Research Areas:

My research has so far focused on the passivity, nonlinear control, optimization, and control of uncertain systems, with applications in biological systems, robotic systems, and power systems. Currently, I'm working on the control algorithm development and implementation that can scale to larger systems.

A. Passivity and Immersion (P&I) Approach

1. Passivity and immersion (P&I) approach for constructive stabilization and control of nonlinear systems

This work proposes a control algorithm as a stepping stone for the stabilization and control of structured and unstructured systems discussed in the literature. The foundation behind this proposed controller design theory utilizes an invariant target manifold giving rise to a non-degenerate form, through which the definition of certain passive outputs and storage functions provide the control law for stabilizing the system. The proposed control framework is developed by integrating the notions of immersion and passivity hence labeled as the "Passivity and Immersion (P&I) approach." Immersing the system dynamics into the user-defined lower order target dynamics and using the concept of attractivity of the manifold based upon the passivity theory results in encompassing various design paradigms under a single roof of the P&I approach.

2. Passivity and Immersion (P&I) Approach With Gaussian Process for Stabilization and Control of Nonlinear Systems

The virtual derivatives computation and successive derivations of virtual inputs in an adaptive backstepping controller cause the explosion of complexity. Moreover, the feedback linearization has poor robustness features and necessitates exact estimation of the feedback control law's coefficients. Due to measurement noise, the model-based estimation techniques for identifying uncertainties result in inaccurate gradient and Hessian calculations. Such limitations lead to model and measurement uncertainties that prevent effective stabilization and control of nonlinear systems. Machine learning-based data-driven approaches offer effective tools for identifying dynamical systems and uncertainties with minimal prior knowledge of the model structure. Therefore, the contribution of this research is two-fold: First, the general controller design theory is proposed which utilizes the idea of an invariant target manifold giving rise to a non-degenerate two form, through which the definition of certain passive outputs and storage functions leads to a generation of control law for stabilizing the system. Since the above concepts are linked with the Immersion and Invariance (I&I) design policy and the passivity theory of controller design, the proposed methodology is labeled as the "Passivity and Immersion (P&I) based approach". Second, the proposed P&I approach is integrated with a Bayesian nonparametric approach, particularly the Gaussian Process for stabilization and control of the partially unknown nonlinear systems.

3. Synchronization of uncertain chaotic systems with minimal parametric information

The chaotic synchronization is mainly hampered by uncertain system dynamics in terms of underlying parameters. To obtain accurate parameter estimates for the proper synchronization of uncertain chaotic systems (UCSs) through adaptive control, it is necessary to satisfy the persistence of excitation (PE) condition. Furthermore, the challenges imposed by the explosion of complexity in sequential stabilization procedures, slow performances, and lack of information in UCSs hinder the synchronization process through existing control techniques. Therefore, the contribution of this research is two-fold: First, a systematic stabilization approach with minimal calculations is proposed to achieve proper synchronization between chaotic drive and response systems. The key concept of the proposed theory is to obtain an invariant manifold by immersing the error dynamics (resulting from the mismatch between the drive and response systems) into lower-order target dynamics. From there, the control law for synchronizing these chaotic systems can be derived by defining passive outputs and associated storage functions. The proposed framework, which combines the concepts of immersion and passivity, is referred to as the Passivity and Immersion (P&I) approach. Second, unlike adaptive control, the synchronization of UCSs is made possible by selecting the appropriate target dynamics without any parameter estimation (or with minimal parametric information in certain cases).

B. Control Theoretic Perspective in Optimization

The proposed control theoretic perspective is useful for designing any optimization algorithm by obtaining a controlled dynamical system that achieves the desired objective in an optimal way (if possible).

1. Nesterov's Accelerated Gradient Descent: The Controlled Contraction Approach

Inspired by the purported mystery surrounding the origins of Nesterov's Accelerated Gradient (NAG) method, this work has derived the second-order ODE for the NAG-SC method through the notions of manifold stabilization implemented using the P&I approach and the persistence of an invariant manifold. Under the control actions, the contraction of the trajectories of the ODE for NAG-SC in the overall state space is also proved, which further unveils the multifold benefits of NAG-SC. The contracting Nesterov's flows not only ensures a stable numerical integration of ODE but also aids the generalization in supervised learning. Through contraction, the NAG-SC method inherits the properties of geometrical notions, including natural gradient and geodesic convexity, motivating its usefulness in deep learning applications.

2. Controlled gradient descent: A control theoretical perspective for optimization

The Gradient Descent (GD) paradigm is a foundational principle of modern optimization algorithms. The GD algorithm and its variants, including accelerated optimization algorithms, geodesic optimization, natural gradient, and contraction-based optimization, to name a few, are used in machine learning and the system and control domain. In this work, we proposed a new algorithm based on the control theoretical perspective, labeled as the Controlled Gradient Descent (CGD). Specifically, this approach overcomes the challenges of the abovementioned algorithms, which rely on the choice of a suitable geometric structure, particularly in machine learning. The proposed CGD approach visualizes the optimization as a Manifold Stabilization Problem (MSP) through the notion of an invariant manifold and its attractivity. The CGD approach leads to an exponential contraction of trajectories under the influence of a pseudo-Riemannian metric generated through the control procedure as an additional outcome.

3. Unified Control Framework for Optimization: A Fresh Perspective on Constrained Optimization, Optimization-based Control, and Parameter Estimation

A common theme in all the above areas is designing a dynamical system to accomplish desired objectives, possibly in some predefined optimal way. Since control theory advances the idea of suitably modifying the behavior of a dynamical system, this work explores the role of control theory in designing efficient algorithms (or dynamical systems) related to problems surrounding the optimization framework, including constrained optimization, optimization-based control, and parameter estimation. This amalgamation of control theory with the above mentioned areas has been made possible by the recently introduced paradigm of Passivity and Immersion (P&I) based control

C. Granger Causality for prediction in Dynamic Mode Decomposition

The dynamic mode decomposition (DMD) technique extracts the dominant modes characterizing the innate dynamical behavior of the system within the measurement data. For appropriate identification of dominant modes from the measurement data, the DMD algorithm necessitates ensuring the quality of the input measurement data sequences. On that account, for validating the usability of the dataset for tuning the DMD algorithm, this work has proposed two conditions: Persistence of Excitation (PE) and the Granger Causality Test (GCT). The virtual data sequences are designed with the Hankel matrix representation such that the dimensions of the subspace spanning the essential system modes are increased with the addition of new state variables. The PE condition provides the lower bound for the trajectory length, and the GCT provides the order of the model. Satisfying the PE condition enables estimating an approximate linear model, but the predictability with the identified model is only assured with the temporal causation among data searched with GCT.

D. Scalable Optimal Control

1. On Exact Embedding Framework for Optimal Actions in MDPs

This work deals with the embedding framework of Markov decision processes (MDPs) with discrete state and action space to find optimal actions. The optimal control problem of MDPs is efficiently tackled if it can be restructured into an equivalent linearly-solvable MDP (LMDP) through the process of embedding. In this work, we derive a constructive sufficient condition to arrive at an exact embedding solution; thereby, the embedded state cost matches the original system.

2. **Optimal Control of Probabilistic Boolean Control Networks: A Scalable Infinite Horizon Approach**

   We define an augmented state space, and by exploiting Kullback-Leibler (KL) divergence the desirability function, we compute the optimal control using the path integral (PI) approach. We propose sampling-based techniques for the approximation of the PI and hence the optimal control of PBCNs. The sampling-based strategy is amicable to parallel implementation, thereby addressing the optimal control problem of large-scale PBCNs.

3. **Optimal Control of Probabilistic Boolean Networks: An Information-Theoretic Approach**

   In this work, we use an information-theoretic framework to compute optimal control of probabilistic Boolean network using path integral in finite time. In addition, an entropy-based sampling technique is developed to overcome the variance issue and use fewer samples.

E. Power system analysis and control

In recent years, the most researched complex uncertain system is the power systems where there exist many diverse uncertain parameters such as loads, electricity price, wind power generation, and photovoltaic power generation. Hence, the main theme of this work is to address various issues in the existing power system analysis based on the non-iterative method named holomorphic embedding power flow (HEPM). This exploits various concepts from complex analysis and provides a reliable physically existing solution to the power flow problem in various operating conditions.

1. The bifurcation point analysis in the generator outage scenario and in a more realistic view under non-uniform loading is performed using HELM. In addition, various iterative-based methods are proposed in the literature that lags in providing a reliable and accurate power flow solution for hybrid ac-dc systems. As a result, the next issue being addressed is the development of unified-HEPM to calculate the power flow solution of hybrid ac-dc systems.

2. Moreover, the power system has multiple generators, and loads connected together through network configuration should be synchronized where the generator synchronization is modeled as coupled oscillators in the Kuramoto framework. The conventional stability analysis iterative power flow solutions genuinely have convergence issues, that lag reliability, and scalability. To eliminate the dependency of the iterative-based load flow methods, a novel approach to adequately investigate the stability of the synchronized operating point in the multimachine power network using holomorphic embedding is developed.

F. Data-driven Approaches for System Analysis and Control

1. Effective Sequential Learning for Optimal Power Flow: A Soft Actor-Critic Approach

The traditional electric grid is evolving into a smart grid, with the integration of renewables, active loads, intelligent devices, etc. adding to the grid's complexity. Traditional tools used for grid operations and planning should be capable of addressing the evolving complexities. Optimal power flow (OPF) is one such tool underlying much of power system operations and planning. It determines the power generation required to meet an estimated demand while minimizing the generation costs and adhering to grid constraints. As a result, OPF forms a non-linear and non-convex constrained optimization problem. Traditional techniques like the interior point (IP) method optimize with a fixed set of constraints. Supervised learning techniques estimate the requisite generation solely based on input data and fail to incorporate the physical constraints of the device during prediction. In this work, we propose Soft Actor-Critic (SAC) based reinforcement learning to solve the cost-based OPF problem within grid constraints. The proposed method leverages the state-of-the-art agent making it effective, highly sample efficient, and not suffer from brittleness due to hyperparameters. Learning is accelerated by using historical data for initializing neural networks through behavioral cloning.

2. Coherency Identification in Multimachine Power Systems Using Dynamic Mode Decomposition

Synchronous generators continue to oscillate in multi-machine power systems in many coherent communities, and each community corresponds to the virtual generator. However, coherent communities can vary in response to different activities under different operating conditions. Hence it is necessary to conduct an online analysis however the resulting control actions are based on the system dynamical model. The system models formed using the first principle fail to represent the processes entirely throughout operating circumstances. Therefore a data-driven approach to system modeling is an effective resource for interpreting real-world activities and analyzing their effects in the future. For that, this work introduces a novel approach for data-driven modeling based on dynamic mode decomposition (DMD) for the coherency identification in a multimachine power system. In order to model the system more efficiently, both steady-state and transient data are considered. An augmented data matrix in the Hankel structure is passed as an input to the DMD algorithm for capturing the behavior of the system accurately. Incorporating the persistency of excitation and Hankel structure in DMD, a rank condition is derived to identify the coherency of generators in post-fault situations.

3. **Voltage Collapse Boundary Detection in a Power System using Gaussian Process Regression**

   The consistently increasing demand, infrastructure restriction forces the power system to operate near its limits. The nonlinear power flow equations and network structure constrain the power transfer capability in large networks. The constraint violations result in voltage collapse blackouts in the worst case. In addition, the uncertainties arising due to the transmission line parameters and measurement noise complicate the power system analysis. Therefore, it is a great deal for a power engineer to explore voltage collapse boundaries under uncertainty to take preventive actions. In this work, a unified machine learning approach is developed to detect the voltage collapse boundary in the presence of uncertainty using the holomorphic embedding and Gaussian process regression. Holomorphic embedding provides the power flow solution space and voltage collapse points, while Gaussian process regression provides the analytical form of the boundary under uncertainty.

Research Lab Development in VJTI (PI and Co-ordinator)

1. **ELECTRICAL: MODELLING, COMPUTATION, AND CONTROL (E-MC 2) LAB (2023)**

   The Savex Technologies Pvt. Ltd., represented by Shri Anil Jagasia, an esteemed alumnus of the Electrical Engineering Class of 1981, is responsible for the development of the Electrical Modelling, Computation, and Control (E-MC^2) Lab.

2. **Center of Excellence in Complex and Nonlinear Dynamical System (CoE-CNDS) (2013) , PI**

   VJTI was selected under TEQIP-II (subcomponent 1.2.1) for establishment of a CoE-CNDS with a funding of INR 5 Crores by World Bank through National Project Implementation Unit (NPIU), MHRD, New Delhi.

3. **Control and Dynamics Laboratory (2003)**

   Established the lab with a grant of five and a half million INR provided by the Govt. of India for the purpose of promoting research and education in the area of Control and Dynamics.

4. **Computational and Dynamics Lab, A joint BARC -VJTI Facility (2005)**

   The facility has been set up in Collaboration with BARC (Atomic research Centre) with an initial Grant of five million INR.

5. **Power Electronics and Hybrid Energy Management Laboratory (2016)**

   The laboratory has been established by the centre in collaboration with L&T as an industrial partner for power different electronic converters like multi-level inverters, motor generator testbed, TI HV motor control kit with BLDC, etc.

6. **Rapid Prototyping Laboratory (2016)**

   To provide precision measurement for the research projects and to provide consultancy facilities for industries.

LIST OF PROJECTS

1. Modeling & PIC Based Simulations of Relativistic Nonlinear Phenomenon in Magnetron
Research Members:
Concerned Professors: Dr.N.M Singh
PhD Student: Ayush Saxena
Research Associate: Swapnil Uday Wagh
Collaboration With: Bhabha Atomic Research Centre (BARC)

2. Bifurcation Analysis of Cascade Failures in Power Grid: Northern Grid Blackout Case Study
Objectives:
- To study power system networks its Complexity and nonlinear behavior.
- Predicting Probable cascade failure point using bifurcation.
- Analyze bifurcation in convertors circuits

Research Members:
Concerned Professors: Dr. H.A. Mangalvedhekar, Dr. F. S. Kazi, Dr. N. M. Singh
PhD Student: Vaishali Rampurkar
Research Associate: Abhishek Pandey
Collaboration With: Power Grid Corporation of India Limited (PGCIL)

3. Passivity-based Control of Under-actuated Non-linear Dynamical Systems
Objectives:
To study various passivity based approaches to design control strategies for nonlinear systems.
Implementation of passivity based controller to complex systems like cooperative control of multi-agent systems, under-actuated nonlinear mechanical systems, etc.
Research Members:
Concerned Professors: Dr. N. M. Singh, Dr. F. S. Kazi
PhD Student: Rachit Mehra, Sneha Mane
Research Associate: Pushpak Jagtap
Collaboration With: CNRS, France

6. Synchronization Control of Nonlinear Heterogeneous Systems & Hybrid Energy Management Systems
Objectives: Designing control law for coordination control of multi-agent systems using various methods and Stabilization and coordination control of infinite agent systems
Research Members:
Concerned Professors: Dr. N. M. Singh, Dr. F. S. Kazi
PhD Student: Aniket Deshpande
Research Associate: Pushpak Jagtap, Swapnil Wagh
Collaboration With: DRDO lab

7. Development of Non-linear Control Law using Multilevel SVM for Suppressing Inverter Non-linear Distortions with Low Harmonics
Objectives:
Develop Medium Voltage Inverter units to be operated in industrial operations, based on nonlinear control algorithm for robust system.
Develop technologies to ensure efficiency of converted power with low harmonic distortions.
Develop critical PWM switching for optimal output.
Research Members:
Concerned Professors: Dr. N. M. Singh
Research Associate: Sushant Bahadure, Snehalata Joshi
Collaboration With: L & T

INDUSTRIAL CONSULTANCY/PROJECTS IN COLLABORATION

Sr. No.	Project	Collaborating Partner/Funding Agency	Fund Involved (Rs.)	Commencement Date
1	Project on Motion control of Underwater vehicles	L&T	23,00,000	24 Mar 2017
2	Special Courses on Power Electronics for Engineers of Central Railway	Central Railway	3,45,000	16 Jan 2017
3	Development of smart grid laboratory	ISGF	5,00,000	13 Sept 2013
4	Control Algorithms for Power Converters	L&T Electrical and Automation	15,00,000	02 July 2014
5	Third Party Inspection for Underground Cables Laid in the Area of NMMC and Complaints of M/s Saljer Electronics Regarding Energy Savings and Performance of this System	Navi Mumbai Municipal Corporation, India	6,90,000	06 Aug 2016
6	Training consultancy for Electrical Machines 1.5 Lacs	Portescap India Pvt. Ltd, Mumbai	1,50,000	June - Dec 2013
7	Markov modeling and Fault analysis of Electrical Systems	ABB India	--	(Dec 2006)

INTERNATIONAL VISITS and SPECIAL TALKS

1. **GRACE, Università del Sannio, Italy, Host: Prof. Luigi Glielmo (2017)**
    - MoU signed between the University of Sannio (UniSannio) Benvento, Italy and VJTI, Mumbai.
    - Dr. N. M. Singh conducted one week course on “Geometric Control Methods” at UniSannio, Benvento, Italy (19-23 June 2017).
    - Dr. N. M. Singh delivered an invited talk, on “Kuramoto Oscillators”, on 26 June 2017 at the UniSannio, Benevento, Italy.
2. **Tufts University, USA, Host: Prof. Alex Stankovic (2016)**

    Exploratory visit arranged by Prof. Alex Stankovic, Tufts University, USA
3. **LSS Supelec, *France*, Host: Prof. Romeo Ortega (2012)**

    Dr. N. M. Singh delivered an invited talk, on “ Underactuated Mechanical Systems”
4. **University of Melbourne, Australia, Host: Professor Iven Mareels (2007)**

    Exploratory visit arranged by Technical Education Quality Improvement Programme (TEQIP), VJTI