Name of the Micro-Specialization: Embedded Control and Software: Modeling and Design

1. **School/Center: Advanced Technology Development Centre**

2. **Brief Description:** Our world is increasingly becoming automated, through the ubiquitous presence and coordinated involvement of embedded systems, controls and software. From medical devices to transportation (ships, railways, cars, aerospace, etc) or security systems to process industries, which affect our daily lives, rapid automation of these systems is taking place thanks to the incorporation and advancement of embedded systems, controls and software. For example, in an automated chemical process plant, the right amount of flow rates at the right time (achieved through control commands) are essential for its operation and are realized based on the calculations of required mixtures of various chemicals, computed by an embedded systems' software which also gives control commands and senses the actual condition through sensors. Hence, it is evident that the requirements of the global industry are clearly shifting towards a large demand in advanced and skilled workforce who have the combined expertise in these areas, resulting in a more complex and multidisciplinary field.

   The present curriculum of relevant individual B.Tech courses such as CSE, EE, ECE, QEDM, ME, CH, AE, CE, AG though might contain related subjects but they do not teach all three in a combined and coordinated manner as per the present industrial requirements. For example, the EE's B.Tech course of IIT KGP has the courses of "Control System Engineering" "Measurements and Electronic Instruments" and "Embedded Systems". However, in real world's (usually complex) practical and industrial systems, the operational control logic is mostly incorporated in an embedded systems which further operates through interfaces with sensors and actuators, which have associated design and development challenges due to this integration and require detailed simultaneous understanding of multi-disciplinary concepts, generally not covered in the existing courses.

   Hence by studying in details about the integrated embedded systems with controls and software one will be equipped to tackle the real industrial world by solving the software challenges along with the embedded design to execute the control algorithm, prevalent in the practical systems such as automated medical devices and automotive systems. Moreover, in practical systems the complexities are such that several embedded systems of similar or different types might interact with each other (e.g.in Aerospace, Automotive) in a well coordinated manner to perform several tasks, requiring the study of their architectural designs, communications and synchronizations among them towards meeting the objective.

   This kind of multi-disciplinary course having the integrated essential aspects of all the three fields of embedded systems, software and controls is expected to create competencies for the new generations of BTech students particularly in the streams of EE, ECE, CSE, QEDM, ME, CH, AE, CE, AG who can actively contribute to the design, development and testing of automated embedded products in various disciplines of the industry.

3. Number of Subjects needed to earn the Micro-Specialization: 3 Subjects + 1 Project **or** 4 Subjects

4. Credits needed to earn the Micro-Specialization: 13-14 credits

5. Structure: **Component I:** One Subject (3-0-0)
Component II: Two Subjects (4-0-0/3-1-0/ 3-0-0)
Component III: Project (0-0-6) or One subject taken from Component II

A. COMPONENT I: MANDATORY REQUIREMENT: (3 credit FOUNDATION COURSE)

TABLE-I

Sub no.	Sub Name	LTP	Credits	Offering Semester	Pre-Requisite (if any)
AT4XXXX	Fundamentals of Embedded Control and Software (TBP)	3-0-0	3	Autumn	None

B. COMPONENT- II: ANY TWO SUBJECTS (3/4 credits each) FROM TABLE-II

TABLE-II

Sub no.	Sub Name	LTP	Credits	Offering Semester	Pre-Requisite (if any)
AT60001	Embedded Control System	4-0-0	4	Autumn	-
AT60002	Principles of Automotive Dynamics & Control	3-0-0	3	Spring	-
AT60003	Embedded Software Design and Validation	4-0-0	4	Autumn	-
AT60004	Security Aware IoT and CPS Design	3-0-0	3	Spring	-
AT60006	Embedded Sensing, Actuation and Interfacing System	4-0-0	4	Spring	-
AT600XX	Embedded Communication Networks (P)	3-0-0	3	Spring	-
CS61063	Computational Foundations of Cyber Physical Systems	3-1-0	4	Autumn	-

C. COMPONENT- III: PROJECT (4 credits) OR ANY ONE (4 credits) SUBJECT FROM TABLE-II

TABLE-III

Sub no.	Sub Name	LTP	Credits	Offering Semester	Pre-Requisite (if any)
ATXXXXX	Project	0-0-6	4	Both semesters	-

Detailed syllabus of the subjects:

1. Fundamentals of Embedded Control and Software (Core)

Objective: The purpose of this course is to provide an overview of the fundamental knowledge required to understand and explore the design and development of an embedded control system considering its hardware, software and control aspects. Using this knowledge the students are expected to gain interest for expanding their depth by taking up more courses relevant to embedded control systems and software which will further enhance their skills and expertise towards development of more elaborate and customized embedded control systems in different applications of interest.

Syllabus: The overall syllabus is of 33 lectures

Module	Description	Lecture Hours
1	Introduction to Embedded Systems and Embedded Control Systems a. What is an embedded system and real examples b. Characteristics/ architecture of an Embedded system c. Block Diagram(s), components and operations of embedded Control System d. Real time requirements and its issues	[2]
2	Basics of Microcontroller a. Architecture b. Functionalities c. Programming (Timers, I/Os, interrupts, etc) and examples d. Serial and parallel interfaces for communications	[5]
3	Real world systems and their state space plant model & MATLAB modeling a. Controller Basics and implementation, PID and its applications & issues b. Mass spring damper c. Two tank interacting system (plant and controller) d. Automotive Systems (Plant and controller)	[5]
4	Modeling to Implementation a. Introduction to different modeling techniques b. MATLAB modeling to software implementation	[4]

5	Analysis of Embedded Software a. Embedded Software Testing b. Optimization techniques of software c. Performance Analysis: WCET calculation	[4]
6	Embedded System Task Scheduling a. General scheduling and embedded requirements b. Basic features of RTOS	[3]
7	Basics of Embedded Communication a. ECU communication protocols b. Case Study: CAN overview	[3]
8	Sensors, actuators, their interfacing in Embedded Control Systems and numerical considerations a. Types of sensors and as per application, e.g., LVDT, Hall effect, pressure, temperature b. Sensing mechanism c. Signal conditioning (amplifiers, filters, etc), ADC/DAC, sampling and issues d. Fixed point, floating point, Quantization errors, etc e. Actuators: Principles, motors, solenoids etc f. Interfacing of sensors and actuators with embedded system	[5]
9	Embedded Motor Control System a. Dynamic Equations b. Motor transfer function c. PWM based operation d. Inverters and their control e. Closed loop motor control using microcontroller	[2]

Text Books/ References:

1. Peter Marwedel, “Embedded System Design”, Springer, 3rd ed. 2018.
2. Wayne Wolf, “Computers as Components: Principles of Embedded Computing System Design”, Morgan Kaufmann Series, 2008
3. Stuart R. Ball, “Analog Interfacing to Embedded Microprocessor Systems”, Elsevier 2004
4. Frank Vahid and Tony Givargis, “Embedded System Design: A Unified Hardware/Software Introduction”, Wiley 2006.
5. Ali Mazidi, “AVR Microcontroller and Embedded Systems” Prentice Hall.
6. K. Ogata, “Modern Control Engineering”, Pearson, 2015.
7. Charles L. Phillips and H. Troy Nagle, “Digital Control System Analysis and Design”, (3rd edition): Prentice Hall.
8. Lee, Leung and Son, “Handbook of Real-Time and Embedded Systems”, CRC Press.
9. Edward A. Lee and Sanjit Arunkumar Seshia, Introduction to Embedded Systems: A Cyber-Physical Systems Approach, MIT Press.

Course Teachers:

1. Somnath Sengupta
2. Ayantika Chatterjee
3. Banibrata Mukherjee
4. Arnab Sarkar (To join, shortly)

Overlap:

Overlap % with Embedded Control System (AT60001): 40 %
Overlap % with Embedded Software Design and Validation (AT60003): 40 %

This proposed course will be primarily offered as a foundation course for Micro specialization. This course has a good amount of overlap with two core courses of ATDC namely, (1) Embedded Control System (AT60001) and (2) Embedded Software Design and Validation (AT60003). The reasons for introducing this course in spite of good overlap with the existing core courses are as follows: As per the structure of micro specialization, only one core/foundation course is allowed. However, the objectives and requirements of proposed micro specialization cannot be fulfilled by choosing any one of the core existing courses because the spectrum of this microspecialization essentially should cover both embedded control aspects as well as embedded programming and software design aspects. Therefore, it necessitates the overviews and partial combination of both the core courses. However, during formulating the syllabus it has been ensured that the difficulty level is as per the targeted UG students' capability and requirements for earning the microspecialization degree.

Detailed Syllabus of the elective subjects:

AT60001: Embedded Control System (L-T-P: -4-0-0, CRD-4)

1: Introduction: Mathematical modeling of physical systems: Review of differential equation, transfer function and state variable representations; Examples of modeling different types of systems.

2: Control System Design: Closed loop control: Analysis of simple control loops; Stability; Time and Frequency domain specifications of control system performance. Simple approaches for controller design; Discretization. Practical realization of a control loop

3: Controller Implementation: Architecture of embedded controllers and description of various components; Design and implementation of control loops : Choice of embedded computing platforms, i/o and communication

4: Real-time Issues: Real-time issues in controller implementation: Scheduling algorithms and their performance analysis; Constraints of the operating systems; Real-time operating systems; Validation techniques for control systems. Performance assessment of control algorithms on the target implementation architecture for the given application.

5: Applications: Case studies from automotive, aerospace, process control and other application domains.

AT60002: Principles of Automotive Dynamics & Control (L-T-P: -3-0-0, CRD-3)

1: Introduction to Automotive Systems
Overall Architecture, operation, Overall process, Driving Cycles, Challenges.
Brief overview of Powertrain Architecture, Embedded Systems Architecture, Communication Networks (CAN, LIN, Flexray, etc)
2: Automotive Components and Their Models, Powertrain Components, Transmission, Drives, Battery, Auxiliary and their effects in dynamics
3: Engine Basics and its control

4: Types of IC engines, Construction, Operation, Dynamics, Control, OBD-II Engine controls - Fuel Injection, λ Closed loop, EGR, Throttle, Knock.
5: Vehicle Dynamics Kinematic Models, Motion Analysis, electronic Stability Control, Control of Semi active and active suspension
6: Revision of Control Basics Closed Loop system, transfer functions, poles and zeros, bode plots, stability, Common control schemes like PID control and its application to vehicle dynamics
7: Control loops in various ECUs (Overview)
Engine Management System, Transmission Control Unit, Electric Power Assist System, Supervisory Control Unit, Battery Management Systems
8: Automotive Sensors and Actuators
Sensors and actuators for significant components, their characteristics and basic modeling
9: Electric and Hybrid Vehicle System
Basics of EV and HEV system, types, modeling and energy management based supervisory control.
10: Introduction to Autonomous Vehicles
Control requirements of AV, AV sensors and actuators, Case study: L1-L2 level of AV.
11:Automotive standards :Autosar, Functional Safety Standard (ISO 26262)

AT60003: Embedded Software Design and Validation (L-T-P: -4-0-0, CRD-4)

1. Introductory Lecture
2. Specification Models for Embedded Systems: Finite State Machine, Concurrent State Machine, Hierarchical State Machine/State Charts, Message Sequence Chart, Timed Automata, Hybrid Automata
3. Model/Implementation Validation:Temporal Logic,Model Checking, Program verification (using CBMC)
4. Communication Validation : Protocol Converter Synthesis
5. HW basics: Basics of Computer Architecture (ISA, Pipeline, Cache), Bus protocols : CAN, Flexray, Sensors, ADC/DAC
6. Realtime Operating System Basics: Real time scheduling, Modern RTOS examples and case studies
7. Embedded Software Testing and Software Engineering Aspects
8. Hardware-software Codesign, Task Mapping, Task Scheduling
9. Performance Validation : Timing Analysis of Embedded Software:WCET Analysis of C Programs, Real Time Calculus (RTC) — extra topic (if time permits)
10. Tools and related assignments: Simulink/Stateflow (in ESDV lab), Uppaal (in ESDV lab), Spin/CBMC (in ESDV lab

AT60004: Security Aware CPS and IoT Design (L-T-P: -3-0-0 CRD-3)

1. Security Issues of Cyber Physical System: Types of attack models in CPS, Jamming attack in CPS and Anti-jamming, Case Study:Jamming Attacks on Mobile CPS in Target Tracking Applications.

2. FSM based and Graph based Security Aware CPS design

3. Security aware CPS design methodologies: Security mechanisms for CAN, Security aware TDMA Based Real Time System, Security mechanisms for V2V Communication

4. ICS/SCADA System and Embedded Systems Security for CPS

5. Security Requirements for Internet Of Things:Introduction to IoT, Relationship Between CPS and IoT, Threats to Internet Of Things(IOT) Architectures.

6. IoT threats specific to Access Control and Privacy: Insufficient Authentication/Authorization, Threats to Access Control, Privacy, and Availability.

7. Authentication/Authorization for Smart Devices:Transport Encryption, Secure Cloud/Web Interface, Secure Software/Firmware, Physi-cal Layer Security.

8. IOT Node Authentication: Public-Key-Based Authentication, Identify-Based Authentication, Lightweight Cryptography.

9. Security in Enabling Technologies: Security in Identification and Tracking Technologies, Security in Integration of WirelessSensor Network and RFID

10. Security Challenges for cloud assisted IoT applications: Secure data sharing challenges, Encrypted Computation. Case Studies: Security forIOT in Retail and Health-care.

AT60006: Embedded Sensing, Actuation and Interfacing System (L-T-P: -4-0-0, CRD-4)

1. Introduction: Overview of Embedded System, Architecture; Importance of advanced sensors, actuators and interfacing circuits: Applications.

2. Embedded Sensors and Actuators: Various types of sensors, actuators, their descriptions and applications: Thermal, Electrical, Magnetic, Mechanical, Pneumatic etc.

3. Interfacing of Sensors and actuators to embedded controller: Signal conditioning circuit, loading effect, Op-Amp based circuit implementation, ADC, DAC, environmental effects, Driver circuits and elements, Signal Processing: Sampling, Z-transform, Digital Filters.

4. Advanced Techniques for Direct Interfacing of Resistive Sensors to Embedded controller: Embedded Processor Based Excitation System; Direct interfacing Resistive Sensors and its array to Microcontrollers

5. Advanced Interfacing Techniques for the Capacitive Sensors to Embedded controller: Microcontroller Compatible Oscillator Based Active Bridge Circuit for wide range measurement, Auto balancing bridge for Lossy Capacitive Sensor.

6. Miniatuarized sensors, actuators and interface: Requirement of miniatuarization, Technology used, Various types of miniaturized sensors and actuators, Working Principle, CMOS compatible miniatuarization process, System-on-Chip integration, Applications.

7. Energy Harvesting and its applications in embedded network: Energy harvesting techniques: Vibration: Piezoelectric, Electromagnetic,; Solar, RF; Interfacing circuits; Sensors and Actuators in Wireless networks, Power sources to embedded system: battery, Supercapacitor, Power Management circuits-Buck/boost/switched capacitor converter, Applications

8. Security aspects of cyber physical sensor system: System concepts and applications, Various attacks on sensor systems and their remedies.

9. Case studies and Applications: Automotives applications: Smart remote pressure and temperature sensor in vehicle tires, Integrated Hall Sensors, Accelerometers, Gyroscopes; Biomedical:

Wearable/implantable Integrated Biomedical Sensors; Smart Home for Elder-People based on Wireless Sensors; Tutorials and assignments on design of signal conditioning circuit, interfacing circuits, and complete embedded system for various application.

AT600XX : Embedded Communication Networks (L-T-P: -3-0-0, CRD-3)

1. Introduction: Key Concepts, Event vs. State Based Communication, Finding the Best Real-Time Protocol

2. Communication Protocols for Embedded Systems: Inter System Protocol and Intra System Protocol; -Inter system protocol: USB Communication protocols, UART Com-munication protocols, USART Communication protocols; -Intra System Communication Protocols: I2C Protocol, SPI Protocol, CAN Protocol, CAN FD; Flexray, JTAG and Boundary Scan.
3. Advanced Topics: Industrial control network: Modbus, Smart Grid Communication Protocol Standards, Time Sensitive Networking, Remote Upgrade of Firmware, Automotive Ethernet and Time triggerred ethernet, Communication standards for IIoT.
4. Dependable I/O Systems: Redundancy, Dependable Individual Sensors and Actuators, Fieldbus, Intelligent I/O
5. Error Detection and Correction: Key Concepts, Shannon’s Theorem, Liner Block Codes, CRC Codes, Convolutional Codes, Data Error Detection and Recovery, Control Flow Error Detection, Detecting and correcting I/O and memory errors.

6. Uncertainty in I/O: Robust Control Theory, Effects of Uncertainty

7. Basics of Fault Tolerance Computing: Faults and their manifestation, System Fault Response stages, Reliability and Availability Techniques in Embedded System, Fault Injection , Basics of hardware fault tolerance and software fault tolerance.

8. Fault Tolerance Analysis of Safety-Critical Embedded Systems : Fault tolerant net-work, Software Defect Masquerade Faults in Distributed Embedded Systems, Critical Message Integrity Over a Shared Network, Fault Tolerance Tradeoffs in Moving from Decentralized to Centralized Embedded Systems.

CS61063: Computational Foundations of Cyber Physical Systems (L-T-P: -3-1-0, CRD-4)

1. What are Cyber-Physical Systems?
i. Cyber-Physical Systems (CPS) in the real world ii. What are the special design considerations for CPS? iii. Basic principles of design and validation of CPS

2. Principles of Automated Control Design (basic control theory)
i. ODEs, Lipschitz continuity: existence of solutions, equilibria, Stability criteria ii. Eigenvalues, pole placement, introduction to PID control iii. Stability Analysis: Lyapunov Functions (CLFs, MLFs), stability under slow switching iv. Tutorial: Control Design using Simulink

3. Engineering Challenges in Implementing a CPS

i. From continuous control laws to software based control systems [1 hour] ii. Architectural Platforms for implementing CPS [6 hours] A. ECU Architectures and Real Time Operating Systems B. Network (e.g. WirelessHart) and Bus Protocols (e.g. Flexray) C. Sense and Actuation (fault tolerant algorithms for sense and actuation) iii. Principles of CPS Implementation [6 hours] A. From features to software components B. Mapping software components to ECUs: Real Time Scheduling strategies 1 C. Performance Analysis - effect of scheduling, bus latency, sense and actuation faults on control performance D. Methods for Robust CPS implementation iv. Tutorial: Control, Bus and Network Scheduling using Truetime

4. Safety and Security Assurance of Cyber-Physical Systems
i. Advanced Automata based modeling and analysis: [4] A. Basic introduction and examples B. Timed and Hybrid Automata C. Definition of trajectories, zenoness D. Formal Analysis: Flowpipe construction, reachability analysis ii. Analysis of CPS Software: [4] A. Weakest Pre-conditions, B. Bounded Model checking iii. Tutorials [4] A. Control Verification using Matlab Toolbox S-Taliro B. Hybris Automata Modeling : Flowpipe construction using Flowstar, SpaceX and Phaver tools C. CPS SW Verification: Frama-C, CBMC iv. Secure Deployment of CPS [6] A. Attack models B. Secure Task mapping and Partitioning C. State estimation for attack detection

5. CPS Case studies and Tutorials
i. Automotive and Avionics : SW controllers for ABS, ACC, Lane Departure Warning, Suspension Control etc, Flight (pitch, yaw, roll) Control Systems ii. Heathcare : Artificial Pancreas iii. Mass Transportation : European Train Control Systems (ETCS)

<u>Component III. Project</u>

<u>For this project, one guide should be from the parent department of the student and other can be from ATDC.</u>

<u>Possible area project/topic:</u>

1) Embedded control for electrical and electronic devices
2) Developing plant models and controller logic for automotive systems
3) Evaluating performance of a developed algorithm in an actual real time environment with various constraints, resource management and performance metrics
4) Developing xEV diagnostic algorithms for onboard application
5) Embedded Sensing System
6) Energy harvesting applications
7) Embedded applications in biomedical
8) Secure CPS framework design
9) Secure analytics on IoT sensor data
10) Encrypted computation on IoT sensor data