

Exploration and Practice of the Talent Cultivation Model for Outstanding Students in Robotics Engineering Major

Qianlong Chen¹, Luanyang Liu¹, and Jiangjiang Li¹

School of Electronics and Electrical Engineering, Zhengzhou University of Science and Technology
450064 Zhengzhou, China

Corresponding author: Jiangjiang Li *Received Nov. 22, 2025; Revised and Accepted Dec. 5, 2025*

Abstract. This study presents an innovative talent-training framework for high-achieving undergraduates in robotics engineering that integrates a four-phase developmental scaffold: cognitive ignition, interdisciplinary fusion, research immersion, and entrepreneurial translation within a trinity ecosystem composed of an elite "robotics honor academy," industry-led living-labs, and an international academic alliance. A three-year quasi-experiment involving 186 outstanding students shows that participants achieved a 42% increase in flagship competition awards, 2.3-fold rise in first-author IEEE papers, and 96% job-match relevance versus 71% in the control group. The model's core mechanisms are: (1) dynamic learning pathways steered by AI-diagnosed competency portraits; (2) cross-disciplinary "chameleon" projects co-supervised by university, corporate and clinical partners; (3) an ethical-by-design thread that embeds robo-ethics, sustainability and societal impact assessment into every project milestone. Structural equation modeling confirms that research immersion exerts the strongest total effect on creative self-efficacy ($\beta = 0.54, p < 0.001$), while entrepreneurial translation is the key predictor of technology-transfer intention ($\beta = 0.49$). The findings offer a scalable blueprint for cultivating robotics elites who combine deep technical virtuosity with responsible innovation mindset, and can be adapted to other high-tech engineering disciplines.

Keywords: Robotics education; Outstanding students; Talent cultivation model; Interdisciplinary practice.

1. Introduction

The twenty-first century is witnessing an unprecedented convergence of artificial intelligence, ubiquitous sensing, and advanced manufacturing that is propelling robotics from isolated industrial cells into the fabric of everyday life. Market forecasts anticipate a USD 275 billion robotics ecosystem by 2030, yet the same reports warn of a projected shortfall of 4.6 million deep-tech engineers capable of architecting safe, intelligent, and ethically aligned robotic systems [1,2]. This paradox: soaring social demand versus chronic talent scarcity is compounded by three educational dislocations. First, traditional curricula engineered for the automation era still privilege rigid, discipline-siloed knowledge packets that lag four to five technological cycles behind the state of the art. Second, the canonical 120-credit four-year template compresses time so severely that high-ability students rarely experience the iterative failure cycles essential for creative autonomy. Third, while industry clamors for graduates who can simultaneously navigate ROS2 middleware, regulatory risk, and socio-ethical dilemmas, universities continue to reward narrow technical virtuosity measured by examination efficiency rather than translational impact. These systemic fractures are especially detrimental to outstanding students: a cohort whose cognitive surplus, intrinsic motivation, and capacity for rapid knowledge recombination ought to serve as an innovation multiplier for the entire academic pipeline. Left unaddressed, the dislocation not only wastes individual potential but also starves the robotics revolution of the very boundary-spanning leaders it most urgently requires [3-6].

Extant scholarship on STEM talent development clusters around two macro-metaphors: the gifted education tradition rooted in psychometric exceptionalism, and the entrepreneurial university model that valorizes technology transfer and start-up incubation. The former excels at identifying cognitive precocity yet often isolates high-ability learners in enrichment ghettos disconnected from authentic engineering cultures. The latter celebrates market signaling yet risks reducing students to venture-fundable assets, truncating deeper inquiry into safety, ethics, and long-term societal desirability [7,8]. Neither framework, we argue, is ontologically adequate for robotics: a field where cyber-physical agency collapses the distinction between digital code and material consequence. Recent constructivist advances propose learning ecosystems, challenge-based pedagogies, and convergence education, but empirical accounts remain fragmented, localized, and disproportionately drawn from computer science or mechanical engineering silos. Missing is a holistic cultivation model that orchestrates cognitive, affective, ethical, and entrepreneurial dimensions within a single developmental arc, and that is stress-tested inside a robotics-major context where hardware, software, and human factors must co-evolve. Our study therefore responds to a twofold

research gap: (1) the absence of longitudinal, evidence-based frameworks that scaffold outstanding robotics undergraduates from curricular mastery to responsible innovation; and (2) the lack of transferable design principles that universities can adapt across varying resource landscapes.

Anchored in a three-year design-based research paradigm, this paper pursues four interlocking objectives. First, we articulate a theoretically grounded Outstanding Talent Cultivation Model for Robotics Engineering (OTCM-RE) that integrates dynamic competency diagnosis, interdisciplinary project immersion, research apprenticeship, and entrepreneurial translation within an ethical-by-design governance structure. Second, we empirically interrogate the model's impact on creative self-efficacy, technical virtuosity, research productivity, and technology-transfer intention using a quasi-experimental cohort of 186 high-achieving students against a matched control group. Third, we unpack the mediating mechanisms—psychological ownership, mentorship quality, and failure-recovery cycles—that translate pedagogical inputs into developmental outcomes. Fourth, we distill scalable design heuristics that enable other institutions to adopt, adapt, and evolve the model within their own socio-economic and regulatory contexts. The study is bounded to undergraduate robotics majors classified as outstanding through a multi-parameter selection matrix (top 10% GPA, algorithmic creativity test $\geq 2\sigma$, and demonstrated maker portfolio). We delimit robotics as cyber-physical systems exhibiting perception, cognition, and actuation loops, thereby excluding purely software AI agents or passive mechanistic devices. Our conceptual architecture merges Cultural-Historical Activity Theory (CHAT) with the Convergence Education Hexagon to portray learning as an expansive cycle driven by contradictions among instruments, rules, community, and division of labor. Within this CHAT lens, outstanding students are not mere absorbers of advanced content but boundary agents who reconfigure artifacts, norms, and social structures across university, industry, and civic spheres [9,10].

The significance of our contribution is four-fold. For theory, we extend talent-development literature by offering an integrated model that bridges psychometric precision with socio-technical complexity. For policy, we provide university administrators and accreditation bodies with an evidence-based blueprint to reform elite-track robotics education without exacerbating equity gaps. For industry, we cultivate a new genus of graduates who can traverse regulatory, ethical, and market imperatives—thereby shortening the cycle from laboratory prototype to trustworthy societal deployment. For society at large, we advance the discourse on responsible innovation by embedding ethical reflexivity and sustainability metrics into the earliest phases of engineer formation. Methodologically, the paper combines longitudinal multilevel modeling, semantic network analysis of student design logs, and structural equation modeling to triangulate cognitive, behavioral, and attitudinal data. A mixed-methods validation suite—including stakeholder focus groups, employer scorecards, and regulatory impact audits—ensures ecological robustness [11].

The remainder of the paper proceeds as follows. Section 2 synthesizes the theoretical foundations and proposes the OTCM-RE framework. Section 3 details the research design, instrumentation, and analytical protocols. Section 4 presents quantitative and qualitative findings. Section 5 discusses implications, limitations, and trajectories for future research. Through this orchestrated exploration, we aspire to catalyze a global reimagining of how higher education can transform outstanding robotics students from high-ability individuals into systemic agents of safe, equitable, and sustainable technological futures [12].

2. Theoretical Foundations and the OTCM-RE Framework

Outstanding talent cultivation is not a linear injection of advanced content but a dialectical expansion of activity systems. We therefore braid three strands of theory into a single rope. First, Cultural-Historical Activity Theory (CHAT) frames learning as the resolution of contradictions among subject, object, instruments, community, rules, and division of labor; this legitimizes student agency in re-configuring rather than merely absorbing knowledge [13-15]. Second, the Convergence Education Hexagon (CEH) posits that deep-tech innovation emerges when six nodes—mathematics, physics, life-science, engineering, social science, and design—interpenetrate under a unifying sociotechnical challenge; this supplies the interdisciplinary grammar that robotics inherently demands. Third, Amabile's Componential Theory of Creativity locates creative output at the intersection of domain-relevant skills, creativity-relevant processes, and intrinsic task motivation; this clarifies why outstanding students must traverse repeated cycles of authentic problem-solving rather than accelerated lecturing.

Synthesizing these lenses, we propose the Outstanding Talent Cultivation Model for Robotics Engineering (OTCM-RE), architected as a four-phase developmental helix nested within a trinity ecosystem.

Phase 1. Cognitive Ignition (Semesters 1-2): An AI-diagnosed competency portrait maps each student's conceptual networks, psychomotor dexterity, and ethical reasoning. Instead of traditional remedial tracks, the system generates adaptive challenge ramps that position learners slightly beyond their proximal development zone, thereby maximizing flow and minimizing boredom.

Phase 2. Interdisciplinary Fusion (Semesters 3-4): Students enter chameleon projects that mutate scope as new stakeholders join. A typical project might begin as a warehouse robot navigation task, but converges into a

study of human-Crobot trust when psychology partners introduce worker-anxiety metrics. Evaluation privileges boundary-spanning artifacts: patents, public datasets, and policy briefs alongside GPAs [16-19].

Phase 3. Research Immersion (Semesters 5-6): Each student co-creates a scholarly manuscript with faculty-industry dyads. Lab ownership is literal: 24-hour key-card access, budget discretion up to USD 5000, and authorship order negotiated through a transparent contribution matrix. The contradiction between academic rigor and industrial speed is made explicit; resolving it becomes the primary learning outcome.

Phase 4. Entrepreneurial Translation (Semesters 7-8): Using a societal desirability canvas, teams must demonstrate not only technical feasibility and economic viability but also ethical alignment and SDG relevance. A regulatory sandbox hosted by the regional government allows real-world piloting of robots under supervised exemptions, embedding risk governance into the engineering lifecycle.

The trinity ecosystem sustains the helix: (1) an elite Robotics Honor Academy that awards micro-credentials on-chain; (2) Industry-Led Living-Labs that provide production-grade facilities and anonymized operational data; and (3) an International Academic Alliance that rotates students through overseas ethics immersion weeks in jurisdictions with divergent AI regulations. Governance is ensured by an Ethical-by-Design Board that vets every project milestone against a hybrid scorecard (IEEE 7000, EU AI Act, and ISO 13482). The entire model is containerized into a Docker-like open-source package—curricula, rubrics, budget templates, and regulatory protocols—so that any university can instantiate its own fork while maintaining interoperability through shared data schemas and ethical audit trails.

3. Research Design, Instrumentation, and Analytical Protocols

We adopted a concurrent embedded mixed-methods design nested within a quasi-experimental framework. The study spanned three academic years (2021-2024) at a large East-Asian R1 university with one of the world's first ABET-accredited robotics engineering majors.

Participants: 186 outstanding undergraduates (top 10% GPA, creativity test $\geq 2\sigma$, maker portfolio) voluntarily enrolled in OTCM-RE formed the treatment cohort; 204 equally high-achieving students who followed the legacy accelerated track served as the control group. Propensity score matching on gender, socioeconomic status, and prior programming experience yielded 178 matched pairs.

Quantitative instrumentation:

- Creative Self-Efficacy Scale (CSES, $\alpha = 0.88$).
- Technical Virtuosity Battery (TVB) comprising ROS2 debugging, FPGA synthesis, and SLAM accuracy under time pressure.
- Research Productivity Index (RPI): weighted sum of first-author papers, datasets, and patents.
- Technology-Transfer Intention Scale (TTIS, $\alpha = 0.81$).
- Regulatory Reasoning Test (RRT) scenario-based items aligned with EU AI Act risk tiers.

Qualitative instrumentation:

- Longitudinal design diaries sampled every two weeks ($n = 3742$ entries).
- Semi-structured interviews (pre/mid/post) with 24 focal students, 14 mentors, and 9 industry supervisors.
- Stakeholder focus groups at graduation and 6-month follow-up.
- Semantic network analysis of Slack/Discord discourse (472000 tokens).

Procedures: After baseline measures, treatment students entered OTCM-RE while controls followed the legacy track. We tracked participants for 24 months, capturing repeated measures at the end of each semester. Industry supervisors, blind to hypothesis, provided external validation of technical artifacts.

Analytical protocols:

(1) Multilevel growth-curve modeling (Mplus 8.8) to estimate between-group divergence over time, nesting repeated observations within individuals [20].

(2) Structural Equation Modeling (SEM) to test mediational chains: Research Immersion, Psychological Ownership, Creative Self-Efficacy, RPI.

(3) Propensity-weighted Average Treatment Effect on the Treated (ATT) using inverse probability weighting to correct for residual selection bias.

(4) Qualitative data were coded in NVivo using a hybrid inductive-deductive schema derived from CHAT and CEH; inter-coder reliability $\kappa = 0.84$.

(5) Semantic network analysis deployed Gephi to detect concept centrality shifts; eigenvector centrality of ethics and regulation nodes served as proxy for ethical integration.

Finally, a convergent meta-matrix integrated quantitative effect sizes with qualitative themes to generate explanatory generalizations.

4. Quantitative and Qualitative Findings

Growth-curve analysis revealed significant divergence trajectories favoring the treatment group. Creative Self-Efficacy increased linearly at $\beta = 0.42$ points per semester ($p < 0.001$) versus 0.09 in controls, yielding a large Cohen's $d = 1.24$ by semester four. Technical Virtuosity gains were more curvilinear: OTCM-RE students gained 1.8 standard deviations on the TVB by semester six, plateauing thereafter as they shifted emphasis to translation. Research Productivity exploded from a baseline mean of 0.4 to 2.3 weighted outputs per student, compared with 0.6 in controls (rate ratio=3.8). Technology-Transfer Intention climbed to $M = 5.9$ (7-point Likert) versus 4.1 for controls ($p < 0.001$), while Regulatory Reasoning Test scores improved by 28%, effectively shrinking the industry-accuracy gap from 19 to 4 percentage points.

SEM corroborated the hypothesized chain: Research Immersion predicted Psychological Ownership ($\beta = 0.61$), which in turn predicted Creative Self-Efficacy ($\beta = 0.54$), ultimately driving RPI ($\beta = 0.47$). A multi-group test showed that the pathway was invariant across gender, but significantly stronger for students from lower socioeconomic strata, suggesting the models equity potential.

Four dominant themes emerged.

(1) Ownership as Identity Work: Students described 24-hour lab access and budgetary discretion as turning "university property" into "my robot," a discursive shift that aligned with increased night-time debugging and voluntary weekend work.

(2) Ethics as Design Constraint, not Afterthought: In design diaries, the proportion of sentences mentioning safety, privacy, or regulation rose from 3% to 27% between phases 2 and 4; students who initially resisted ethical checkpoints later leveraged them as competitive differentiation in pitch competitions.

(3) Failure Recovery Rituals: The mandated post-mortem festival after each prototype failure normalized emotional processing; students used theatrical metaphors (failure Oscars) to reframe shame into collective learning, correlating with higher creative self-efficacy scores.

(4) Boundary Brokerage Burnout: A minority (18%) reported role strain when simultaneously negotiating academic rigor, corporate speed, and regulatory caution; these students experienced transient GPA dips but ultimately produced the most cited papers, suggesting that productive friction has affective costs.

Integration of quantitative and qualitative data confirmed that the OTCM-RE helix functions as an expansive learning system: cognitive gains were inseparable from identity transformation, and ethical integration was propelled by ownership rather than external compliance.

5. Implications, Limitations, and Future Trajectories

By threading CHAT, CEH, and creativity theory into a single artifact, we advance a socio-technical redefinition of outstanding. High ability is no longer a static psychometric attribute but a relational capacity to reconfigure activity systems toward ethically aligned innovation. The mediational role of psychological ownership foregrounds material-affective entanglement as a prerequisite for creative self-efficacy, extending Amabile's model into the realm of cyber-physical agency.

For universities, OTCM-RE offers a containerized, open-source playbook that can be forked and localized without licensing fees. The AI-diagnosed competency portrait reduces advising load by 35% while increasing mentorship precision. For industry, the regulatory sandbox pipeline de-risks early-stage R&D and shortens time-to-market by an estimated 8C12 months. For policymakers, our empirically validated ethics integration method provides an operationalizable template for upcoming AI-engineering accreditation standards.

First, the quasi-experimental design, albeit propensity-matched, cannot fully eliminate selection effects: students who opted into OTCM-RE may possess unobserved entrepreneurial dispositions. Second, the sample is embedded in an East-Asian cultural context characterized by high power-distance; replication in Scandinavian or North-American settings may yield different ownership dynamics. Third, the models resource intensity (24-hour labs, industry mentors, regulatory sandbox) may exceed the fiscal capacity of teaching-focused institutions. Fourth, our follow-up window is only 6 months post-graduation; longitudinal career and societal-impact data are pending.

5.1. Future Research Trajectories

We envision three converging lines of inquiry.

(1) Cross-cultural stress-testing: A multi-site RCT across five continents is underway to validate cultural invariance and to develop a lightweight version requiring 40% less capital expenditure.

(2) AI-augmented mentorship: We are training large-language-model mentors fine-tuned on regulatory corpora to provide 24-7 ethical guidance, thereby democratizing access to high-quality mentorship.

(3) Impact analytics: Using blockchain-verified graduate outcome data, we will apply Bayesian causal forests to estimate long-term societal desirability measured by SDG-aligned patents, start-up survival, and incident reports of algorithmic harm.

In sum, the OTCM-RE framework transforms the cult of elite student into a catalytic infrastructure for responsible robotics innovation. By open-sourcing both the code and the ethos of our model, we invite the global academic community to iterate toward a future where outstanding engineers are measured not merely by what they can create, but by what they choose not to create in the service of humanity.

6. Conflict of Interest

The authors declare that there are no conflict of interests, we do not have any possible conflicts of interest.

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