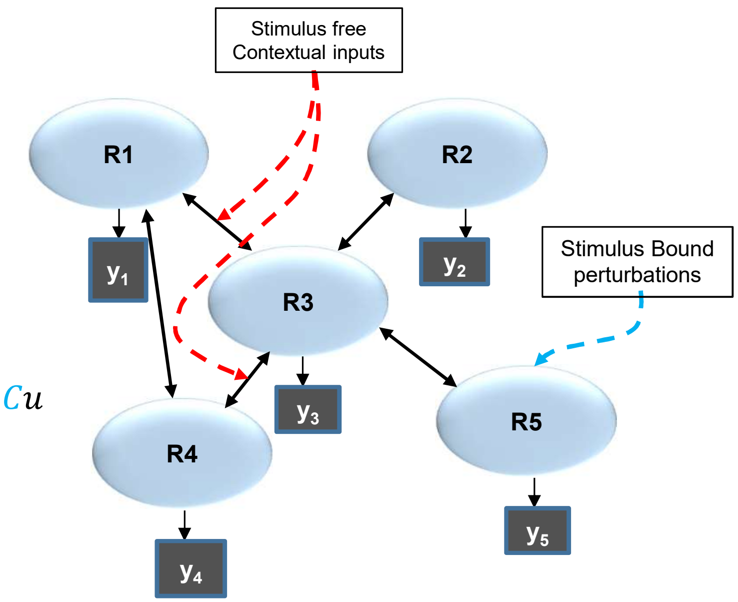


Dynamic Causal Modeling

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

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

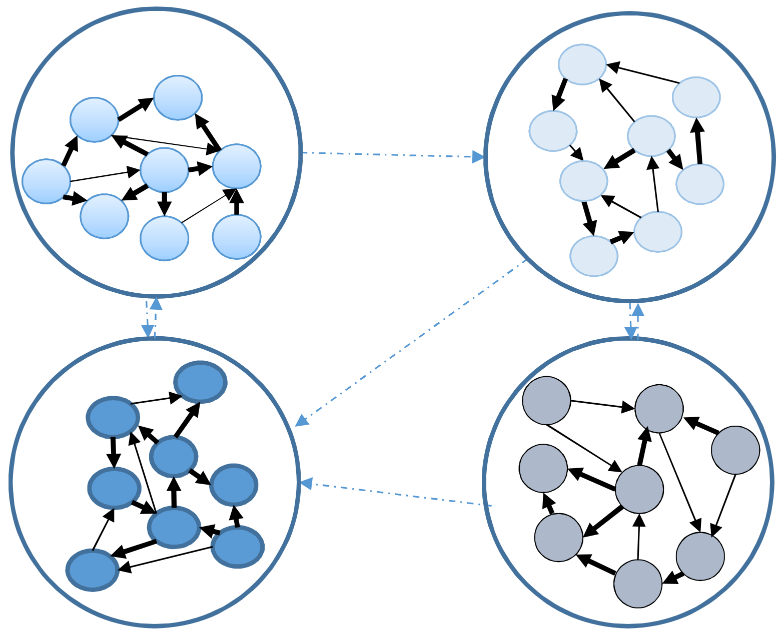
$$\hat{\theta} = \{A, B^{j}, C\}$$



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



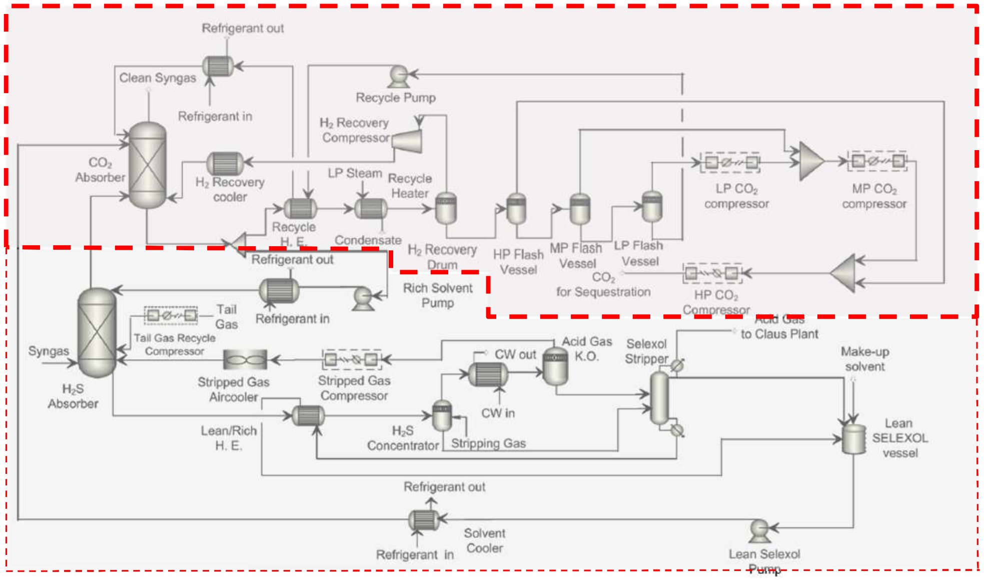
Acid Gas Removal Unit

- **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



Connectivity Results: AGR unit

Strong connectivity from:

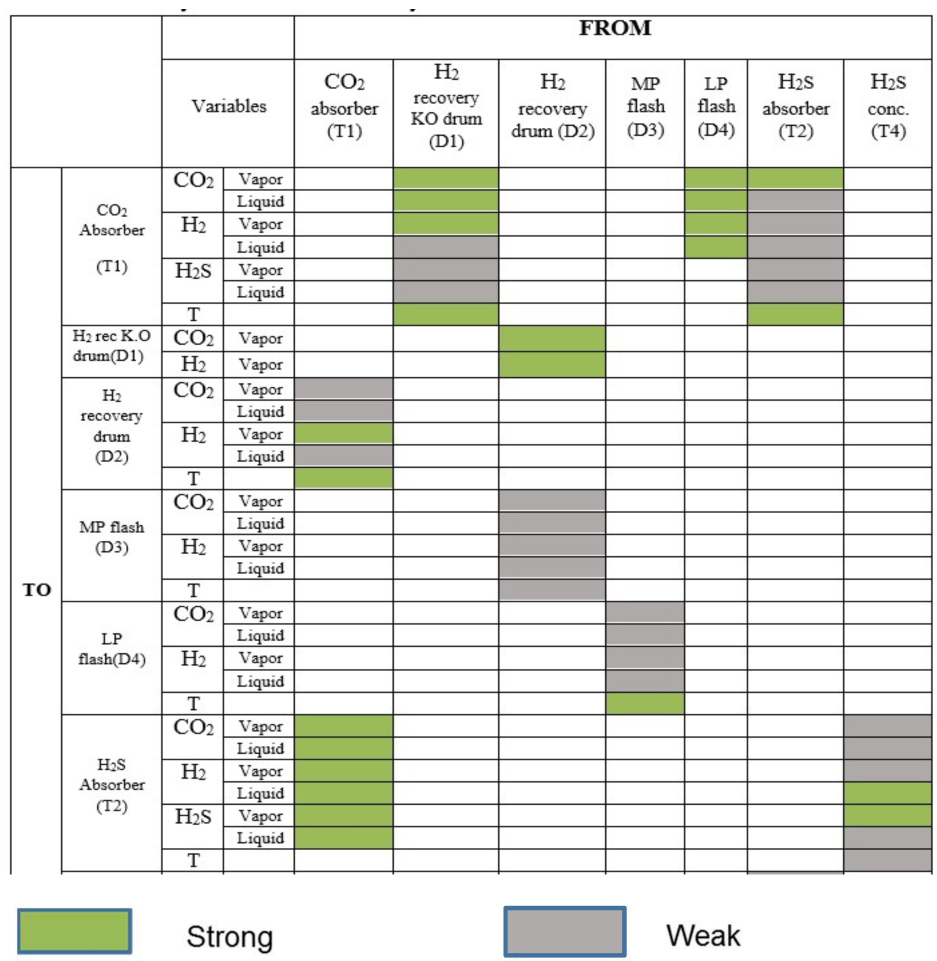
- CO_2 absorber to H_2S absorber
- H_2 recovery drum to CO_2 absorber
- LP flash drum to CO_2 absorber

Coupling between unit operations is due to strong species interaction from one unit to another

Weak connectivity from:

- H_2S absorber to CO_2 absorber
- H_2S concentrator to H_2S absorber

Based on these connectivity strengths(depending on threshold), generate islands

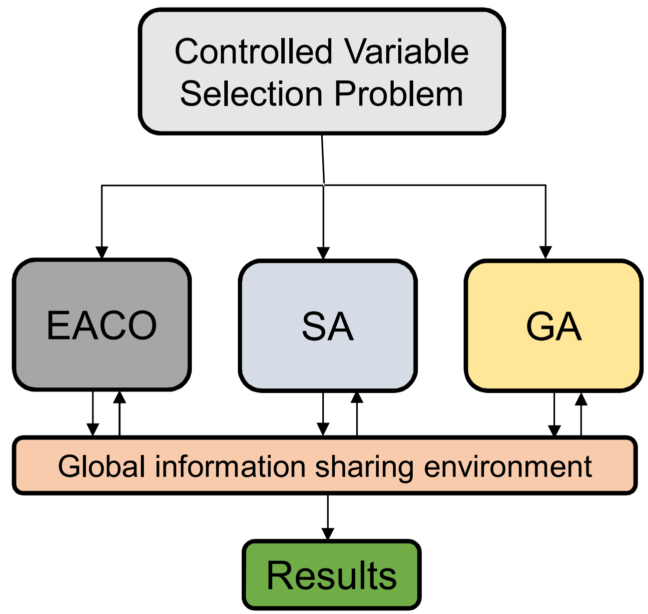


Development of multiagent optimization for self organizing controlled variable selection (CVS)

- Mixed integer non linear problem is passed into the multi-agent framework.

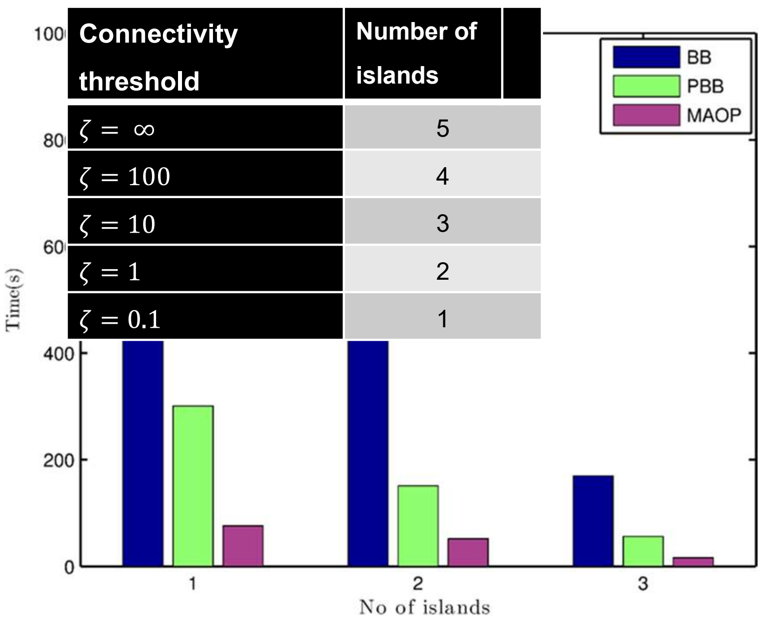
- Each solver represents a meta heuristic biological agent.
- Each agent is initialized with required parameters.
- After every iteration, communication and sharing of information ensues.
- Solution is compared and stored.
- Best solutions are retained for post-processing.

- Accuracy and runtime depends on how we have decomposed the process.

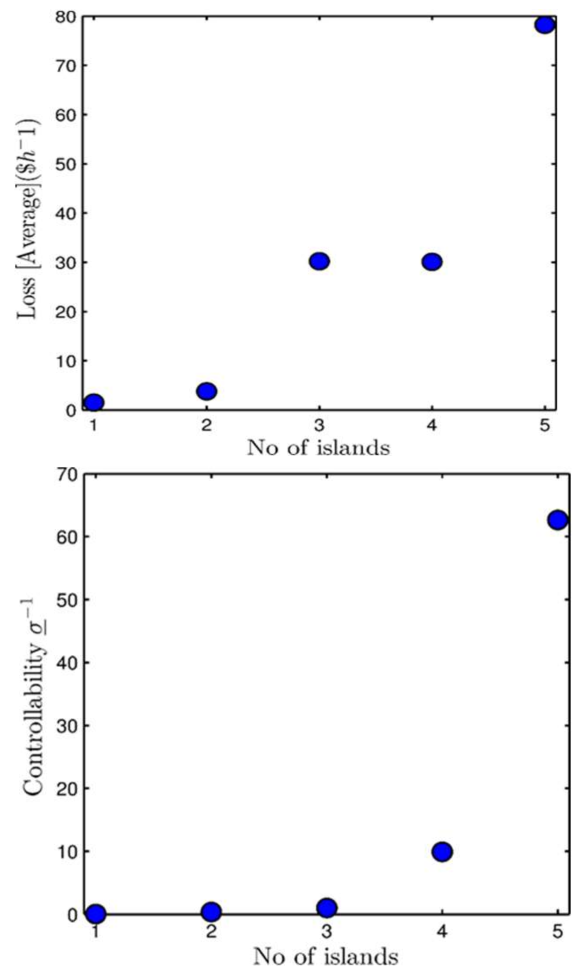


Results

Connectivity threshold	Number of islands
$\zeta = \infty$	5
$\zeta = 100$	4
$\zeta = 10$	3
$\zeta = 1$	2
$\zeta = 0.1$	1

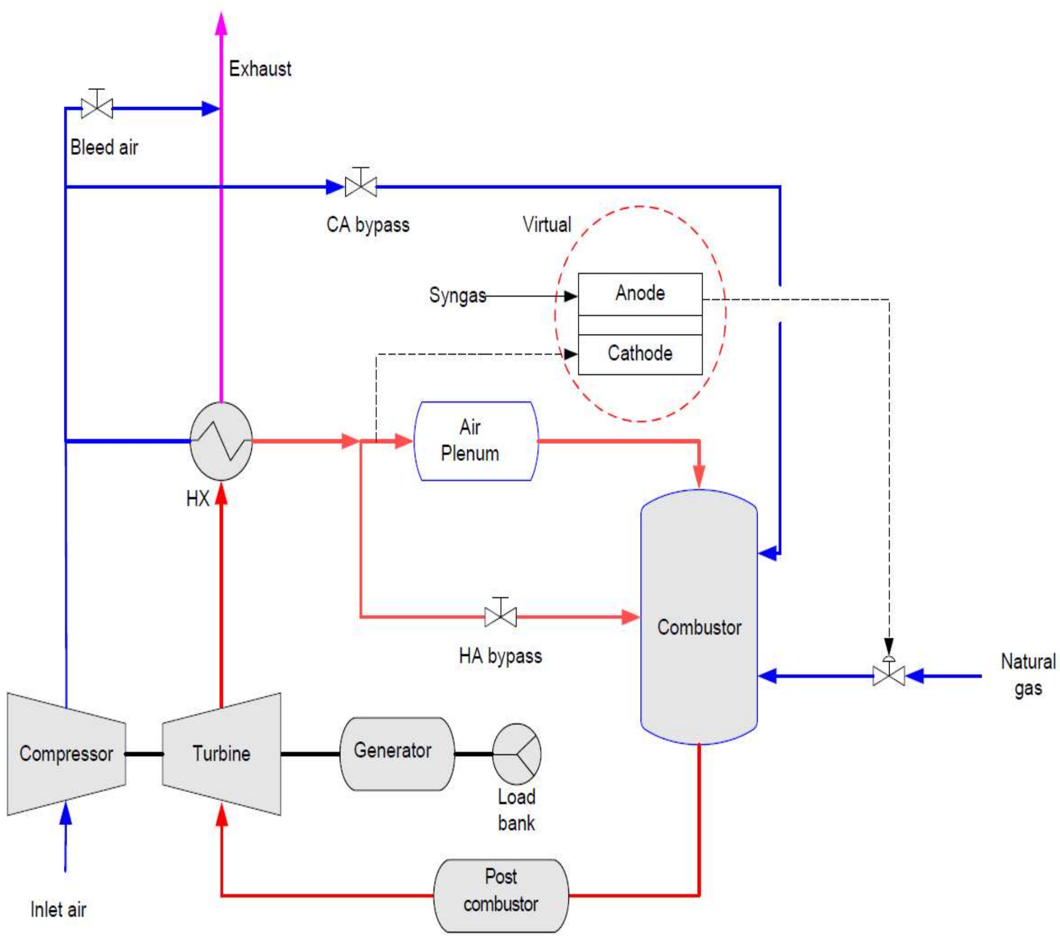


Running time for BB (branch and bound), PBB (Parallelized branch and bound) and MAOP (Multiagent optimization) for the cases of 1, 2 and 3 islands respectively.



Plot of Economic loss (Average case)(top) and controllability(bottom) against number of islands considered.

CVS for Hyper Facility



Why Hyper?

- Hybrid gas turbine fuel cell system promises high efficiency
- Waste heat from fuel cell is fed to turbine

Cyber Physical

- Numerical model simulates the fuel cell (virtual component)

Goal: Select controlled variables for optimal economic performance and controllability

Approach:

- Identify transfer function models from first principles model developed in SIMULINK
- Estimate noise variance from experimental data
- Develop cost function in SIMULINK and regress as a function of inputs
- Deploy multiagent platform for performing optimization

Method & Results

- APriori

$$y = G_p u + G_d d + W_n e$$

$$\left\|(G_p)_i\right\|_\infty \geq 1 \;\forall\, i$$

$$\left\|(G_p)_i\right\|_\infty \geq \left\|(G_d)_i\right\|_\infty \;\forall\, i$$

$$\tau\left(u_i, y_j\right) \leq \xi_j$$

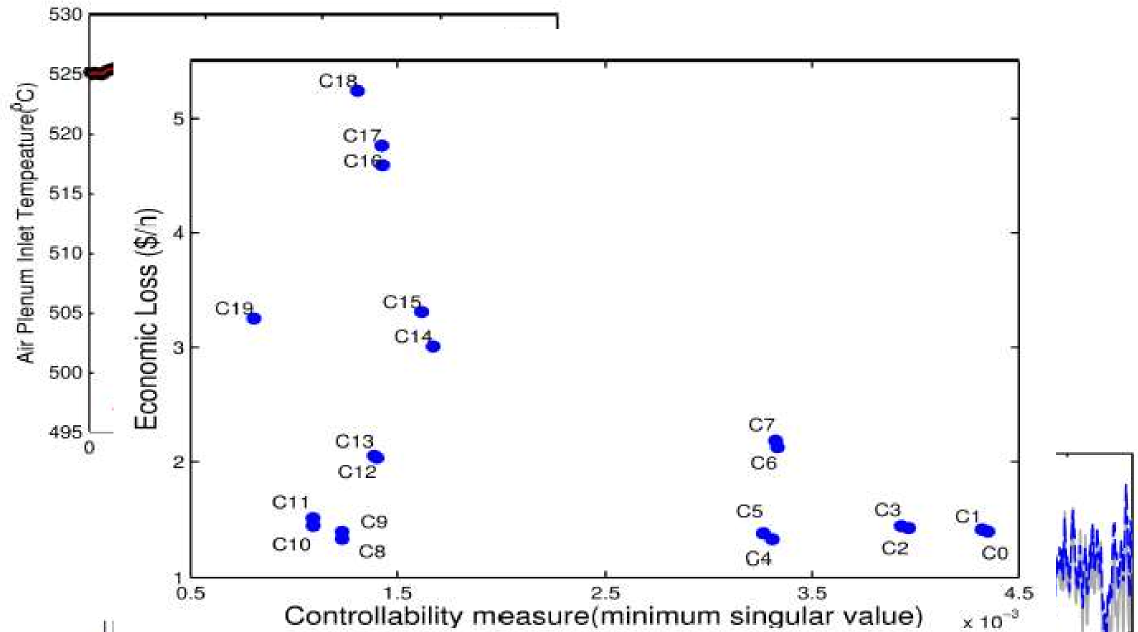
- Optimization:

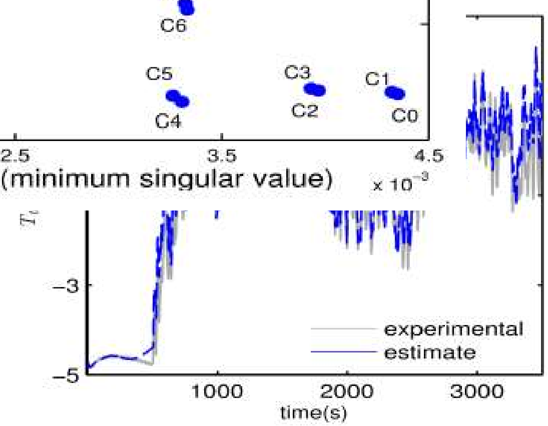
$$\min_{P_n} \left(L(P_n), J_c(P_n)\right)$$

$$J_c(P_n) = \underline{\sigma}^{-1}\left(\hat{G}(P_n)\right)$$

$$L = \frac{1}{6n_u}\left\|\left(G_p J_{uu}^{\frac{1}{2}}\right)^{-1}\left(G_p J_{uu}^{-1} J_{ud} - G_d\right) W_d\, W_n\right\|_F$$

- Posteriori Analysis:
  Remove correlated variables
  Check performance

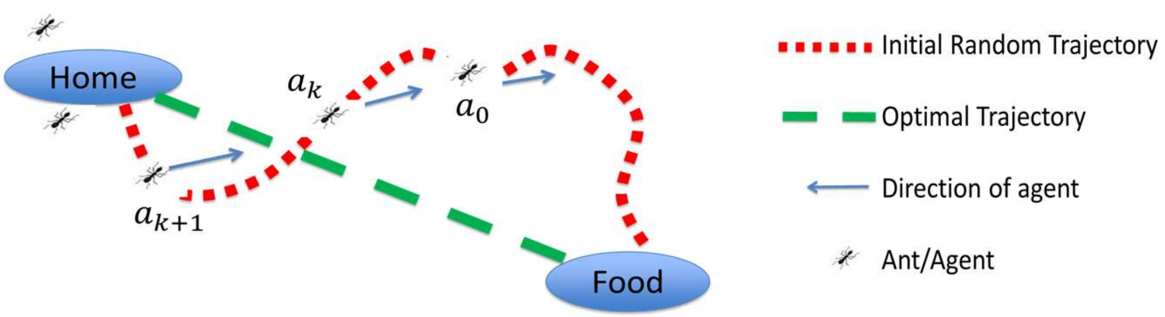




Task 3.0 Development and Implementation of Biomimetic Controller Design Method

Development of Deterministic Biomimetic Controller Design (Q1-Q6)

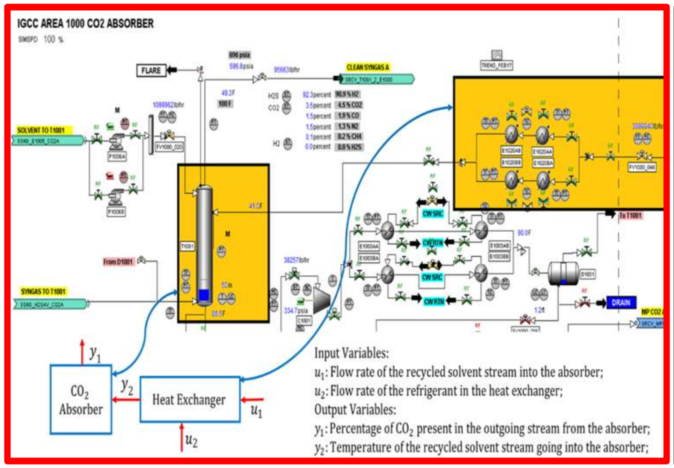
- Biologically-Inspired Optimal Control Strategy (BIO-CS) has been developed
- BIO-CS is inspired by ant's rule of pursuit idea in combination with optimal control concepts
- Unique features of BIO-CS for improved computational performance:
  - ✓ Algorithm termination at a suboptimal solution corresponding to a specific agent
  - ✓ Possibility of parallelizing optimal control problems associated with different agents



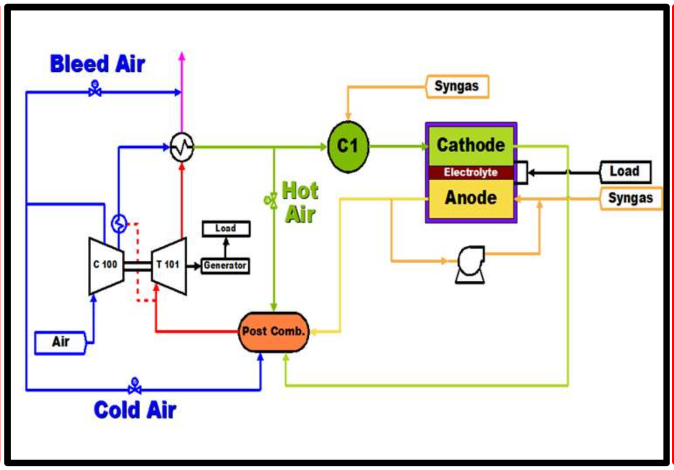
Development of Deterministic Biomimetic Controller Design (Q1-Q6)

- Proposed strategy has been implemented to address chemical and energy systems

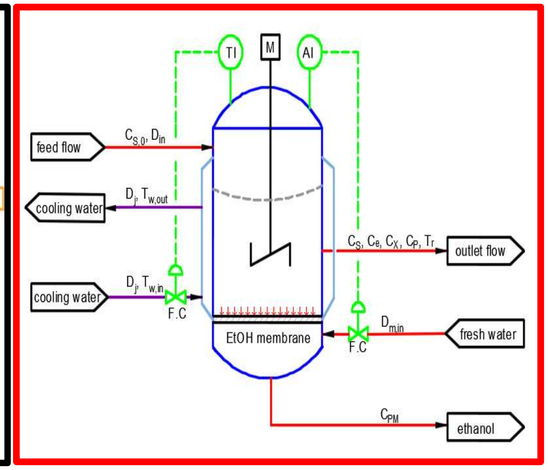
DYNSIM simulation of IGCC-AGR



HYPER system



Fermentation process

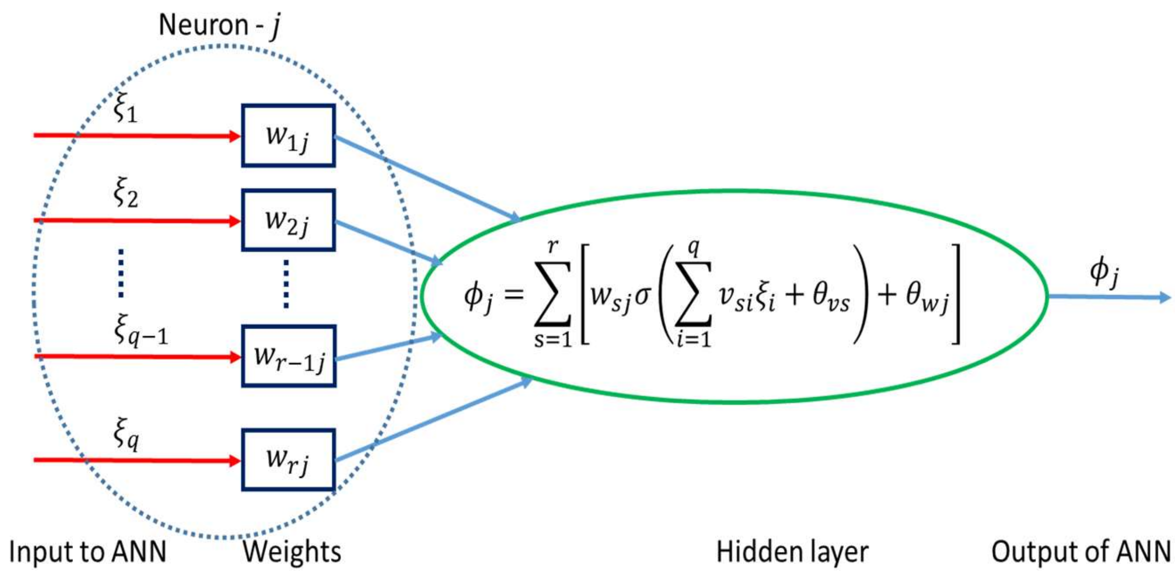


Research Outputs (for this subtask):

- Mirlekar, G., Li, S., and Lima, F., V., 2017. Design and implementation of a Biologically-Inspired Optimal Control Strategy (BIO-CS) for chemical process control. *Industrial & Engineering Chemistry Research,* 56(22), p. 6468–6479.
- Mirlekar, G., Pezzini, P., Bryden, M., Tucker, D., and Lima, F., V., 2017, May. A biologically-inspired optimal control strategy for hybrid energy systems. In *American Control Conference (ACC)*, IEEE.

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
- Adaptive component is inspired by Neural Network (NN) present in biological systems and captures plant-model mismatch or abnormal conditions of the system

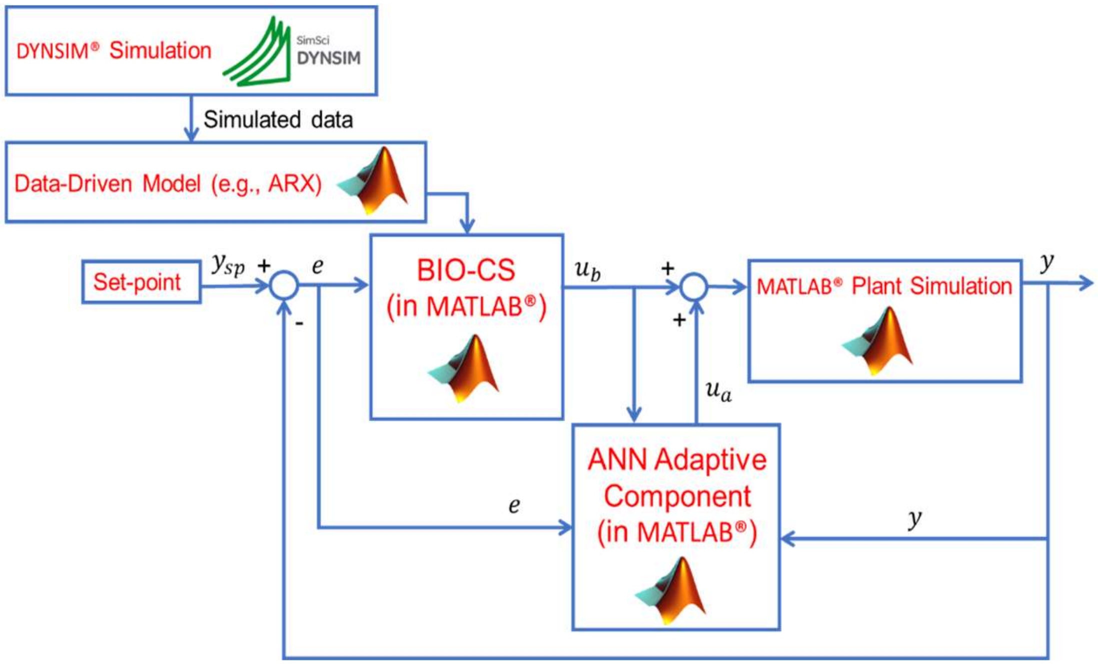


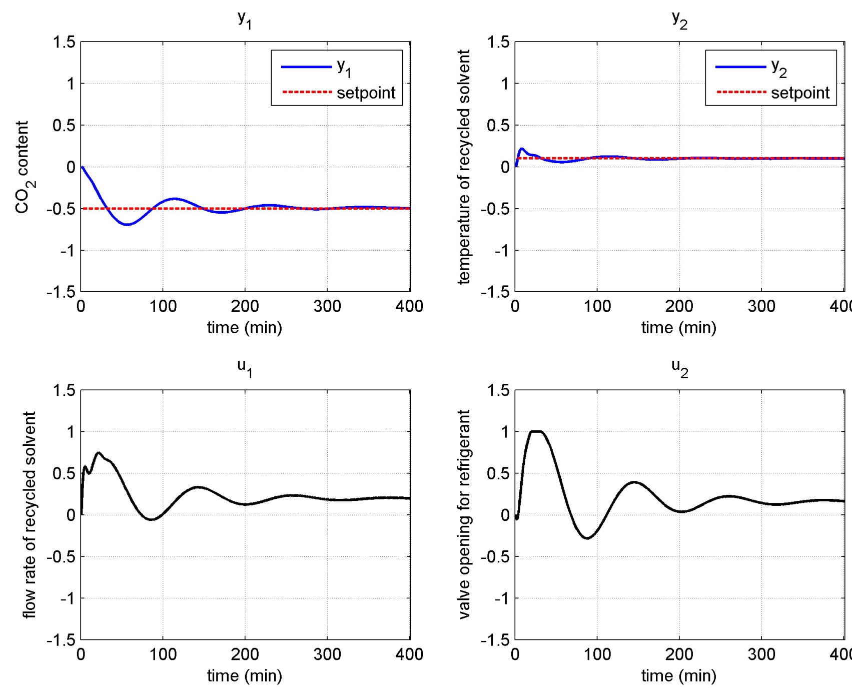
Research Output (for this subtask):

- Computational Tool #1: Computational Modules in MATLAB® for Biomimetic Control Algorithms

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

- Proposed framework has been applied to IGCC-AGR sub-system in MATLAB®



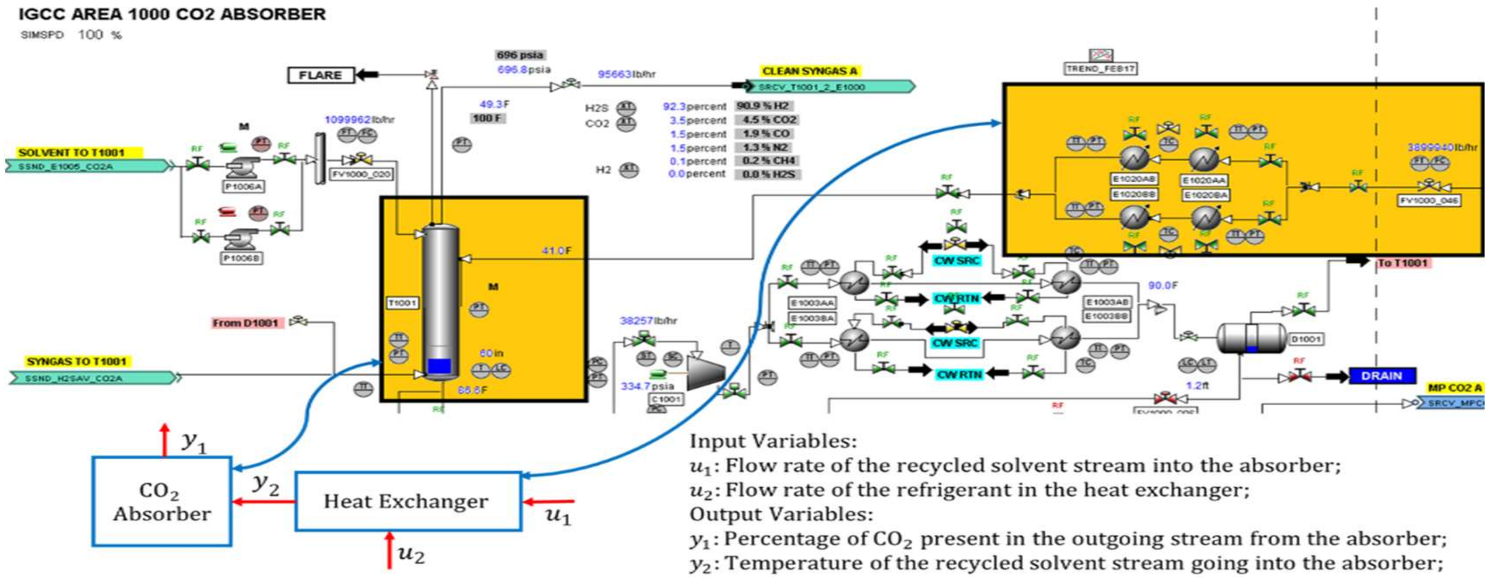


Scaled variables

Research Output (for this subtask):

- Computational Tool #1: Computational Modules in MATLAB® for Biomimetic Control Algorithms

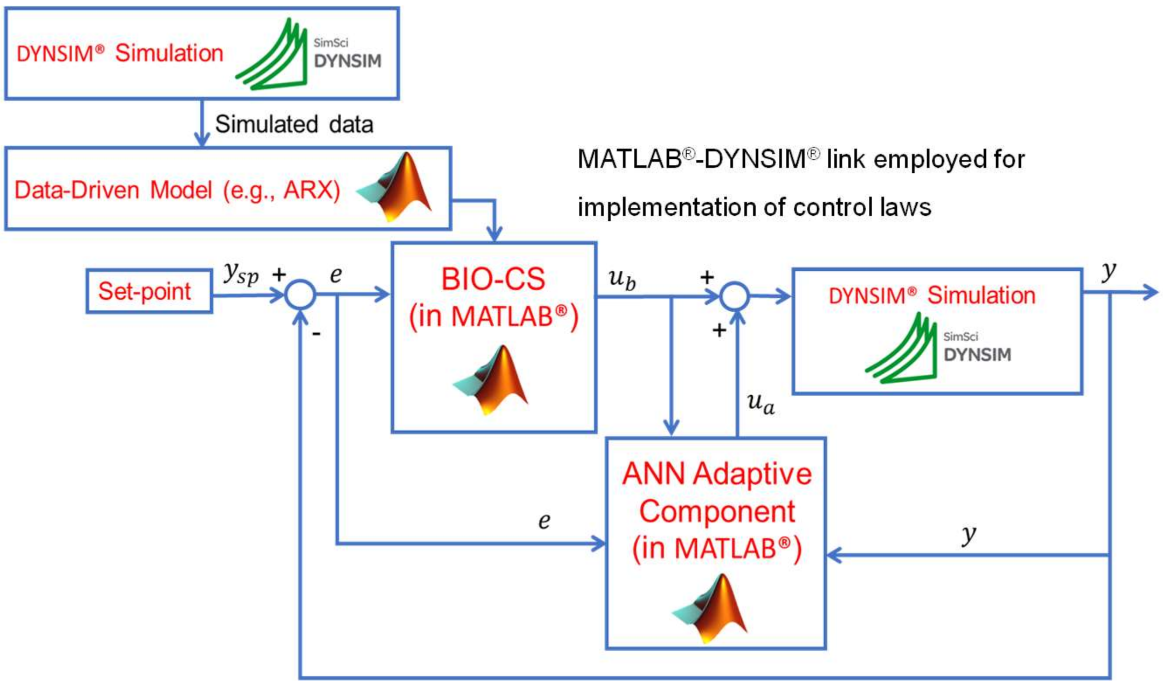
Implementation of Biomimetic-based Method in AVESTAR-WVU Center (Q6-Q12)

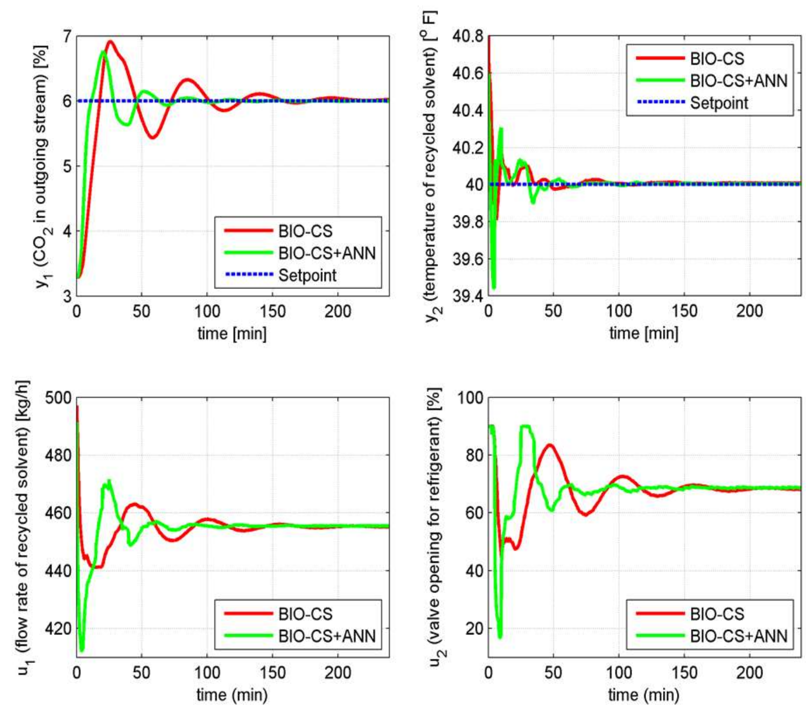


DYNSIM simulation of IGCC-AGR (Integrated Gasification Combined Cycle – Acid Gas Removal):

- 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 purposes
- Goal: setpoint tracking of y_1 while keeping the other output y_2 at a steady setpoint

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





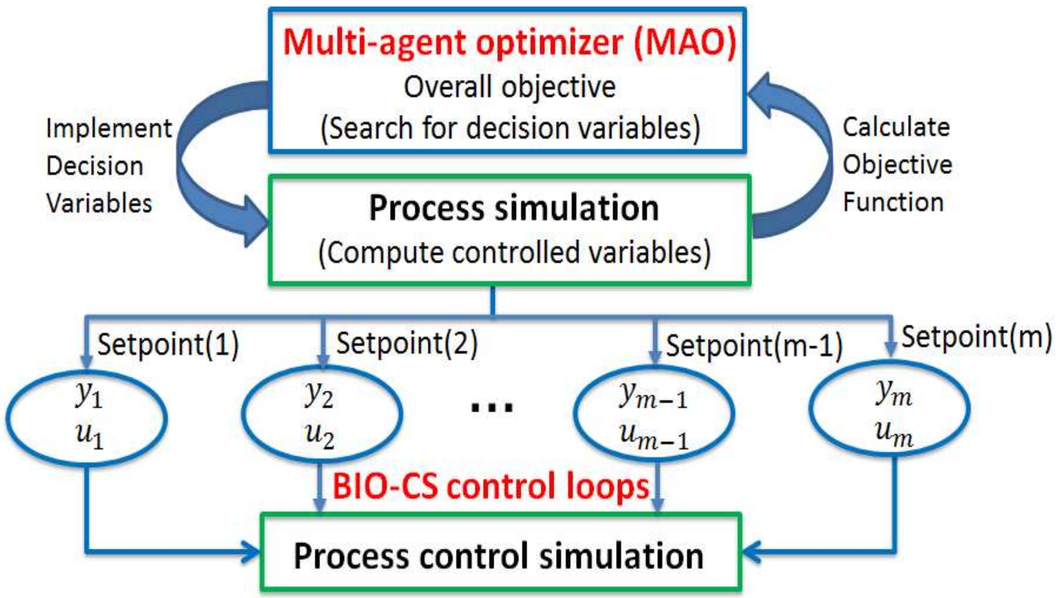
Research Output (for this subtask):

- Mirlekar, G., Al-Sinbol, G., Perhinschi, M., G., and Lima, F., V., 2018. A biologically-inspired approach for adaptive control of advanced energy systems. Submitted for publication in *Computers & Chemical Engineering.*

*In collaboration with Dr. Perhinschi's group

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

Overall framework:

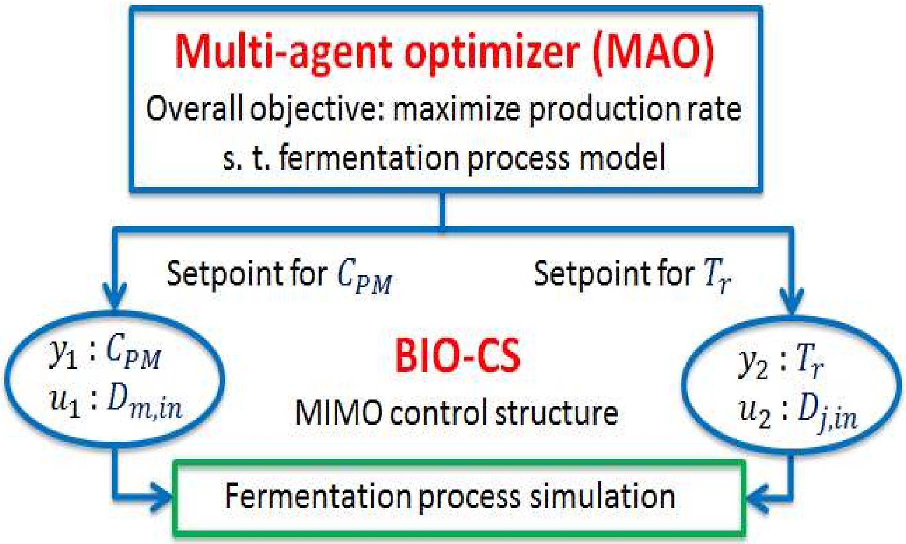


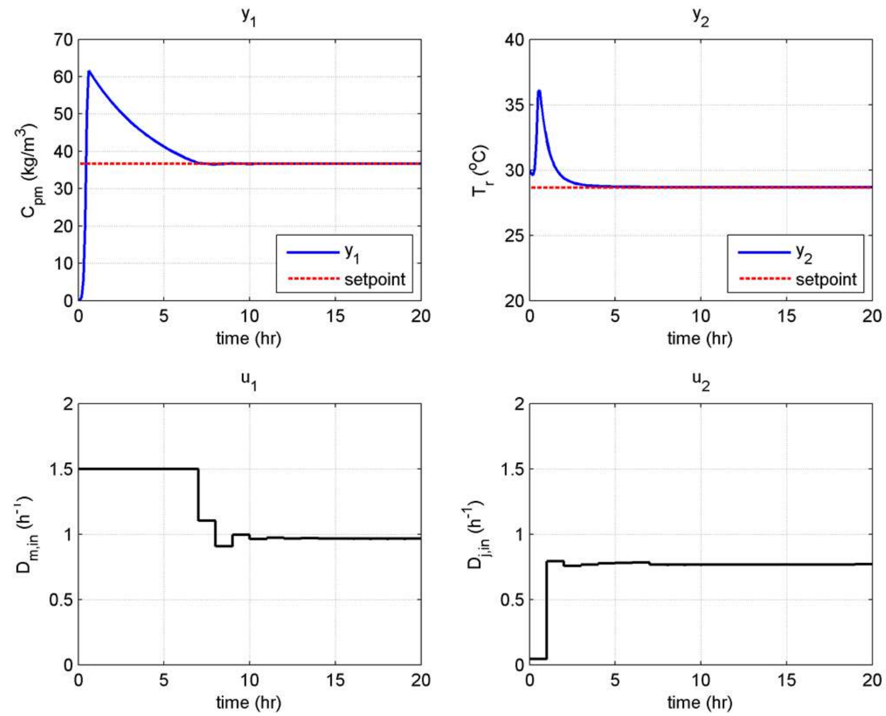
- Multi-agent optimizer provides optimal setpoints or setpoint trajectories for the process considering an overall objective
- BIO-CS is implemented for the control loops to take the system to those desired setpoints optimally

*In collaboration with Dr. Diwekar's group

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

Fermentation process implementation case study:





Research Outputs (for this subtask):

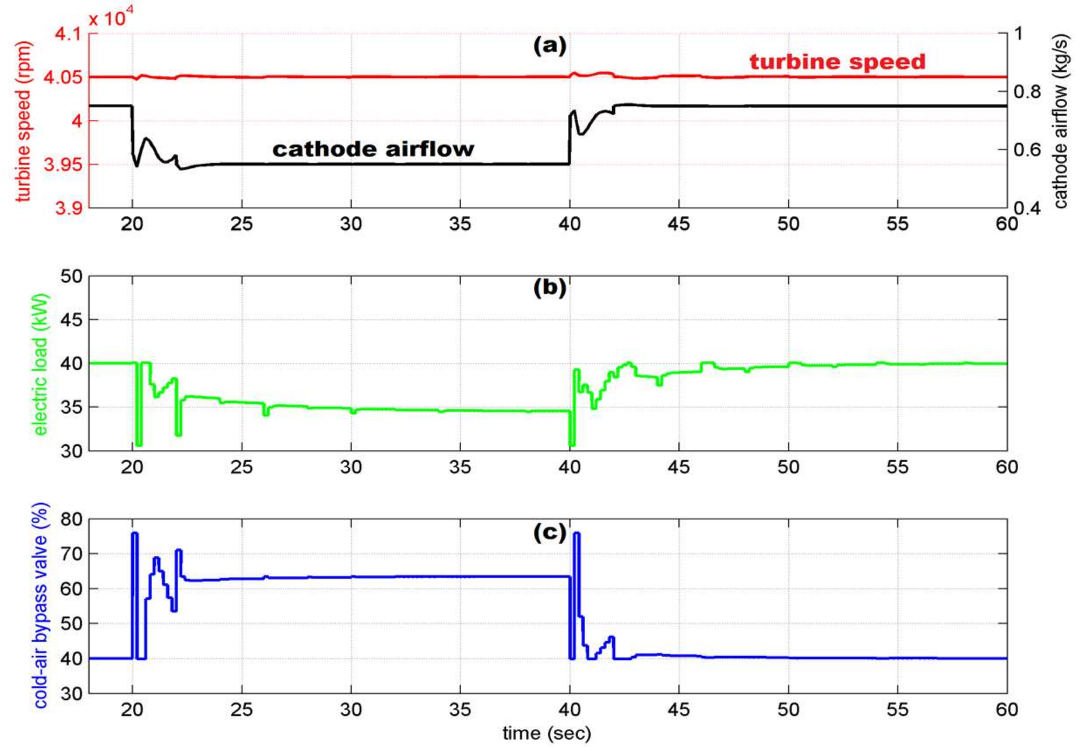
- Mirlekar, G., Gebreslassie, B., H., Li, S., Diwekar, U., M., and Lima, F., V., 2018, Biomimetic agent-based optimization and advanced control framework for nonlinear chemical processes. *In preparation for publication*.
- Mirlekar, G., Gebreslassie, B., H., Li, S., Diwekar, U., M., and Lima, F., V., 2018, July. An integrated biomimetic control strategy with multi-agent optimization for nonlinear chemical processes. Accepted in the *Proceedings of the IFAC ADCHEM Symposium*.
- Computational Tool #2: Biomimetic Controller Design Toolbox in MATLAB®

*In collaboration with Dr. Diwekar's group

Ongoing Collaboration

BIO-CS application to HYPER process:

- Coupling effects among different energy system components have been addressed employing transfer function model of HYPER process
- BIO-CS has been implemented for setpoint tracking and disturbance rejection scenarios
- WVU-NETL CRADA has been developed between parties



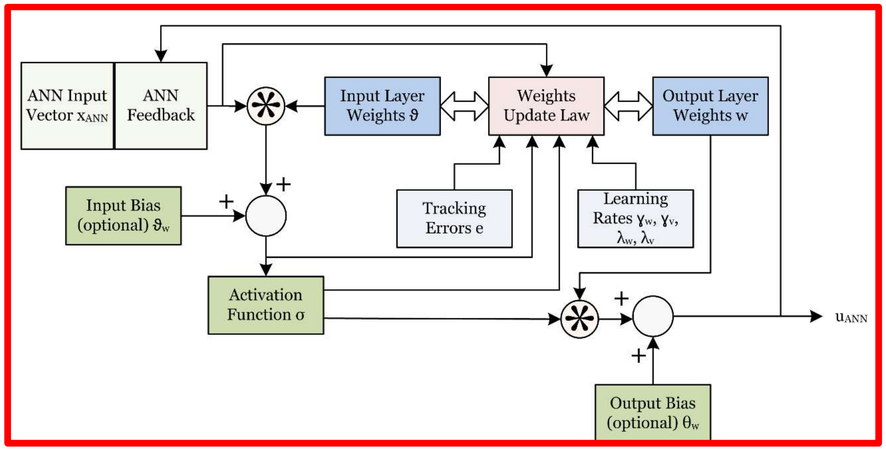
Future directions for investigation:

✓ Consider high-order transfer functions or models of higher complexity that represent the HYPER system

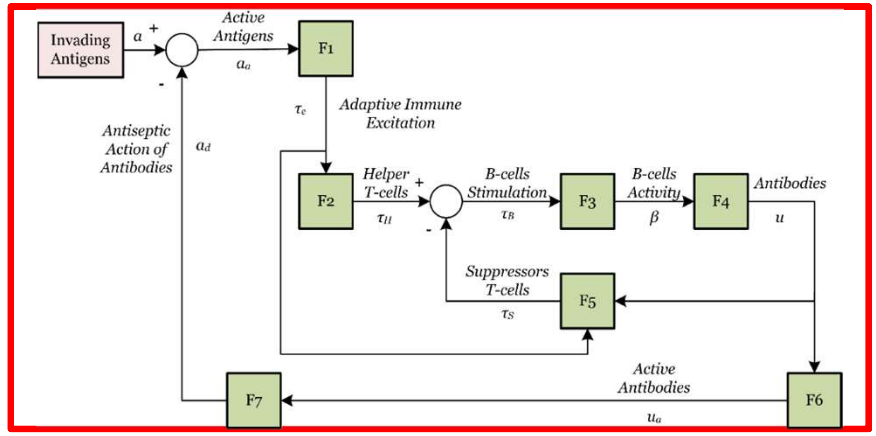
✓ Employ ant-colony-based solver (EACO) towards model simplification or model-free control

Task 4.0 Development of Biomimetic Adaptive Controllers with Intelligent Monitoring, Cognition, and Decision Capabilities

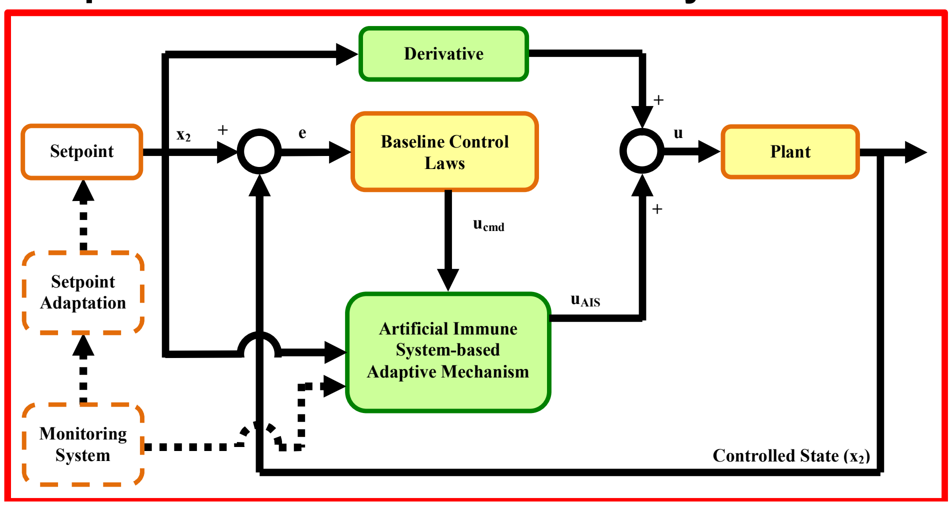
Single-Hidden-Layer ANN



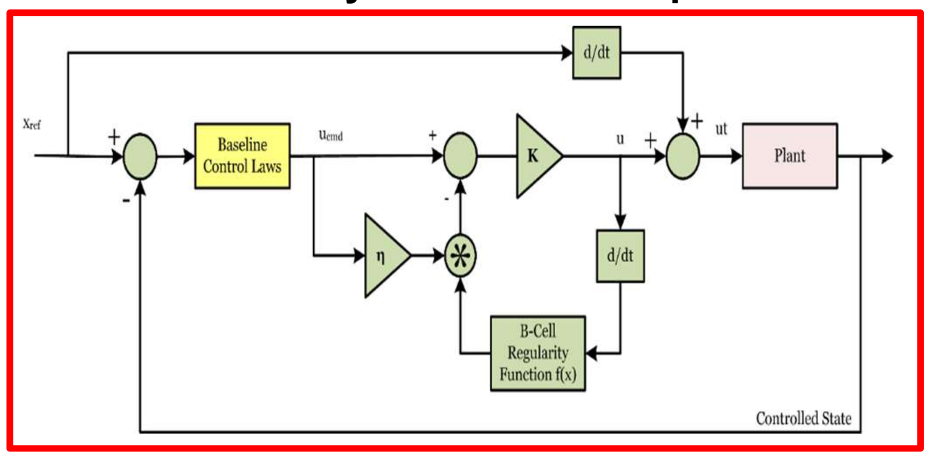
Humoral Immune System Mechanism



Adaptive Control Based on Immunity Mechanism



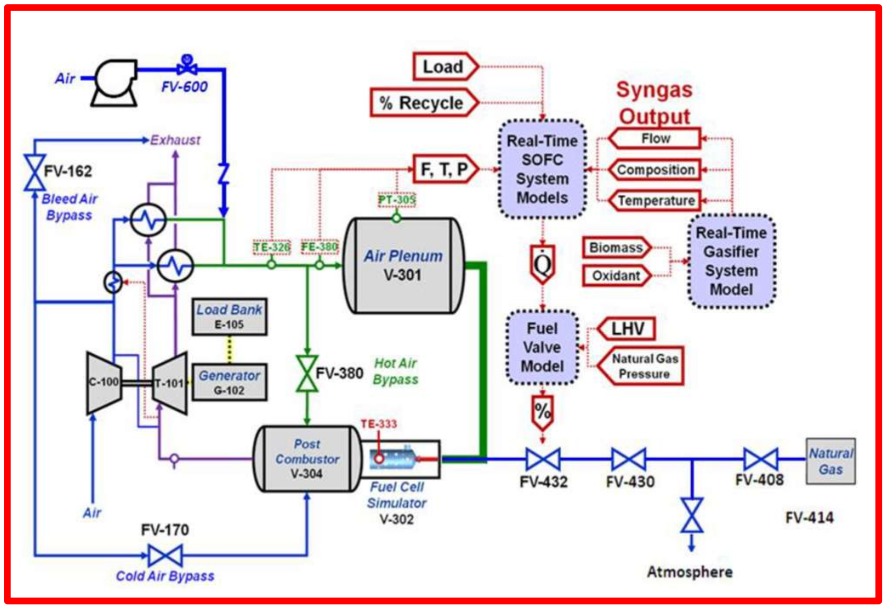
Artificial Immune System-based Adaptive Mechanism



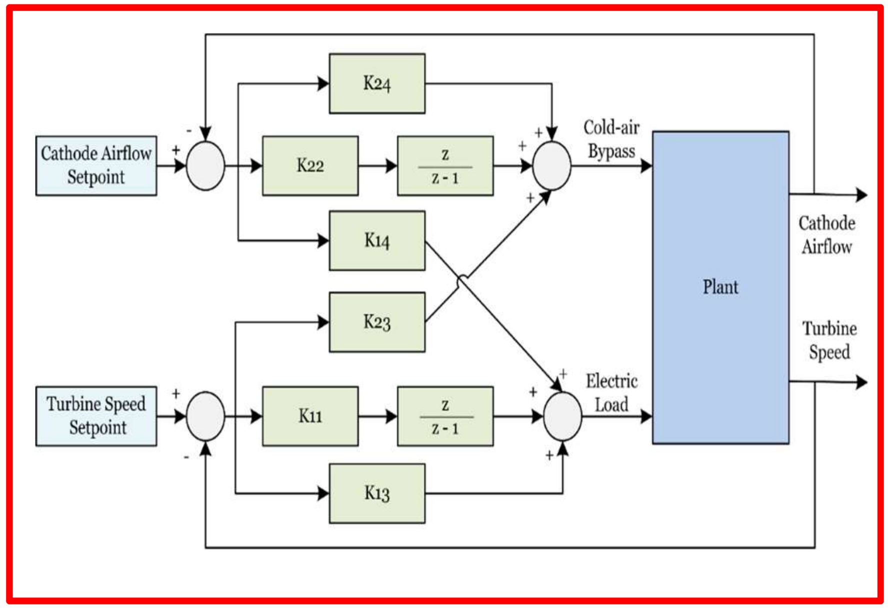
System Integration and Demonstration (Q7-Q12)

- Immunity-based schemes for abnormal conditions detection, identification, and evaluation were implemented and tested successfully on an AGR unit and on the NETL HYPER system's simplified model.
- Adaptive control mechanisms based on ANN and immunity feedback were integrated with the biomimetic control laws developed within Task 3.
- Adaptive mechanisms were shown to improve robustness and capability to maintain control under a variety of simulated abnormal conditions.

Fuel Cell-Gas Turbine Hyper System



Hyper System Baseline Control Laws



Task 5.0 Development of a Multi-Agent Optimization Framework for Control Structure Design, and State and Parameter Estimation

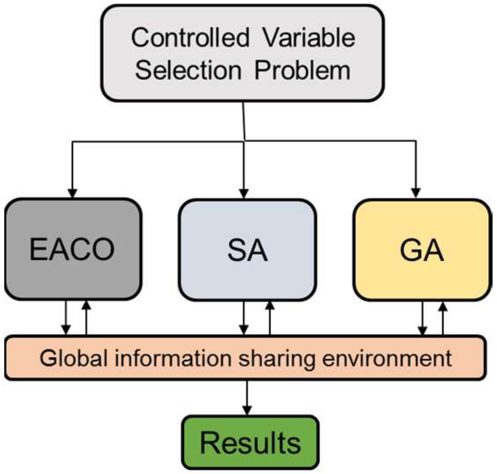
- MAOP is a nature-inspired optimization method, which supports cooperative search by group of algorithm agents coordinated in an environment with certain predefined sharing protocol.
- An agent in MAOP is an autonomous entity with personal declarative memory and behavioral components.
- Agents explore 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.

Diversity of Algorithms Explored

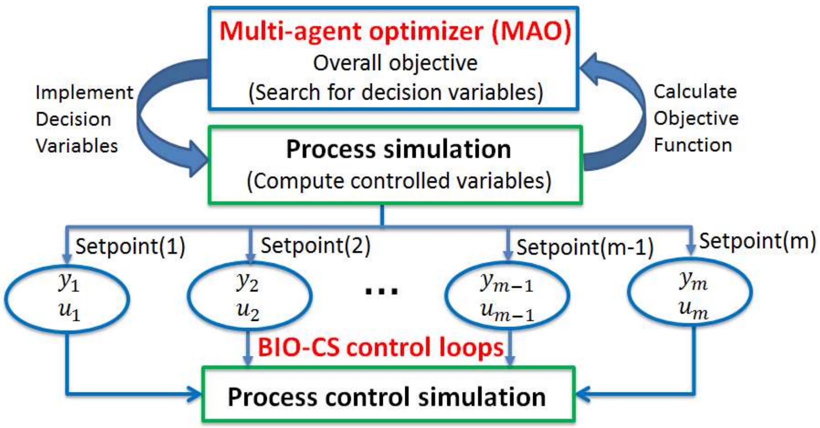
- Homogenous Multi-Agent Optimization (HMAO)
  - ✓ same algorithms and with different algorithmic parameters
  - ✓ run in parallel
  - ✓ cooperate through the sharing memory environment
- Heterogeneous Multi-Agent Optimization (HTMAO)
  - ✓ use diverse algorithms
  - ✓ run in parallel
  - ✓ cooperate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

Applications

- ✓ **Controlled Variable Selection Problem**



- ✓ **BIO-CS Controller**



Research Outputs: Publications

1. Bankole, T. and Bhattacharyya, D., 2016, July. “Algorithmic modelling of structural connectivity for process plants”. In *American Control Conference (ACC), 2016* (pp. 5038-5043). IEEE.
2. Bankole, T., Pezzini, P., Harun, N.F., Bryden, K., Tucker, D. Bhattacharyya, D., Diwekar, U. “Optimal Controlled Variable Selection for Cyber-Physical Systems”. In Proceedings of the Power & Energy Conference, June 24-28, 2018, Lake Buena Vista, Florida, USA(*Under review*)
3. Mirlekar, G., Pezzini, P., Bryden, M., Tucker, D. and Lima, F. V., 2017, May.” A biologically-inspired optimal control strategy for hybrid energy systems”. In *American Control Conference (ACC)*, (pp. 4821-4826). IEEE.
4. Mirlekar, G., Gebreslassie, B. H., Li, S., Diwekar, U. M. and Lima, F. V., 2018, July. “An integrated biomimetic control strategy with multi-agent optimization for nonlinear chemical processes”. Accepted for the *Proceedings of the IFAC ADCHEM Symposium*.
5. Bankole, T., Jones, D., Bhattacharyya, D., Turton, R. and Zitney, S.E., 2018. “Optimal scheduling and its Lyapunov stability for advanced load-following energy plants with CO_2 capture”. *Computers & Chemical Engineering*, *109*, pp.30-47.
6. Bankole, T. and Bhattacharyya, D., 2018 “Exploiting Connectivity Structures for Decomposing Process Plants”. Journal of Process Control (*Accepted*)
7. Bankole, T. Pezzini, P., Harun, N.F., Bryden, K., Tucker, D. Bhattacharyya, D. “Optimal Control Structure Design for Cyber-Physical Systems”. Proceedings of Power & Energy Conference (*Accepted*)
8. Bankole, T. Gebreslassie, B., Bhattacharyya, D., Diwekar, U. “Biomimetic Approach to Control structure design” (*Under internal review*)
9. Mirlekar, G., Gebreslassie, B. H., Li, S., Diwekar, U. M. and Lima, F. V., 2018, “Biomimetic agent-based optimization and advanced control of nonlinear chemical processes”. *In preparation*.
10. Mirlekar, G., Al-Sinbol, G., Perhinschi, M. G. and Lima, F. V., 2018. “A biologically-Inspired approach for adaptive control of advanced energy systems”. Submitted for publication in *Computers & Chemical Engineering.*
11. Mirlekar, G., Li, S. and Lima, F. V., 2017. “Design and implementation of a Biologically-Inspired Optimal Control Strategy (BIO-CS) for chemical process control”. *Industrial & Engineering Chemistry Research,* 56(22), p. 6468–6479.
12. Li, S., Mirlekar, G., Ruiz-Mercado, G. J. and Lima, F. V., 2016. “Development of chemical process design and control for sustainability”. *Processes,* 4(3), 23; doi:10.3390/pr4030023.
13. Perhinschi, M. G., Al-Sinbol, G., Bhattacharyya, D., Lima, F. V., Mirlekar, G. and Turton, R., 2015. “Development of an immunity-based framework for power plant monitoring and control”. *Advanced Chemical Engineering Research*, 4(1), p.15-28.

Research Outputs: Publications

14. Al-Sinbol G., Perhinschi M. G., Pezzini P., Bryden K. M., Tucker D., “Investigation of Biomimetic Adaptive Mechanisms for Hybrid Power Plant Control”, International Review of Automatic Control, Vol. 10, No. 5, pp 390-398, Sept.-Oct. 2017
15. Al-Sinbol G., Perhinschi M. G., “Development of an Artificial Immune System for Power Plant Abnormal Condition Detection, Identification, and Evaluation”, International Review of Automatic Control, Vol. 10, No. 3, pp 218-228, May-June 2017
16. Al-Sinbol G., Perhinschi M. G., Bhattacharyya D., “Evolutionary Optimization of Power Plant Control System Using Immunity-inspired Algorithms”, International Review of Chemical Engineering, Vol. 9, No. 1, pp 8-15, January 2017
17. Perhinschi M. G., Al-Sinbol G., “Artificial Dendritic Cell Algorithm for Advanced Power System Monitoring”, International Review of Automatic Control, Vol. 9, No. 5, pp 330-340, September 2016
18. Al-Sinbol G., Perhinschi M. G., “Generation of Power Plant Artificial Immune System Using the Partition of the Universe Approach”, International Review of Automatic Control, Vol. 9, No. 1, pp 40-47, doi: 10.15866/ireaco.v9i1.8170, January 2016
19. 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, Iss. 1, pp. 15-28, September 2015
20. Gebreslassie B. Diwekar U., (2018), “Heterogeneous multi-agent optimization for synthesizing optimal waste blends”, Clean Technologies and Environmental Policy, 20, 137.
21. Mukharjee R., B. Gebreslassie, and U. Diwekar (2017), “Design of novel polymeric adsorbents for metal ion removal from water using computer-aided molecular design”, Clean Technologies and Environmental Policy, 19, 483.
22. B. Gebreslassie and U. Diwekar (2017), “Homogenous multi-agent optimization for process systems engineering problems with a case study of computer aided molecular design”, invited paper, Chemical Engineering Science, 159, 194.
23. B. Gebreslassie, and U. Diwekar (2016), “Efficient ant colony optimization (EACO) algorithm for deterministic optimization”, International Journal of Swarm and Evolutionary Computation, 5(1), 1000131.
24. B. Gebreslassie, and U. Diwekar (2015), “Efficient Ant Colony Optimization for Solvent Selection using CAMD”, Proceedings of PSE-2015/ESCAPE-2015, 743.
25. B. Gebreslassie, and U. Diwekar (2015), “Efficient ant colony optimization for computer aided molecular design: Case study solvent selection problem”, Computers and Chemical Engineering, 78, 1.

Research Outputs: Presentations

1. Bankole, T., Pezzini, P., Harun, N. F., Bryden, K. M., Tucker, D. and Bhattacharyya, D. "Optimal Control Structure Design for Cyber-Physical Systems," In *AIChE Annual Meeting* (Computing and Systems Technology Division), Minneapolis, MN, Oct 29 -Nov 3, 2017.
2. Bankole, T., Bhattacharyya, D., Gebreslassie, B., Diwekar, U. "A Novel, Biomimetic Approach to Self-Organizing, Optimal Control Structure Design," In *AIChE Annual Meeting* (Computing and Systems Technology Division), Minneapolis, MN, Oct 29 -Nov 3, 2017.
3. Bankole, T., Mirlekar, G., Al-Sinbol, G., Gebreslassie, B., Lima, F., Perhinsci, M., Diwekar, U. D., Turton, R. and Bhattacharyya, D. "Development of Biomimetic Approaches for Intelligent Control System Design, Monitoring and Optimization of Advanced Energy Systems" In *AIChE Annual Meeting* (Computing and Systems Technology Division), Minneapolis, MN, Oct 29 -Nov 3, 2017.
4. Bankole, T., Jones, D., Bhattacharyya, D., Turton, R. and Zitney, S.E., "Optimal Scheduling of Advanced Energy Plants with CO_2 Capture" In *AIChE Annual Meeting* (Computing and Systems Technology Division), San Francisco, CA, Nov 13 -18, 2016.
5. Mirlekar, G., Al-Sinbol, G., Perhinschi, M., G., and Lima, F., V., "Development of a biologically-inspired approach for advanced adaptive control of clean energy systems". In AIChE Annual Meeting (Computing and Systems Technology Division), Minneapolis, MN, 2017.
6. Mirlekar, G., Pezzini, P., Bryden, K., M., Tucker, D. and Lima, F., V., "A biologically-inspired optimal control framework: application to the Hybrid Performance (Hyper) system." In AIChE Annual Meeting (Computing and Systems Technology Division Poster Presentation), Minneapolis, MN, 2017.
7. Mirlekar, G., and Lima, F., V., "Design and implementation of a Biologically-Inspired Optimal Control Strategy (BIO-CS) for advanced energy systems". In AIChE Annual Meeting (Computing and Systems Technology Division), San Francisco, CA, 2016.
8. Gebreslassie, B., H., Mirlekar, G., Diwekar, U., M., and Lima, F., V., "Optimal control design based on efficient ant colony algorithm, case study: chemical process control". In AIChE Annual Meeting (Computing and Systems Technology Division), San Francisco, CA, 2016.
9. Gebreslassie, B., H., Diwekar, U., M., Mirlekar, G., and Lima, F., V., "Optimal control based on Efficient Ant Colony Optimal Control (EACOC) algorithm: case study chemical process control". In AIChE Midwest Regional Conference, Chicago, IL, 2016.
10. Mirlekar, G., Gebreslassie, B., H., Diwekar, U., M., and Lima, F., V., "Design and implementation of a biomimetic control strategy for chemical processes based on efficient ant colony optimization". In AIChE Annual Meeting (Computing and Systems Technology Division), Salt Lake City, UT, 2015.
11. Lima, F., V., Li, S., Mirlekar, G., Sridhar, L., N., and Ruiz-Mercado, G., J., "Modeling and advanced control for sustainable process systems". In AIChE Annual Meeting, Salt Lake City, UT, 2015.

Research Outputs: Presentations

12. Al-Sinbol G., Perhinschi M. G., Bhattacharyya D., “Power Plant Abnormal Condition Detection Using the Artificial Immune System Paradigm”, poster presentation at the 2016 AIChE Annual Meeting, San Francisco, CA, November, 2016.
13. Gebreslassie B. and U. Diwekar, “Synthesizing optimal nuclear waste blends using Multi-agent optimization framework”, 2017 AIChE Midwestern Regional Meeting, Chicago
14. Gebreslassie B. and U. Diwekar, “Multi-Agent Optimization Framework (MAOP) for Synthesizing Optimal Radioactive Waste Blends.”, 2016 AIChE Annual Meeting, San Francisco, CA.
15. Berhane H. Gebreslassie and Urmila M. Diwekar , “Multi-Agent Optimization Framework (MAOP) for Large Scale Process System Engineering Optimization Problems)”, 2016 AIChE Midwestern Regional Meeting, Chicago
16. Berhane H. Gebreslassie and Urmila M. Diwekar , “Multi-Agent Optimization Framework (MAOP) for Large Scale Process System Engineering Optimization Problems)”, 2015 AIChE Annual Meeting, Salt Lake City, UT
17. Gebreslassie B. and U. Diwekar, “Efficient Ant Colony Optimization (EACO) Algorithm for Deterministic Optimization”, 2015 AIChE Midwestern Regional Meeting, Chicago
18. Gebreslassie B. and U. Diwekar, “Efficient Ant Colony Optimization (EACO) Algorithm for Deterministic Optimization”, 2014 AIChE Annual Meeting, Atlanta, GA.

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