Physical AI & Humanoid Robotics — Textbook Outline

Introduction

* **Focus:** AI Systems in the Physical World — Embodied Intelligence.
* **Goal:** Bridge the gap between digital intelligence and physical robotics. Students apply AI knowledge to control humanoid robots in simulation and real-world environments.
* **Why It Matters:** Humanoid robots share human form, making them ideal for tasks in human environments. Embodied intelligence moves AI from digital-only to physical-world applications.

Quarter Overview

* **Theme:** Physical AI — AI systems that function in reality and understand physical laws.
* **Skills Learned:** Design, simulate, and deploy humanoid robots capable of natural human interactions.
* **Tools:** ROS 2, Gazebo, NVIDIA Isaac Sim, Unity, GPT models.

Module 1: The Robotic Nervous System (ROS 2)

Focus: Middleware for robot control.
Key Concepts:

* ROS 2 architecture: Nodes, Topics, Services.
* Python integration via `rclpy`.
* URDF (Unified Robot Description Format) for humanoids.
* ROS 2 package development and launch file management.

Module 2: The Digital Twin (Gazebo & Unity)

Focus: Physics simulation and environment modeling.
Key Concepts:

* Simulate physics, gravity, and collisions in Gazebo.
* High-fidelity rendering and human-robot interaction in Unity.
* Sensors: LiDAR, Depth Cameras, IMUs.
* Build digital twins of humanoid robots for testing and experimentation.

Module 3: The AI-Robot Brain (NVIDIA Isaac)

Focus: Advanced perception and training.
Key Concepts:

* NVIDIA Isaac Sim for photorealistic simulations and synthetic data generation.
* Isaac ROS for hardware-accelerated VSLAM and navigation.
* Nav2 for bipedal path planning.
* Reinforcement learning for robotic control.
* Sim-to-Real transfer techniques.

Module 4: Vision-Language-Action (VLA)

Focus: Converging LLMs and Robotics.
Key Concepts:

* Voice-to-Action: OpenAI Whisper integration.
* Cognitive Planning: Translate natural language commands to ROS 2 action sequences.
* Multi-modal interaction: voice, gesture, vision.
* Capstone: Autonomous humanoid performing complex tasks via natural language input.

Learning Outcomes

Students will be able to:

* Understand Physical AI and embodied intelligence.
* Master ROS 2 for robotic control.
* Simulate humanoid robots with Gazebo and Unity.
* Develop AI-powered humanoid robots using NVIDIA Isaac.
* Integrate GPT/LLM models for conversational robotics.
* Build humanoid robots capable of natural interactions.

Weekly Breakdown

Weeks	Topics

| 1–2 | Introduction to Physical AI; sensor systems (LiDAR, cameras, IMUs, force sensors).
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| 3–5 | ROS 2 Fundamentals: Nodes, topics, services, actions, Python packages, launch files.
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6–7	Robot Simulation with Gazebo & Unity: URDF/SDF, physics and sensor simulation, visualization.
8–10	NVIDIA Isaac Platform: Isaac Sim, AI perception pipelines, reinforcement learning, Sim-to-Real.
11–12	Humanoid Robot Development: Kinematics, dynamics, locomotion, balance, manipulation.
13	Conversational Robotics: GPT integration, speech recognition, multimodal interaction.

Capstone Project

Goal: Autonomous humanoid robot
Tasks:

* Receive voice commands.
* Plan and navigate paths.
* Identify objects using computer vision.
* Manipulate objects based on tasks.
* Demonstrate human-like interactions.

Hardware Requirements

1. Digital Twin Workstation

* GPU: NVIDIA RTX 4070 Ti+ (ideally 3090/4090 for smoother Sim-to-Real)
* CPU: Intel i7 13th Gen+ or AMD Ryzen 9
* RAM: 64 GB DDR5
* OS: Ubuntu 22.04 LTS

2. Physical AI Edge Kit

* Brain: NVIDIA Jetson Orin Nano/NX
* Eyes: Intel RealSense D435i/D455
* Balance: USB IMU (BNO055)
* Voice: USB Microphone/Speaker (ReSpeaker)

3. Robot Lab Options

Option A: Proxy (Budget) — Quadruped or robotic arm (Unitree Go2 Edu)
Option B: Mini Humanoid — Small table-top humanoids (Hiwonder TonyPi Pro, Unitree G1, Robotis OP3)
Option C: Premium Lab — Full-scale humanoids with ROS 2 control (Unitree G1)

4. Cloud Alternative

* AWS RoboMaker or NVIDIA Omniverse Cloud instances for simulation.
* Edge kits still required for deployment.

Key Concepts & Principles

* **Embodied Intelligence:** AI coupled with physical body to interact with real-world environments.
* **ROS 2:** Middleware for robot control; modular architecture for distributed control.
* **Digital Twin:** Simulation of robot and environment for safe experimentation.
* **VLA (Vision-Language-Action):** Integration of LLMs with robotics for task execution.
* **Sim-to-Real Transfer:** Train models in simulation before deploying to real robots.

Assessments

* ROS 2 package development
* Gazebo simulation implementation
* Isaac-based perception pipelines
* Capstone project: Autonomous humanoid robot

Suggested Textbook Structure

1. Introduction to Physical AI
2. ROS 2 and Robotic Nervous System
3. Digital Twin Simulation with Gazebo & Unity
4. AI-Robot Brain with NVIDIA Isaac
5. Vision-Language-Action Integration
6. Capstone Project: Autonomous Humanoid
7. Appendices: Hardware setup, cloud resources, sensor reference, ROS 2 guides