# ECE497
# Evolutionary Robotics

## Course summary

The course will explore the automated design of autonomous robots, integrating topics in Cognitive Science, AI, and Robotics. Designing machines with the adaptivity, robustness, and flexibility of living organisms is a complex problem. Nowhere is this more evident than in robotics. Instead of hand-designing their brains and bodies, we will use AI techniques to automate the exploration of the problem space. Although we will be using robots as our test bed, automated design can be applied to any complex problem. The course will cover topics such as the design of robot morphologies, neural controllers, evolutionary computation, autonomous embodied agents, physical simulations, and computer-designed organisms. Students will complete programming assignments which will accumulate to form the backbone of a final project, providing hands-on experience with the topics covered.

## Course description

The goal of this new elective is to explore the space at the intersection between AI, Cognitive Science, and Autonomous Robotics. This course will survey current developments in evolutionary and bio-inspired approaches to autonomous adaptive robotics. The goal of this growing field is to develop methods which permit the design of robots capable of developing their skills autonomously through an evolutionary and/or learning process. It focuses on approaches requiring minimal human intervention in which the behavior displayed by the robots and the control rules producing such behavior are discovered by an adaptive process automatically based on a reward or fitness function which rates how well the robot is doing. In order to accomplish this, we will study behavior and cognition from the perspective of how brains interact with their bodies and their environment using simulated artificial organisms that can learn and evolve over time.

The course will provide hands-on opportunities for the students to create embodied agents in simulation, controlled by neural networks, capable of developing the behavioral skills required to perform a task through learning methods, with a strong focus on biologically inspired ideas.

We will introduce autonomous robots in simulation, feedforward neural network controllers as well as more complex dynamical and recurrent ones, evolutionary algorithms and other learning and optimization techniques, and a variety of biological and cognitive tasks. We will use concrete experiments to illustrate the fundamental aspects of embodied intelligence. We will provide theoretical and practical knowledge, including tutorials and exercises, and provide an integrated review of recent research in this area carried within partially separated research communities.

# Audience

The course is targeted toward students in any field of engineering who are interested AI, bio-inspired AI, Cognitive Science, and Autonomous Robotics, and who have a strong interest in science, discovery, and innovation.

# Minors

This course has been approved as an elective in the Robotics minor and in the Cognitive Science minor. Work is underway to make this be an approved elective in the AI minor.

# Prerequisites

Programming will be important in this course; therefore, CSSE220 will be required. Other than that, there is no pre-requisite on any knowledge regarding Cognitive Science, Robotics or AI, we will provide all the knowledge necessary in the classroom. If you have any questions, please get in touch with Prof. Izquierdo.

# Learning objectives (draft)

- Ability to design and simulate robot controllers.
- Proficiency in using robot simulation tools to test and evaluate robot performance.
- Understanding of the limitation and challenges of robot simulation.
- Ability to evaluate and compare the performance of different robot designs and control strategies using simulation.
- Familiarity with different evolutionary algorithms and their strengths and weaknesses.

In addition to those main hands-on learning objectives, we also have broader conceptual objectives:

- To study behavior, learning, memory, decision-making, perception, attention, individual and group behavior, connectionism, and embodied cognition
- To learn to employ optimization techniques to explore the space of possibilities.
- To explore examples of how nature solves problems.
- To discuss the possibility to let systems and machines learn, evolve, develop for themselves.
- To compare and contrast living machines with human-made counterparts (e.g., brains).
- To discuss robustness and flexibility across human-made designs and nature's designs.
- To introduce topics in the science of complexity (i.e., emergence, self-organization).

Upon successful completion of the course, students should be able to:

- Explain and discuss ideas and methods in the field of evolutionary and adaptive robotics, including: Embodiment and situatedness, Evolutionary algorithms, Neurorobotics, Embodied AI, Feedforward artificial neural networks, Dynamic and recurrent neural networks, Developmental robotics, Lifetime learning, Neural plasticity, Biomechanics, Legged locomotion, Spatial orientation behaviors, Minimally cognitive behaviors, Cognitive robotics,
- Carry out a scientific experiment, including: form hypotheses, design, and conduct experiments, collect data, analyze results, and report findings.

# Overall plan

The quarter will be divided into two parts. In the first part, we will cover the relevant aspects that will allow us to carry out the simplest possible initial project. In the second part, we will circle back around to explore more advanced topics, leading to a second and final project.

**Part 1: Fundamentals** (weeks 1-5)

We will fist cover the fundamentals of adaptive robotics across its four key dimensions: bodies, neural controllers, learning mechanisms, and tasks. For bodies, we will consider simple 2D Braitenberg-like vehicles. For neural controllers, we will consider traditional multi-layered feedforward neural networks. For learning mechanisms, we will consider both gradient descent learning and evolutionary algorithms. For tasks, we will consider spatial orientation behaviors. There will be a programming assignment for each of the first three weeks, and then a midterm project due in week 5.

**Part 2: Advanced topics** (weeks 6-10)

Once students get to experiment with these four dimensions, we will dive into more advanced topics for each. For bodies, we will consider physical simulators and physical robots. For neural controllers, we will consider dynamical and recurrent neural systems. For learning mechanisms, we will consider combining evolutionary and lifetime learning, as well as development. For tasks, we will consider minimally cognitive behaviors as well as more complex forms of legged locomotion.

There will be a programming assignment in weeks 6 and 7, and then a larger final project due in week 10. The last few weeks of the course will be reserved for discussing open areas of research in the field of bio-inspired evolutionary and adaptive robotics. Students will be asked to present the ideas in papers from the last five years in the field and to propose alternative studies. The students will also be given time to work on their final programming project.

# Reading resources

Throughout the quarter, we will provide readings online as PDFs from books, papers, and online sources, including:

1. Braitenberg. Vehicles: Experiments in Synthetic Psychology (1986).
2. Nolfi and Floreano. Evolutionary Robotics: The Biology, Intelligence, and Technology of Self-Organizing Machines (2000, 2004).
3. Floreano and Mattiussi. Bio-Inspired Artificial Intelligence: Theories, Methods, and Technologies (2008, 2023).
4. Vargas et al. The Horizons of Evolutionary Robotics (2014).
5. Nolfi. Behavioral and Cognitive Robotics (2021).
6. Hwu and Krichmar. Neurorobotics: Connecting the Brain, Body, and Environment (2022).
7. Cangelosi and Asada. Cognitive Robotics (2022).
8. Billard et al., Learning for Adaptive and Reactive Robot Control: A Dynamical Systems Approach (2022).

## Other (tentative)

**Grading scheme**: The late policy for this class is as follows: material one day late, 25% deduction; two days late, 50% deduction; three days late, 100% reduction.

**Eight programming assignments** (45% of the grade). Over the span of the first six weeks, each student will gradually build a software system that allows them to conduct an evolutionary robotics experiment. Note: because the software will form a final, integrated system, if you fail to hand in one assignment, you must hand it in along with the new assignment the following week.

**Readings** (20%)**.** There will be at least one 10-minute multiple-choice quiz given out every week covering the topics discussed in lectures and readings.

**Reading materials**. All books suggested are optional; PDFs will be provided of all readings.

**Final project** (30%)**.** Over the final weeks of the quarter, each student will use their software to perform an evolutionary robotics experiment. Several weekly deliverables will be submitted, a written report describing the experiment will be handed in at the end of the quarter, and an oral presentation will be given during the exam period.

**Participation** (5%). Class participation counts towards your final grade. Students are allowed to miss up to and including three classes without being required to provide justification. Missed classes beyond that must be cleared with the instructor. Participation will be tracked with attendance sheets in class.

**No laptops or phones may be used during class** to provide a distraction free classroom.