Mini Pi Plus: A Compact Modular Humanoid Platform for Onboard Whole-Body Learning and Deployment

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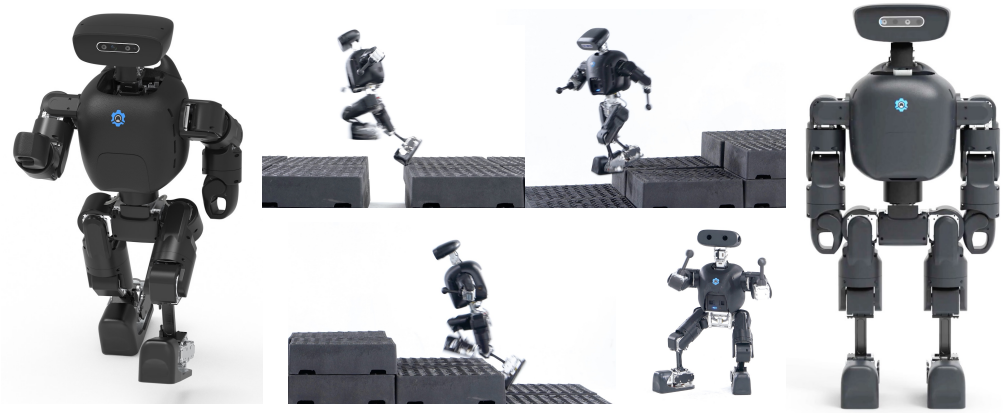

Figure 1: Mini Pi Plus during representative real-robot deployments. The behaviors exercise the integrated hardware, middleware, simulation, and onboard policy-deployment workflow.

Abstract: Humanoid research remains constrained by the cost, size, and integration burden of full-body robot platforms, while many research systems remain difficult to reproduce beyond the originating laboratory. We present Mini Pi Plus, a standardized 27-DoF humanoid research platform standing 75 cm tall and weighing 13.84 kg. The platform combines modular hardware, onboard computation, ROS 2 middleware, simulation assets, and policy deployment into a unified system for learning-based whole-body control. Mini Pi Plus extends the 12-DoF Mini Pi biped while reusing its lower-body hardware, actuator interfaces, and low-level software stack. This paper focuses on the platform operating point rather than a new control algorithm: we document the mechanical, electrical, communication, middleware, simulation, and deployment interfaces that make the compact full-body configuration usable for learning-based experiments. Representative onboard deployments spanning lower-body locomotion with independent upper-body commands, perceptive terrain traversal, and whole-body roll vaulting illustrate how the shared workflow connects simulation assets, ONNX policy export, ROS 2 runtime, middleware, and branch-isolated motor execution on hardware.

Keywords: Humanoid Robot; Modular Robotics; Learning Infrastructure; Sim-to-Real

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1 Introduction

Humanoid robots have rapidly advanced in locomotion, perception, and whole-body control, yet existing research platforms occupy widely separated points in the design space. Full-size humanoids provide strong dynamic capability, but their cost, mass, space requirements, and maintenance burden can limit frequent experimentation in ordinary laboratories. Smaller platforms are easier to handle and safer to operate, but many trade away full-body actuation, dynamic capability, onboard perception and computation, or an integrated path from simulation to real-robot deployment. This leaves an underrepresented platform regime: a compact humanoid that retains a complete body, sufficient onboard resources, and the infrastructure required for modern learning-based control.

Realizing such a platform is not simply a matter of scaling down an existing robot. Actuation, structural mass, power distribution, thermal capacity, communication bandwidth, sensing, onboard computation, robot descriptions, simulation models, and deployment interfaces impose coupled constraints. A compact robot may be mechanically manageable while still requiring substantial low-level integration before a learning or control method can be evaluated on hardware. These layers must therefore be designed as a coherent system.

We present Mini Pi Plus, a compact 27-DoF humanoid research platform standing $75\,\mathrm{cm}$ tall and weighing $13.84\,\mathrm{kg}$. The default configuration comprises 12 leg DoFs, 8 arm DoFs, a one-DoF waist, a two-DoF head, and four gripper DoFs. It integrates modular joint actuators, onboard computation and depth perception, branch-isolated CAN FD communication, power management, ROS 2 middleware, unified robot descriptions and simulation assets, and ONNX-based policy execution. The described hardware and software stack are available beyond the originating development team, making the configuration reproducible by external users.

Mini Pi Plus extends the earlier 12-DoF Mini Pi biped with waist, arm, head, and gripper modules while reusing its lower-body hardware, actuator protocol, communication conventions, and low-level software stack. This reuse reflects a cross-layer modular design in which mechanical, electrical, communication, description, and deployment boundaries are aligned across supported configurations. The resulting workflow connects robot description and simulation to policy training, model export, onboard inference, middleware, and real-robot execution.

We present Mini Pi Plus through platform characterization and representative whole-body workloads, including locomotion with independently controlled upper-body motion, perceptive terrain traversal, and whole-body roll vaulting. These behaviors are used as deployment examples for the integrated platform rather than as claims of new locomotion or reinforcement-learning algorithms. The paper asks a platform-level question: whether a compact full-body humanoid can package the mechanical, electrical, communication, perception, and software interfaces needed for modern learning-control deployment. Our contributions are:

- **A compact 27-DoF humanoid research platform** that combines a complete humanoid morphology, onboard perception and computation, and a $75\,\mathrm{cm}$, $13.84\,\mathrm{kg}$ form factor suitable for frequent laboratory use.
- **An integrated and modular hardware–software architecture** spanning joint actuation, branch-isolated communication, power and computation, ROS 2 middleware, robot descriptions, simulation assets, actuator ownership, and ONNX-based policy execution.
- **A representative whole-body deployment workflow** connecting simulation assets, ONNX policy export, ROS 2 runtime, middleware, and branch-isolated motor execution for locomotion, perceptive terrain traversal, and roll-vault behaviors.

2 Related Work

Humanoid platforms span a broad range of scales and design objectives. Full-size and near-human-scale systems such as Atlas, Digit, H1, GR1, and Optimus demonstrate dynamic locomotion

Table 1: Focused comparison with compact and mid-scale commercial humanoid platforms. Mini Pi Plus reports the paper configuration; competitor specifications are vendor-published. Costs use official list prices when available, otherwise public distributor or launch prices.

Platform	Height	Mass	Active DoF	Cost
Mini Pi Plus	75 cm	13.84 kg	27	$5,500
Unitree R1	123 cm	29 kg	26	$5,900
Booster K1	95 cm	19.5 kg	22	$5,999+
Unitree G1	132 cm	35 kg	23	$13,500
Booster T1	118 cm	30 kg	23	$29,800
EngineAI PM01	140 cm	42 kg	23	RMB 88,000

and whole-body capabilities, while mid-scale and compact systems such as Berkeley Humanoid, ARTEMIS, Unitree R1/G1, Booster K1/T1, and EngineAI PM01 reduce some of the cost and infrastructure requirements [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12]. Compact platforms including NAO, ROBOTIS OP3, BRUCE, Zeroth, and ToddlerBot further improve portability, operational safety, and ease of repeated experimentation [13, 14, 15, 16, 17]. Table 1 focuses on the platforms most directly comparable to Mini Pi Plus using vendor-published specifications and public price pages [8, 9, 10, 11, 18, 12, 19]. For vendors offering multiple variants, the table reports the base or standard configuration unless otherwise stated.

Platform scale introduces important trade-offs. Larger humanoids are better matched to human-scale environments and objects, but typically impose greater cost, space, maintenance, and safety requirements. Compact humanoids are easier to transport, operate, and repair, but limited packaging volume can constrain the number of active joints, actuator capability, onboard computation, sensing, battery capacity, and thermal performance. The number of DoFs alone is therefore not sufficient to characterize a research platform; full-body morphology must be considered together with actuation, perception, computation, and the intended experimental workload.

A humanoid research platform also requires more than a mechanical body. Learning-based control depends on robot descriptions, simulation assets, communication interfaces, state estimation, middleware, policy export, onboard inference, and reliable motor execution. ROS 2 provides a common distributed software substrate, while simulators such as MuJoCo and Project Instinct-style environments support model-based control and large-scale robot-learning workflows [20, 21]. Recent learning-based methods have demonstrated agile locomotion, perceptive terrain traversal, imitation, and whole-body skills [22, 23, 24, 25], but deploying these methods on a new robot still requires a consistent path from simulation models and policy outputs to the physical actuator interfaces.

Mini Pi Plus targets this combined platform-design regime: a compact full-body humanoid that couples mechanical capability with onboard perception, computation, middleware, simulation assets, and policy deployment. Rather than introducing a new locomotion, parkour, or reinforcement-learning algorithm, this paper focuses on the co-design, interfaces, and deployment workflow of the platform that supports such methods.

Platform thesis. The central claim of a platform paper is not that a robot can perform a visually compelling demonstration once. The claim is that the platform exposes a useful experimental operating point and gives other researchers enough mechanical, electrical, communication, and software detail to reproduce that operating point. We therefore present Mini Pi Plus along three axes: morphology and integration, cross-layer modularity, and deployment workflow. The first axis asks whether the robot fits the compact full-body regime while retaining actuation, perception, compute, power, and communication resources. The second asks whether mechanical modules, actuator ownership, robot descriptions, and branch assignments are organized so that supported configurations can share infrastructure. The third asks whether modern learning-control policies can be carried from simulation assets and exported models to onboard execution through a consistent runtime path.

Figure 2: Mini Pi Plus system overview. Compact hardware, cross-layer modular interfaces, and a continuous learning-to-deployment workflow connect the robot body to real-robot execution.

Table 2: Main Mini Pi Plus platform characteristics used in this paper.

Quantity	Value
Default configuration	Mini Pi Plus with Orin compute, gripper end effectors, and waist module
Height / mass	$75\,\mathrm{cm}$ / $13.84\,\mathrm{kg}$
DoF composition	12 legs + 8 arms + 1 waist + 2 head + 4 gripper = 27
Actuator module mass	$7.185\,\mathrm{kg}$
Non-actuator mass	$6.655\,\mathrm{kg}$ for structure, electronics, battery, and other components
Actuation	Integrated joint modules with shared actuator command interface
Communication	Branch-isolated CAN FD network for limbs, waist, head, and expansion
Compute and sensing	Orin compute option with USB-connected depth sensing for perceptive tasks
Middleware and deployment	ROS 2 middleware, URDF, simulation assets, ONNX policy execution

3 Platform Design

Mini Pi Plus is the full-body member of the Mini Pi platform family. Unless otherwise stated, this paper describes the default 27-DoF configuration with Orin compute, gripper end effectors, and a one-DoF waist. The platform inherits the 12-DoF lower-body hardware and low-level actuation stack from Mini Pi, then adds waist, upper-body, head, and end-effector modules for full-body experiments. The same platform family also supports 22-DoF and 23-DoF ball-hand variants and a 26-DoF gripper variant without the waist module; these alternatives reuse the same actuator interface, communication organization, robot-description workflow, and deployment stack.

3.1 Compact Full-Body Hardware

The default robot stands $75\,\mathrm{cm}$ tall and weighs $13.84\,\mathrm{kg}$. Its 27 DoFs consist of 12 leg DoFs, 8 arm DoFs, one waist DoF, two head DoFs, and four gripper DoFs. This configuration keeps the robot below $1\,\mathrm{m}$ and $15\,\mathrm{kg}$ while retaining full-body actuation, onboard compute, depth sensing, battery power, and the communication interfaces needed for learning-control experiments.

Mini Pi Plus uses integrated joint modules that combine the motor, reduction stage, encoder, driver board, and heat-dissipation structure. The actuator family includes HTDW-5036 modules for load-bearing leg joints, HTDP-5031 for the waist, HTDW-4438 for the arms, and HTDW-3536 for the head or smaller upper-body joints. Early height–mass and torque estimates are used only for com-

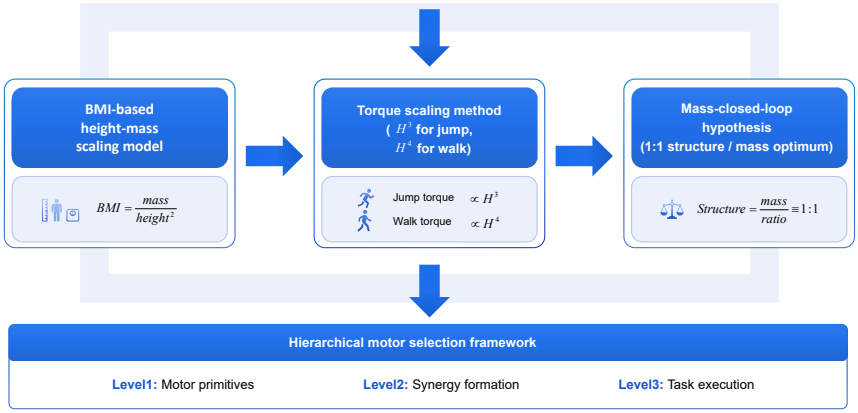

Figure 3: Practical platform design loop. Coarse height–mass and torque estimates narrow the design space, while final choices are made through component selection, CAD/BOM accounting, actuator tests, thermal checks, simulation, and prototype iteration.

ponent screening; final actuator selection is based on module ratings, CAD/BOM mass accounting, prototype measurements, current limits, and thermal behavior during integrated operation.

3.2 Cross-Layer Modularity

The platform treats modularity as a cross-layer property rather than a mechanical feature alone. The Mini Pi lower body is reused as the 12-DoF base of Mini Pi Plus. Added waist, arm, head, and end-effector modules use consistent actuator protocols, connector conventions, robot-description boundaries, and deployment settings, so embodiment changes are localized to mechanical modules, branch assignments, robot descriptions, and task configuration files.

The default Mini Pi Plus configuration uses gripper end effectors and the waist module. Ball-hand and no-waist variants are handled as configuration choices above the shared actuator and middleware layers. This organization is intended to reduce re-integration effort when changing between the 22–27-DoF Mini Pi Plus variants, while avoiding any claim that control policies transfer without robot-specific calibration, observation/action mapping, or task adaptation.

3.3 Communication, Power, and Compute

The main control box integrates seven CAN FD interfaces. In the default waist-equipped configuration, the branch allocation is left arm, right arm, left leg, right leg, waist, head, and expansion. This avoids placing all actuators on a single shared bus and makes limb- or module-level communication boundaries explicit. Each channel is specified to support up to 10 motors within $1\,\mathrm{ms}$, corresponding to a stated capacity of 70 motors at $1\,\mathrm{kHz}$ or 140 motors at $500\,\mathrm{Hz}$.

Power is also organized by branch. The robot uses a 6S battery at $97.2\,\mathrm{Wh}$ and a power-management board with branch current, voltage, and temperature monitoring. The power-management unit divides battery input into seven monitored branches and provides overcurrent, undervoltage, temperature, balancing, coulomb-counting, and CAN-reporting functions. The default robot uses the Orin compute option for ONNX inference through `instinct_onboard`; RK3588 remains a product-

Figure 4: Modular expansion from the Mini Pi lower-body base to Mini Pi Plus. The added waist, arms, head, and end effectors reuse actuator, communication, description, and deployment boundaries.

family compute option. Depth cameras, including ZED Mini and Intel RealSense D435i configurations, are supported through USB device binding and task-specific launch files.

4 Learning-to-Deployment Stack

4.1 Middleware and Actuator Interface

The software stack is built around ROS 2 and a custom middleware layer, `hightorque_midware`, that separates high-level modules from motor drivers. Upstream nodes such as planners, kinematics solvers, policy runners, and whole-body controllers publish through standardized interfaces instead of commanding the driver layer directly. The middleware publishes joint positions, velocities, and torques, and it accepts per-joint target position, target velocity, feed-forward torque, K_p, and K_d commands.

The motor-side driver evaluates an impedance-style command law,

$$\tau_{\mathrm{cmd}} = \tau_{\mathrm{ff}} + K_p(p_{\mathrm{des}} - p_{\mathrm{act}}) + K_d(v_{\mathrm{des}} - v_{\mathrm{act}}).$$

The control stack uses a $1\,\mathrm{kHz}$ middleware-to-driver update path and a $30\,\mathrm{kHz}$ current-loop command layer. Actuator ownership is handled through UUID sessions: a controller requests a lease for a set of motor IDs, and the middleware executes only commands associated with the active session. Maintenance commands that alter coordinate references require global mutual exclusion, and session monitoring returns actuators to a controlled fallback state when the active controller is lost. This ownership model lets locomotion, debugging, calibration, and behavior nodes share the same ROS 2-facing interface without allowing conflicting motor commands.

4.2 Simulation, Export, and Onboard Execution

The platform maintains robot descriptions and deployment interfaces across simulation and hardware. Robot-specific changes are concentrated in robot descriptions, launch files, sensor bindings,

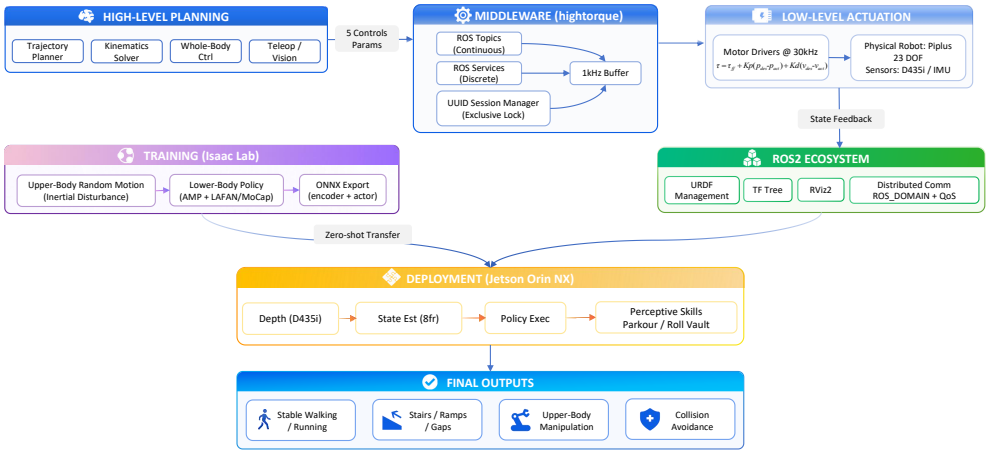

Figure 5: ROS 2 middleware and actuator ownership architecture. The middleware exposes joint-state and command interfaces, arbitrates actuator ownership, and forwards accepted commands to the motor-driver layer.

task configurations, observation/action definitions, and runtime settings. The hardware deployment path is:

$$\text{robot description} \rightarrow \text{simulation asset} \rightarrow \text{policy training} \rightarrow \text{ONNX export}$$
$$\rightarrow \text{ROS 2 runtime} \rightarrow \text{middleware} \rightarrow \text{motor execution} \rightarrow \text{real robot deployment}.$$

Policies trained in Project Instinct-style environments are exported to ONNX and deployed through `instinct_onboard`. The same deployment pattern is used for lower-body locomotion, perceptive terrain traversal, and roll vaulting: task-specific changes are concentrated in robot descriptions, observation/action mappings, runtime configuration, and perception inputs, while the ROS 2, middleware, CAN FD, and motor-command layers remain shared. The paper uses these learning-control tasks as representative deployment examples rather than as claims of new locomotion, parkour, or roll-vault algorithms.

5 Representative Deployments

5.1 Platform Characterization

Platform characterization combines the measured physical properties in Table 2 with the architecture and deployment workflow described above. Mini Pi Plus remains in a manageable size and mass range while carrying a 27-DoF humanoid body, onboard power, branch-isolated communication, compute, and depth sensing. The purpose of this characterization is to locate the robot in the compact full-body design space and to separate the platform contribution from task-level algorithmic comparisons against other humanoids.

5.2 Deployment Protocol

The real-robot deployments use the default 27-DoF Mini Pi Plus configuration from Table 2. Policies run onboard through the same ONNX deployment path, actuator commands pass through `hightorque_midware`, and motor traffic uses the branch-isolated CAN FD network. Task-specific differences are kept at the level of robot descriptions, observation/action mappings, terrain or

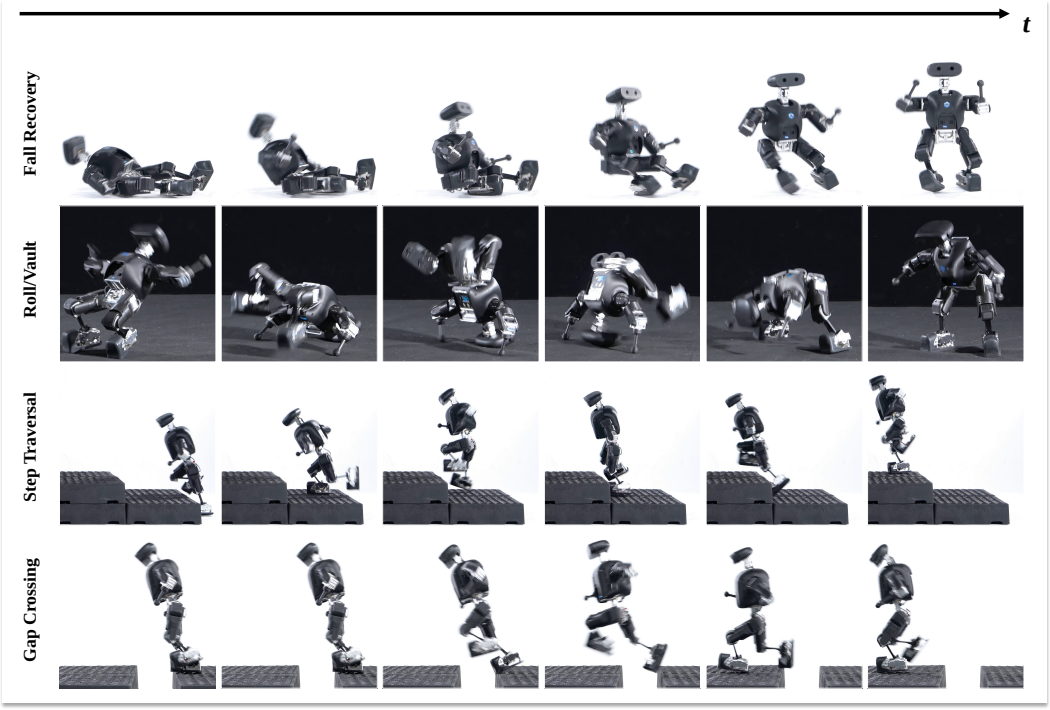

Figure 6: Representative real-robot task scenes using the Mini Pi Plus workflow: lower-body locomotion with independent upper-body control, perceptive terrain traversal training by project instinct[26], and whole-body roll vaulting.

motion-reference inputs, perception settings, and runtime configuration. This organization is intended to make each behavior a test of the shared platform workflow rather than a separate hand-wired demonstration stack.

Figure6 illustrates the representative behaviors. The tasks are intentionally heterogeneous: lower-body locomotion checks whether upper-body motion can be superimposed on a deployed walking policy, perceptive terrain traversal exercises the depth-to-policy-to-actuator path, and roll vaulting exercises full-body dynamic execution with upper-body, waist, head, and lower-body recovery coupled in one behavior.

The lower-body locomotion deployment controls the 12 lower-body joints while the upper body is commanded independently. During training, smooth randomized upper-body targets inject inertial disturbances, and at deployment the upper body can be commanded through a separate interface while the lower-body policy remains active. The perceptive terrain traversal and roll-vault demonstrations adapt Project Instinct-style perception and training infrastructure to Mini Pi Plus without changing the shared ROS 2, middleware, CAN FD, and ONNX deployment layers.

6 Conclusion

Mini Pi Plus provides a compact 27-DoF humanoid platform that couples full-body hardware with modular mechatronics and a continuous learning-to-deployment workflow. The contribution is the integration of a $75\,\mathrm{cm}$, $13.84\,\mathrm{kg}$ humanoid body with branch-isolated communication, onboard compute, ROS 2 middleware, simulation assets, ONNX deployment, and representative whole-body hardware deployments. The resulting platform offers a reproducible compact humanoid operating point for whole-body learning experiments while making the mechanical, communication, middleware, and deployment interfaces explicit for future algorithmic and empirical studies.

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