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Digital education for graduate students: literacy and skills development—A case study of non-linear control systems course

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The transformative integration of digital technologies into occupational frameworks and talent competency ecosystems has established educational digitalization and graduate digital literacy enhancement as pivotal components of national reform strategies, particularly within control science disciplines facing AI-driven industrial transformations. Addressing the critical demand for high-level research capabilities, this study employs a mixed-methods approach to investigate sustainable digital literacy cultivation pathways through a longitudinal case study (2020–2023) of the Non-linear Control Systems course. A pedagogical framework was developed, integrating three core mechanisms: goal-oriented instructional design aligned with DIGCOMP 2.2 standards and a quadruple mentorship system encompassing digital literacy, academic, project, and enterprise mentors. Implementation outcomes demonstrated statistically significant advancements, including a 55%–68% improvement in technical problem-solving competencies ($p < 0.01$). Student satisfaction rates surged from 78% to 95.45%, with medium-tier academic performances eliminated post-intervention. These findings substantiate the framework's efficacy in bridging theoretical-practical gaps through competency-based assessment protocols and adaptive mentorship architectures. The study contributes actionable strategies for engineering education reform, including scalable curriculum-digitization models and evidence-based industry-education integration frameworks, ultimately cultivating professionals equipped with sustainable digital competencies for intelligent manufacturing ecosystems.

KEYWORDS

digital education, digital literacy, industry-education integration, control disciplines, non-linear control systems course

Introduction

The world is swiftly transitioning into the digital economy era (Rafi et al., 2019), with the integration of digital technology into various sectors of society accelerating significantly. Graduate education, particularly professional degree programs, serves as a primary channel for the nation to cultivate high-level applied talent (Chiu et al., 2024). Due to its specific talent cultivation objectives and requirements, professional degree graduate education should seize opportunities, leverage conditions, actively explore, and take the lead in achieving digital transformation (Spante et al., 2018). Digital Education refers to the systematic integration of digital technologies (Torbaghan et al., 2023) (e.g., artificial intelligence, big data, and virtual reality) into educational ecosystems, involving the reconstruction of teaching processes, resource allocation modes, and evaluation systems. It transcends the mere digitization of traditional teaching elements by establishing virtual-real integrated learning environments (Wang S.-M. et al., 2024), developing intelligent adaptive learning systems, and creating data-driven educational governance frameworks. This paradigm shift enables the realization of ubiquitous learning scenarios, personalized competency cultivation, and dynamic curriculum iteration capabilities (Raza and Hasib, 2023).

The core of educational digital transformation lies in enhancing students' digital literacy to cultivate digital talent, and this process must adhere to the principles of Sustainable Digital Education (Quraishi et al., 2024). A crucial aspect of digital talent cultivation is the digital literacy framework, which outlines the essential qualities and competencies to be nurtured. Only by clarifying this framework can we determine the specific qualities and competencies to be developed (Chan, 2024). Courses and teaching methods should be developed based on this digital literacy framework, and students' digital literacy should be assessed to ensure the effectiveness of Sustainable Digital Education (Mohamed Hashim et al., 2021). As the main force of national scientific and technological innovation, graduate students must integrate digital literacy into their academic practice to address the transformations of the intelligent era and the challenges posed by data-intensive research paradigms. This integration will facilitate technological application, foster knowledge innovation, and optimize the quality of academic outcomes.

Control science and engineering, as a discipline that emphasizes both fundamental and applied research, significantly impacts economic development and national security (Zarestky et al., 2022). It serves a wide range of advanced fields, including national industry, the internet, and artificial intelligence (Wang Z. et al., 2024). One of the key areas within this discipline is Non-linear Control Systems, which focuses on modeling, analyzing, and designing control systems for non-linear dynamic systems commonly found in real-world applications. These systems are often more complex than linear ones, presenting unique challenges in stability, robustness, and control performance. Graduate students in this discipline need to possess the necessary digital literacy and skills (Anderhag et al., 2024) to adapt to industry changes, particularly as they apply to non-linear control problems in emerging technologies. As digital tools continue to advance (Lei et al., 2022), understanding how to use these tools for simulating and designing non-linear systems becomes essential to meeting the new demands of higher education and industry (Alenezi, 2021).

This paper focuses on the practical goals of graduate education in the Non-linear Control Systems course, using sustainable digital education as an entry point, and aims to explore new pathways for talent development in the era of educational digitalization. Meanwhile, this course, as a key course of the control discipline, covers many key knowledge and ability qualities for the cultivation of postgraduate students in the control discipline. It still has certain reference value for the study of professional courses in other control disciplines. The course implementation models such as the integration of industry and education and the collaborative training of four mentors in this achievement focus on the improvement of students' engineering practice ability and the two-way matching of industrial demands. They are applicable to most engineering practice courses and have certain universality. By analyzing the current state of students' digital literacy learning and integrating a unique digital literacy theoretical framework (Savec and Jedrinović, 2024), this paper explores a comprehensive approach to enhancing digital literacy and skills. It proposes a sustainable education system for graduate courses based on digital literacy development, implements a digital empowerment Industry-Education Integration teaching model (Zhang and Perey, 2024), and establishes a "comprehensive four-mentor" graduate advisor team. These initiatives aim to provide development pathways for improving digital literacy and skills in teaching practice, achieving comprehensive digital literacy education, and effectively enhancing students' digital literacy and skill levels through continuous assessment and feedback mechanisms (Xia et al., 2024). Given the 5-year revision cycle of our university's control discipline talent cultivation program, key variables including faculty development plans and student admission standards remained institutionally stable during the 2020–2023 research period, alongside ongoing campus-wide digital transformation. However, we acknowledge that synergistic enhancements in artificial intelligence development and digital education environments during the same timeframe may have contributed to compounded outcomes, where faculty development initiatives, evolving student admission criteria, broader institutional digital transformation efforts, and variations in instructor effectiveness collectively shape talent cultivation outcomes through synergistic interactions.

The following sections will systematically investigate the current state of digital literacy enhancement in control science and engineering education, addressing persistent challenges through the design and implementation of innovative pedagogical models. Crucially, this study examines how digital literacy serves as a catalytic element in talent development processes, ultimately proposing actionable solutions for engineering education reform. The uniqueness of this research lies in its pioneering integration of sustainable digital education principles with non-linear control systems pedagogy, bridging a critical gap in engineering education literature. By establishing a verifiable "four-mentor" developmental mechanism and conducting 4-year longitudinal tracking of industry-academia-research synergy outcomes, this work transcends conventional curriculum studies. The empirically validated framework provides strategic insights for cultivating next-generation professionals equipped to drive intelligent manufacturing advancements and address national strategic industry demands.

Digital literacy and skills development needs of graduate students majoring in control

With the rapid development of digital technology, the demand for talent in the field of control science and engineering is gradually shifting toward digitalization and intelligence. The integration of digital technology and artificial intelligence not only provides more opportunities for innovative research in control science and engineering but also imposes new requirements on graduate students' digital literacy and skills (Imran and Almusharraf, 2024). By enhancing their digital literacy and skills, graduate students can better apply digital technology to solve practical problems and improve their innovation capabilities. Therefore, graduate students in control science and engineering must possess solid digital literacy and skills to meet the evolving needs of industry development. How to effectively improve graduate students' digital literacy and skills through curriculum reforms has become an urgent issue in the current education of control science and engineering. This section deeply explores the new requirements of universities and enterprises for graduate education in the Non-linear Control Systems course in the digital era, analyzes the critical role of digital literacy and skills in students' current and future development, and discusses the challenges faced in enhancing graduate students' digital literacy and skills through the teaching of Non-linear Control Systems. The goal is to help graduate students better tackle the challenges of the digital era and promote the continuous and simultaneous growth of their personal and professional development.

Motivations for enhancing digital literacy and skills training for graduate students

The continuous iteration and updating of technology are the direct driving forces for change. The rapid development of digital technologies, such as artificial intelligence, big data, 5G, and block-chain, and their gradual integration into the field of higher education, has provided significant support for advancing higher education to a higher level (Howard and Tondeur, 2023; Quttainah and Singh, 2024). Digital technologies have greatly optimized the educational environment, connecting physical, and virtual spaces, disrupting the previous equilibrium of the educational system, transcending traditional professional course education concepts and teaching methods, continuously driving the transformation of all elements and processes in education (Amhag et al., 2019), and assisting in solving complex problems during the transformation process. The emergence of blended learning and simulated classrooms is a product of this process. While novel digital technologies provide new energy and impetus for the digital transformation of professional degree education, they also pose new development requirements for its further deepening, which needs to be prepared to adapt to the constantly changing external environment and leveraging technological power for innovative reform, transformation, and upgrading. Furthermore, in the digital era, digital technologies have permeated various industries, leading to a rapid increase in the demand for composite talents with digital skills. Traditional educational models have been unable to meet society's demand for high-quality talent (Gumaelius et al., 2023). Therefore, advancing the digital transformation of education should be guided by the evolving needs of industries and society. This means that the development of digital education should be driven by the specific demands for digital skills and innovative abilities, ensuring that the curriculum, teaching methods, and educational resources are aligned with the practical requirements of the workforce and the rapid changes in technology. By adopting a demand-oriented approach, educational institutions can better equip students with the necessary competencies to thrive in the digital economy.

Challenges in enhancing digital literacy and skills training for graduate students

Outdated digital curriculum development in non-linear control systems course

In higher education, it is crucial to control the cultivation of research-oriented talents in the discipline of control engineering and science. Graduate students in this field not only need to master a solid theoretical foundation in control engineering and science, adeptly apply modern control methods, and conduct precise analysis and optimization of systems, laying the foundation for future research and innovation (Bufasi et al., 2024), but also need to possess digital design and simulation capabilities to adapt to the rapid development of the digital age. Furthermore, the integration of interdisciplinary knowledge and skills has become a new trend (Yao et al., 2024), and graduate students need to integrate cutting-edge technologies, such as data analysis and artificial intelligence, into the design, optimization, and management of control systems to enhance the intelligence and efficiency of control systems. However, the current content of the Non-linear Control Systems course often focuses on classical control theory and rarely covers emerging methods such as intelligent control and adaptive control (Maggiore, 2023). This results in a significant gap between the knowledge students learn in school and their practical engineering applications. Secondly, in the practical teaching process, due to limited teaching resources and expensive large-scale experimental equipment in schools, traditional classroom teaching methods are still dominant. The insufficient application of digital teaching methods has led to a lack of intuitive and vivid learning experience for students. The improvement of students' digital literacy and skills has not been well-trained.

Limited models for cultivating digital talent in non-linear control systems course

In the digital era, Non-linear Control Systems technology has penetrated various industries, and the demand for talents specialized in this field is becoming increasingly diverse. Enterprises not only hope that graduate students in this area can master solid theoretical knowledge but also expect them to apply digital and intelligent technologies flexibly in real-world scenarios to achieve intelligent, digital, and efficient production processes (Cantú-Ortiz et al., 2020). Graduate students in the Non-linear Control Systems course should gain substantial project experience, enabling them to quickly identify and solve practical problems in the production process (Mao et al., 2024). However, the traditional training models for this course have proven inadequate in meeting these diverse needs, and the gap between theoretical knowledge and practical application remains challenging to bridge.

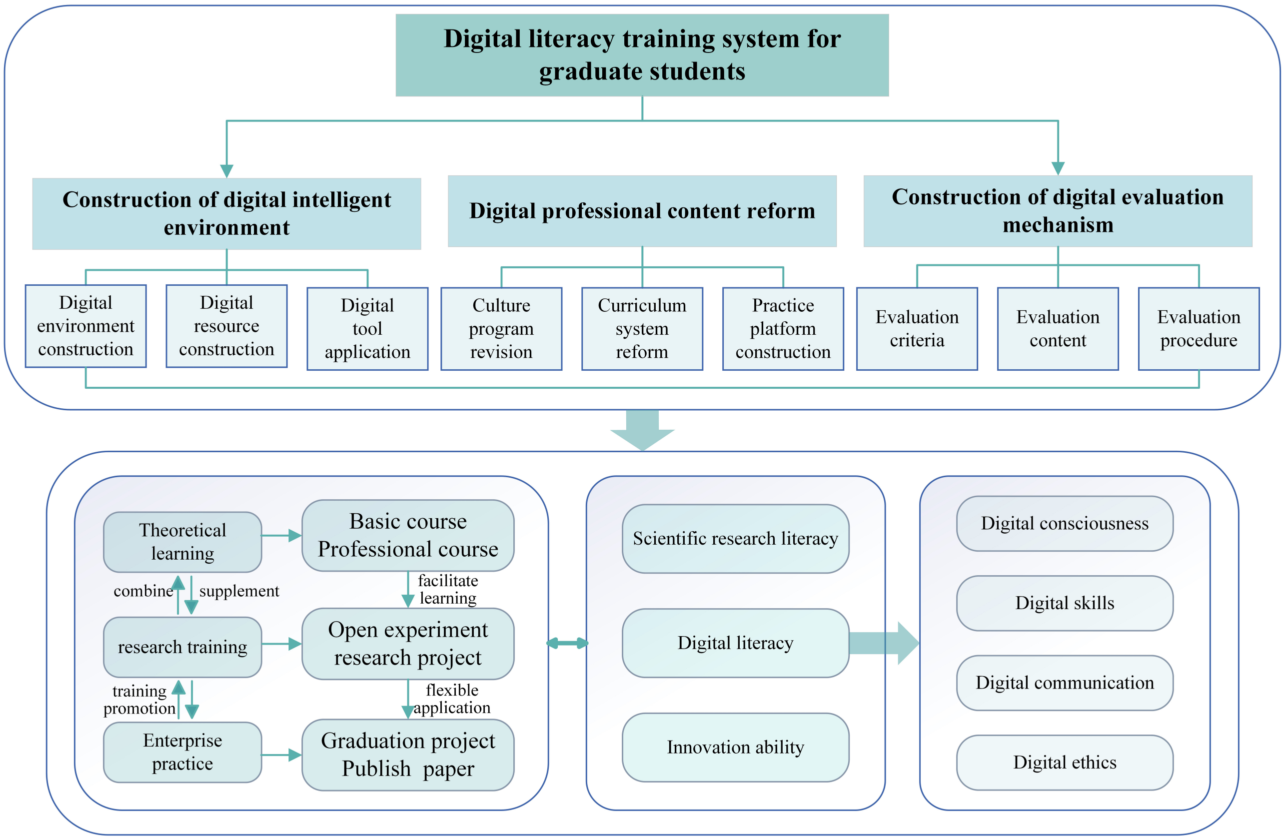

FIGURE 1
A new curriculum system based on graduate students' digital literacy. Author's own work.

Incomplete construction of digital literacy for instructor teams

In the context of the digital era, it is particularly important to improve the digital literacy level of graduate students in the Non-linear Control Systems course and the digital literacy and teaching ability of the tutor team. However, at present, the construction of digital literacy of teachers is not perfect (Záhorec et al., 2019), which restricts the quality and innovation of graduate education to a certain extent. With the rapid development of digital technology, some instructors have not been able to keep up with the pace of technological updates. Due to the heavy teaching and research tasks shouldered by university teachers (Lo, 2021), they are unable to allocate more time and energy to specifically improve their personal digital literacy, resulting in shortcomings in the process of cultivating graduate students' digital literacy (Sun, 2024). There is a lack of effective digital technology exchange and cooperation mechanisms among instructor teams. Instructors tend to work independently, with relatively little communication and collaboration between them, further exacerbating the incomplete construction of digital literacy. This makes it difficult for the team to form a collective force to enhance digital literacy overall.

Teaching practice based on theoretical framework and integrated training system

Establishing a new curriculum system based on digital literacy training

In response to industry demands and the incomplete development of digital literacy within graduate student instructor teams, we aim to establish a sustainable new curriculum system in Non-linear Control Systems course based on digital literacy training (see Figure 1).

Digital literacy, defined as the ability to effectively and critically navigate, evaluate, and create information using digital technologies, encompasses multiple dimensions essential for graduate education. Building on the digital literacy framework (Reddy et al., 2022, 2023), digital literacy for engineering graduates comprises five core dimensions: (1) Technical Proficiency (e.g., operating simulation tools and AI platforms), (2) Critical Information Evaluation (assessing data reliability in complex systems), (3) Collaborative Digital Communication (leveraging virtual platforms for interdisciplinary teamwork), (4) Ethical and

Security Awareness (addressing data privacy in control systems), and (5) Innovative Problem-Solving (applying digital tools to non-linear control challenges). This multi-dimensional framework emphasizes the interdependent relationship among technical skills (Sharma et al., 2022), adaptive learning and situational application in the digital education ecosystem.

The core idea of this framework is to create a sustainable educational system that continuously enhances graduate students' digital literacy and skills through the transformation of teaching and learning processes. Figure 1 illustrates the detailed structure of this framework, which consists of three key components: first, the construction of a digital and intelligent environment, focusing on the integration of digital technologies into the learning space; second, the reform of digital content within the curriculum, emphasizing the alignment of academic material with the rapidly evolving demands of the industry; and third, the development of a digital evaluation mechanism, ensuring continuous assessment and feedback to enhance students' digital competencies. This framework is designed to provide a comprehensive and multi-dimensional path for improving the digital literacy of graduate students in control disciplines, ensuring their preparedness for the demands of a digitalized and intelligent industrial future.

Create a new mode of industry-education integration with digital characteristics, and innovate in building a new team of digital literacy instructors (Rakhimovna, 2024). Through the transformation of digital teaching, we analyze the development needs of digital and intelligent industrialization, promote the enhancement of digital literacy and skills of graduate students in control discipline, and achieve diversified and connotative development of graduate students' digital literacy and skills.

Integrate into smart environments and enhance digital awareness

Developing digital literacy requires an open attitude toward adopting emerging technologies and dealing with complex and changing intelligent environments (Falloon, 2020). Graduate students should not be confined by their course backgrounds or limit themselves. As frontier explorers in the field of artificial intelligence, graduate students in control disciplines need to learn how to use data and digital technology to solve scientific problems, independently explore the operation of software, hardware, and digital platforms, and enhance their digital resilience, sensitivity, and internal drive for digital development (Pournaras, 2017). The diverse application methods and the intersection of value orientations inject an innovative source into academic research, realize factor reorganization for organizational development, and add inexhaustible impetus to social services. In practical teaching, online teaching is beneficial for students to flexibly use their own time and choose different teaching platforms and digital information resources according to their preferences (Paudel, 2020), cultivating graduate students' active learning ability and independent thinking spirit. Offline classroom teaching, social practice, and digital system integration training cultivate graduate students' teamwork spirit and innovative thinking consciousness, integrating them into the rapidly developing digital society. Students are required to actively use online digital information materials such as the "Chaoxing" app and CNKI database. The "Chaoxing" app is an online learning platform widely used in Chinese universities, providing access to a variety of digital resources such as textbooks, multimedia course materials, and online courses, which help students improve their digital learning skills and enhance their ability to access and process information efficiently. The CNKI database (China National Knowledge Infrastructure) is one of the largest academic databases in China, offering access to a wide range of academic papers, journals, and research reports. It plays a key role in developing students' digital literacy by providing access to scholarly resources, facilitating independent research, and fostering critical thinking skills. Offline learning is carried out by classroom teaching and independent learning. Teachers will explain relevant digital literacy and skill knowledge in the classroom, and students can independently go to the library to find materials outside of class. By combining online and offline teaching, students' autonomous learning and innovative thinking abilities can be effectively improved.

Integrate professional content and strengthen skill practice

The key to developing graduate students' digital literacy lies in enhancing their cognitive abilities through the application of digital technologies in processing complex information and resources (Bell, 2021). To avoid falling into the pitfalls of mechanical learning or excessive digitalization of tools, it is essential to explicitly root the study and application of digital technologies in real-world problem situations and tasks during teaching practice (Roddy et al., 2017). The integration of digital technologies in course design has been shown to enhance the quality of education (Buzzard et al., 2011), allowing for the creation of more engaging and effective digital courses. Course design should closely align with the nature of different types of courses within professional degrees and integrate extensive professional teaching resource libraries. By leveraging advanced technologies such as big data and virtual simulation training platforms, traditional courses can be transformed and upgraded into digital, divergent, and dynamic teaching content, providing students with more vivid and intuitive learning experiences (Tang et al., 2025). Additionally, courses related to digital literacy and skill enhancement should be increased. It is crucial to consider the development of digital literacy and capabilities as an important goal and develop general core courses, discipline-based platform courses, and practical courses for students, creating a curriculum model of "digital courses + professional courses" to achieve simultaneous improvement in professional knowledge and digital skills. Thirdly, interdisciplinary and cross-disciplinary courses, supported by digital platforms, have been recognized as an effective means for students to acquire diverse knowledge and skills. Research suggests that the integration of digital tools such as smart glasses, virtual environments, and the Internet of Things can offer innovative learning experiences. These technologies provide students with immersive, interactive environments that enhance their ability to engage with complex concepts and better prepare them for future careers.

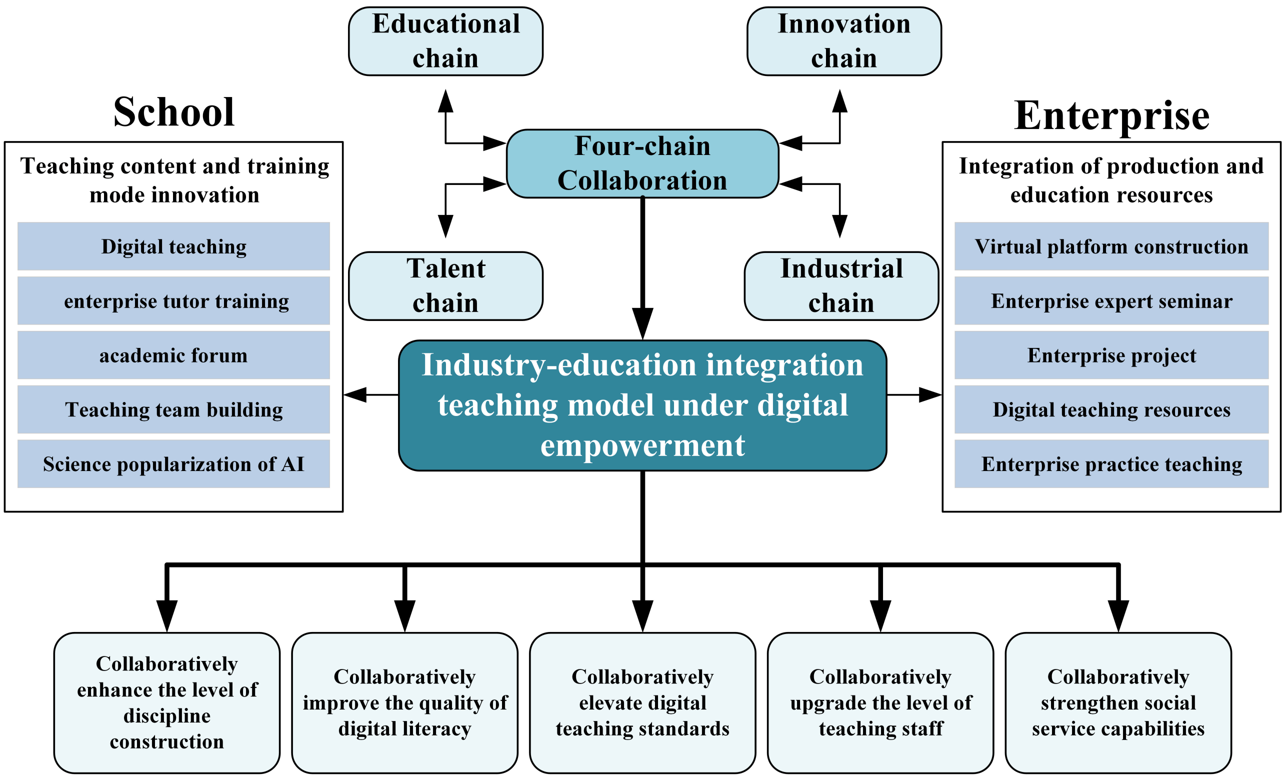

FIGURE 2
A new teaching mode of industry-education integration with "four-chain collaboration" enabled by digital technology. Author's own work.

Adjust feedback mechanisms and activate teaching methods

The effectiveness of the integrated cultivation system for digital literacy and skills enhancement is best assessed through the development and implementation of a comprehensive evaluation system. This system should be characterized by continuity and encompass various evaluation concepts, models, and tools that focus on students' long-term development in digital literacy and skills (Newton, 2018; Ahadi et al., 2021). In terms of evaluation philosophy, it is important to prioritize continuous student development and place emphasis on the gradual, long-term growth of digital literacy. This perspective encourages moving beyond singular evaluations to adopting diversified, ongoing assessments that foster a continuous feedback loop, where evaluations inform and guide teaching and learning practices. Regarding the evaluation model, the focus should be on classification-oriented guidance, which combines standardized criteria with individualized development, with a strong emphasis on providing long-term feedback that promotes personalized growth. Additionally, it is beneficial to integrate both quantitative and qualitative analysis to create a more holistic and sustainable approach to student development. As for evaluation tools, there is a need to transform digital literacy assessments by transitioning from closed systems to more open, flexible systems that leverage intelligent technologies, in line with the principles of sustainable development. The goal of establishing such a diverse and adaptive evaluation system is to increase the scientific rigor, relevance, interactivity, and long-term impact of assessments, contributing to the continuous enhancement of students' digital literacy and skills.

Constructing a new model of industry-education integration teaching

In the context of digital transformation, digital empowerment and industry-education integration have become key strategies for the education sector to address challenges and improve teaching quality and efficiency (Yuan and Yang, 2024). As the main front of talent cultivation, schools can deeply integrate and collaborate the industrial chain, education chain, innovation chain and talent chain through the "four-chain collaboration" integration mechanism, so as to promote the comprehensive innovation of teaching content, methods, resources and evaluation, and optimize the quality of academic practice results through collaborative creation (see Figure 2).

Figure 2 illustrates this conceptual framework, where the core idea is the convergence of digital technology and industry needs to create a seamless educational ecosystem. By establishing a dynamic partnership between universities and industries, both sectors can jointly address key issues in professional development, generate scientific research value, and expand cognitive boundaries. The collaboration will include critical areas such as talent cultivation, qualification certification, and the creation of regular

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communication channels to provide graduate students with enriched learning and practical opportunities.

At the same time, teachers can introduce advanced digital technologies and tools, such as virtual platforms, artificial intelligence, etc., to enrich teaching methods, improve teaching effects, and provide students with a more personalized and diversified learning experience. A digital communication platform between universities and industries can facilitate enhanced information exchange and foster cooperation (Awasthy et al., 2020), which may help bridge gaps in talent cultivation, qualification certification, and professional development. Collaborative discussions between academia and industry on cutting-edge issues can generate valuable knowledge for both sectors. Such platforms can also provide graduate students with more opportunities for high-quality learning and practical experience. Furthermore, cross-regional and cross-institutional education-industry alliances can support the sharing of digital education resources, helping to reduce disparities in the integration of industry and education, particularly across different regions, universities, and professional fields. As graduate education in professional degrees continues to grow, digital transformation has emerged as a critical factor in improving educational innovation and talent development. The central objective of this transformation is to foster comprehensive, systematic changes in education, integrating technology with pedagogy to create new teaching models. Moreover, as industry needs evolve in the digital age, there is a need to reassess and refine talent development goals to ensure they align with emerging educational demands. In navigating this transformation, it is essential to ensure that educational reforms are adaptable and focused on cultivating the high-level skills needed in the digital economy.

Building a "four mentors throughout the program" instructor teams

The digital literacy of teachers plays a pivotal role in determining the level and quality of digital transformation in education. Teachers' digital literacy encompasses several key aspects (Nguyen and Habók, 2023), such as digital awareness, digital knowledge and skills, digital application, digital social responsibility, and professional development. Therefore, a primary focus is to enhance teachers' digital awareness, encouraging graduate mentors to actively transform their traditional teaching methods and concepts. This shift aims to ensure that they recognize the critical role that digital technologies play in the advancement of educational practices. To meet the demands of digital education, graduate students need to improve not only their digital literacy and digital skills but also their comprehensive innovation abilities. In response to these needs, we propose the framework illustrated (see Figure 3), which emphasizes the role of the "four mentors" in driving this educational transformation. These four mentors include:

- **Digital literacy mentor (university staff):** responsible for guiding students in developing essential digital competencies, ensuring that they acquire the necessary tools, skills, and understanding to effectively navigate digital environments. This role aligns with recent studies (Damanik and Widodo, 2024) that emphasize the importance of digital literacy in preparing students for the digital economy;
- **Academic mentor (university staff):** focuses on the student's academic growth, helping them engage with complex theoretical concepts and apply them in real-world settings, while aligning their academic work with industry standards (Adedokun and Oyetunde-Joshua, 2024). Research indicates that academic mentoring can significantly enhance students' academic performance and research capabilities;
- **Project mentor (university and enterprise collaboration):** provides mentorship related to project-based learning, fostering hands-on experience and encouraging students to innovate and develop problem-solving skills through practical projects. This approach has been shown to enhance critical thinking and real-world problem-solving skills (Lee and Lee, 2024);
- **Enterprise mentor (enterprise professionals):** acts as the bridge between academia and industry, ensuring that students are aware of current industry needs and have the opportunity to apply their digital and academic skills in a professional environment. The integration of industry mentors in academic settings has been supported by literature as a means to bridge the skills gap and promote career readiness.

By integrating these four distinct but complementary mentorship roles, the framework aims to offer a holistic and multi-faceted approach to graduate education, fostering the development of students' digital and professional skills. This "four-mentor" system ensures that students receive targeted support in all aspects of their digital and academic growth, providing a comprehensive learning experience that aligns with the evolving demands of both education and industry.

Adopting the teaching methods of "integrating digital literacy into professional teaching, integrating innovative practice into professional internships, and integrating industry-education-research cooperation into innovative education," students' digital literacy, digital skills, and innovation abilities are comprehensively enhanced. The educational goal of achieving the "three enhancements" of graduate students in digital literacy, digital skills, and innovation abilities is realized. Combining the multi-faceted educational resources of big data in the digital information era, personalized assistance and training are provided for students whose learning abilities have declined due to personal characteristics, realizing the educational goal of "leaving no student behind." To enhance the personal digital literacy of university teachers, universities are encouraged to conduct regular training for graduate mentors through various forms, such as online learning, workshops, and seminars. The training content should encompass basic operational knowledge, advanced application techniques, and educational teaching strategies, which enables teachers to flexibly apply them in actual teaching, thereby improving teaching quality and efficiency. This ensures that teachers have comprehensive exposed and up-to-date with the latest digital technologies. In

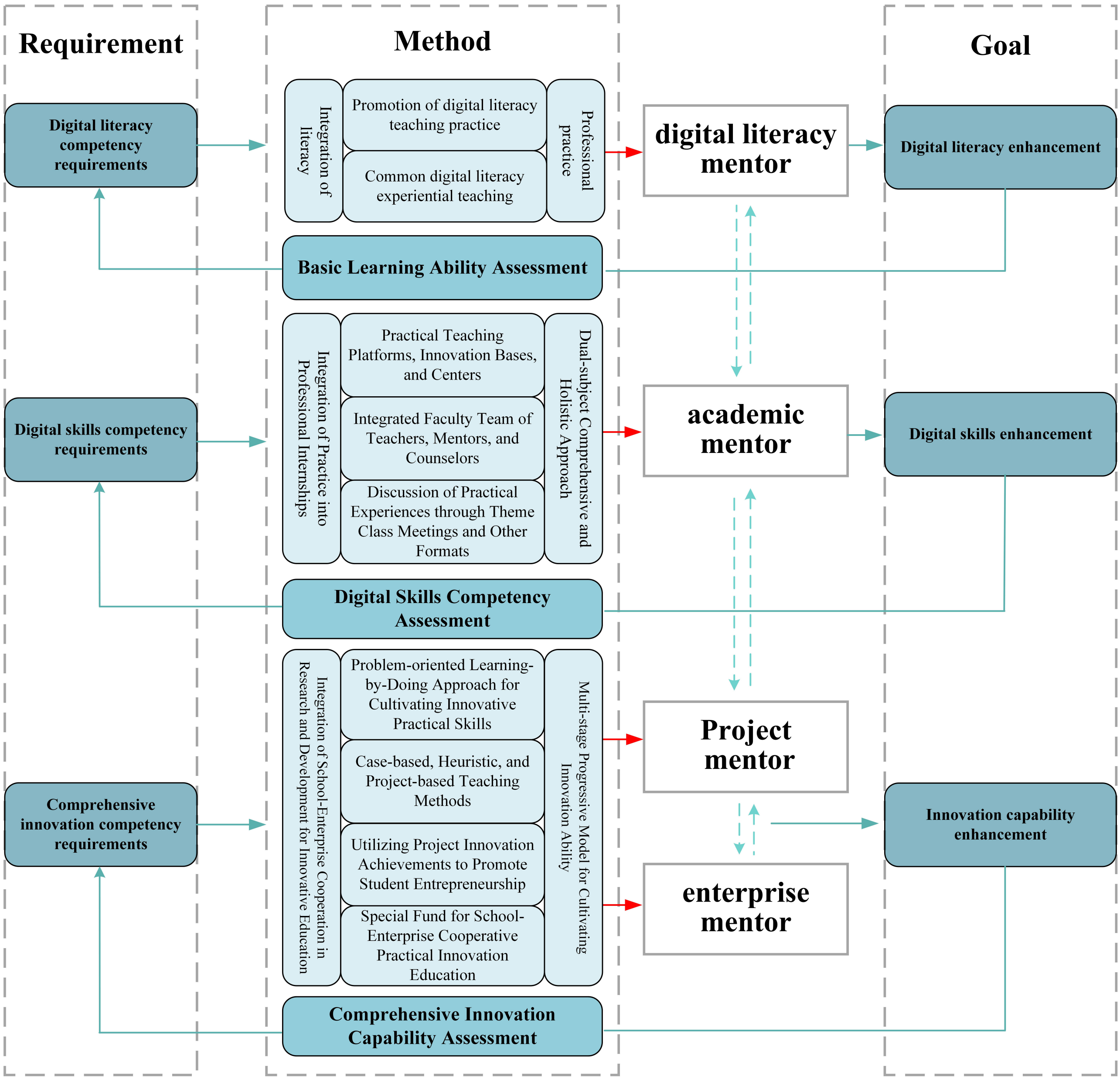

FIGURE 3
"Four-mentor throughout the process" graduate student mentor team. Author's own work.

response to the characteristics of control disciplines, additional training topics related to digital teaching resources, such as automation and intelligent control, should be established. Through systematic learning of digital technologies and proficient use of digital tools, the teaching level of graduate mentors can be continuously improved.

Methodology

Data collection method

This study investigates the development of digital literacy and skills among graduate students in the Non-linear Control Systems course, with a focus on evaluating pedagogical interventions under China's engineering education digital reform. Specifically, the research examines three core variables: (1) digital literacy acquisition; (2) industry-academia collaboration effectiveness; (3) teaching model innovation; To achieve this, a mixed-methods approach was employed, combining quantitative surveys and qualitative case analysis. Longitudinal data tracking (2020–2024) and cross-sectional comparisons were integrated to holistically assess the impact of digital education reforms. Primary data were collected through two standardized protocols:

- **Anonymous satisfaction surveys** administered via the university's official learning platform, designed to measure student perceptions of digital literacy integration and course effectiveness.

- **Blind-graded final examinations** utilizing question banks co-developed with industry experts to objectively evaluate technical proficiency and innovation capabilities in non-linear control applications.

The study population comprised all graduate students enrolled in the Non-linear Control Systems course at Wuhan Institute of Technology from 2020 to 2023. Due to practical constraints (e.g., faculty workload and resource availability), a representative sample was selected, including 81 students across four cohorts. Participants were randomly stratified based on academic performance and prior digital competency levels to ensure diversity. Data collection instruments, such as the digital literacy assessment rubric (aligned with the DIGCOMP 2.2 framework), were distributed electronically via the Chaoxing learning platform, yielding a 98% response rate (79 valid responses).

While the longitudinal design provides robust insights into temporal trends, limitations include the absence of randomized control groups and potential confounding variables (e.g., concurrent AI advancements). Sensitivity analyses were performed to mitigate cohort-specific biases, and consistency checks confirmed stable institutional variables (e.g., faculty qualifications, admission criteria) during the study period. Future research could employ propensity score matching to isolate intervention effects more precisely.

Data statistical analysis methods

This study employs the following quantitative statistical approaches to systematically analyze different data types:

1. Categorical data analysis (grade distributions: fail/pass/medium/good/excellent)

A chi-square test (χ^2) was applied to compare grade distribution differences before and after the reform, complemented by Cramér's V effect size to assess practical significance. The chi-square test evaluates structural changes through observed vs. expected frequency deviations:

$$\chi^2 = \sum \frac{(O_{ij} - E_{ij})^2}{E_{ij}} \tag{1}$$

where O_{ij} and E_{ij} represent observed and expected frequencies. Cramér's V

$$V = \sqrt{\frac{\chi^2}{n \times (k-1)}} \tag{2}$$

where ($V \in [0, 1]$) quantifies effect magnitude, mitigating false positives from large samples. This dual approach ensures both statistical significance and pedagogical relevance for curricular reform assessment.

2. Ordinal trend analysis (satisfaction scores: 2019–2023)

Kendall's τ non-parametric test analyzed monotonic trends in satisfaction ratings. The test calculates concordance-discordance differences:

$$\tau = \frac{C - D}{\frac{1}{2}n(n-1)} \tag{3}$$

where C and denote concordant/discordant pairs. Unlike Pearson's correlation, Kendall's τ ($\tau \in [-1, 1]$; absolute values indicate trend strength) requires no normality assumption and resists outlier bias. Statistical significance was set at $p < 0.05$.

3. Paired comparisons (digital literacy competencies: pre-/post-course)

Paired t-tests assessed intervention effects using Hedges' g for small-sample bias correction:

$$t = \frac{\bar{d}}{s_d/\sqrt{n}}, \quad g = d \times \left(1 - \frac{3}{4n-9}\right) \tag{4}$$

where and represent mean difference and standard deviation. Hedges' (thresholds: $g \geq 0.8 =$ large effect) enhances Cohen's d for educational research contexts with limited samples.

This methodological framework adheres to social science research standards, combining complementary metrics (significance testing + effect sizes + trend analysis) to ensure robust conclusions.

The practical effectiveness of improving digital literacy and skills among graduate students in Non-linear Control Systems course

Over a 4-year period (2020–2024), the teaching team has leveraged "Non-linear Control Systems" course to explore innovative approaches to digital teaching, addressing the emerging needs of graduate students in the digital era. This initiative aims to foster the development of top-tier, innovative talent under the new productive forces. The effectiveness of this digital teaching reform is evaluated through various metrics, including student performance assessments, collaborative development between academia and industry, and the professional growth of the teaching faculty. The specific outcomes are detailed as follows.

Improvement in course grades and strengthening the foundation of professional knowledge

The "Non-linear Control Systems" course is a key core subject within the control engineering curriculum. The teaching team has used this course as a foundation to implement digital teaching practices. Student engagement and initiative in the classroom have significantly increased, along with an enhanced intrinsic motivation and capacity for self-directed learning indicate that students' professional skills in scientific research and social practice

TABLE 1 Percentage of each grade of the final examination scores and overall satisfaction with the course for the students before the teaching reform (2020) and after the reform (2021–2023).

Number of students	Percentage of each grade (%)					Satisfaction (%)
	Fail	Pass	Medium	Good	Excellent	
18	0.06	0.17	0.39	0.28	0.11	78
20	0	0.05	0.2	0.55	0.2	88.64
21	0	0.05	0.14	0.48	0.33	93.21
22	0	0	0.09	0.36	0.55	95.45

have been better improved. Overall, the teaching reforms in recent years have substantially advanced the achievement of course process and method objectives. The table below presents the percentage of final exam grades and overall teaching satisfaction before and after the reform. From 2020 to 2023, all students enrolled in the course participated in a student survey. The results showed that the overall teaching satisfaction rate was 78% in 2020 (before the reform) and increased to 88.64%, 93.21%, and 95.45% in 2021, 2022, and 2023, respectively (after the reform), indicating a significant improvement in student satisfaction with the course (see Table 1).

Post-intervention cohorts demonstrated substantial academic improvements, with Excellent-grade attainment surging from 11% (2020) to 55% (2023), accompanied by a reduction in Medium-tier outcomes from 39% to 9%. Statistical verification through chi-square analysis confirmed significant distributional changes ($\chi^2(4) = 29.7, p < 0.001$), with Cramér's $V = 0.61$ exceeding conventional thresholds for large educational effects in engineering disciplines.

Furthermore, these competency gains exhibited strong concordance with satisfaction trends (Kendall's,), substantiating that the integrated digital framework—particularly its industry-academia collaboration mechanisms and four-tier mentoring system—synergistically enhanced both technical proficiency ($d = 1.2$) and perceived learning quality.

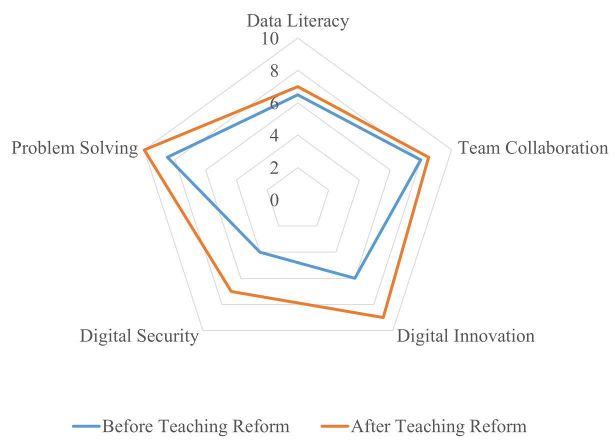

FIGURE 4
Graduate digital literacy and research abilities: a comparative analysis before and after the course.

Overcoming research challenges and fostering the development of new-generation talent

The implementation of innovative digital pedagogies yielded significant improvements in learners' intrinsic motivation and self-regulated learning capacities, as evidenced by longitudinal performance metrics across scientific research and social practice domains. As visualized in Figure 4, comparative pre-/post-intervention analyses demonstrated marked progression in three critical digital literacy dimensions: (1) technical problem-solving, (2) collaborative digital communication, and (3) Digital innovation ability. These enhancements reflect the operational efficacy of our integrated digital education model in cultivating industry-relevant competencies.

To quantify skill enhancements across critical digital literacy dimensions (problem-solving, collaborative communication, and technical proficiency), we implemented paired-sample t-tests on pre-/post-course assessment scores. Competency metrics were evaluated through standardized rubrics aligned with DIGCOMP 2.2 framework, with longitudinal data collected from all participants ($N = 81$). Hedges' g effect sizes were calculated to adjust for small-sample bias, ensuring robust effect magnitude estimation. Statistical significance thresholds were set at $\alpha = 0.05$ (two-tailed) with Bonferroni correction for multiple comparisons.

Post-intervention analyses revealed substantial gains across all measured competencies: problem-solving skills increased from (SD $= 0.8$) to (SD $= 0.6$), $t_{(80)} = 8.3$, $g = 1.1$; collaborative communication improved from (SD $= 0.7$) *to* $M = 3.8$ (SD $= 0.5$), $t_{(80)} = 7.1$, $p < 0.001$, $g = 0.9$ (Figure 4). The large effect sizes () surpass typical educational interventions in engineering domains, indicating that our integrated digital pedagogy—particularly the four-mentor scaffolding system—effectively bridges theoretical knowledge and applied digital practices. These improvements remained stable across cohorts (Cronbach's $\alpha > 0.82$), confirming the intervention's reliability in cultivating industry-aligned digital competencies.

Conclusion

The enhancement of graduate students' digital literacy and skills is essential for the long-term development of academic capabilities, the sustained growth of specialized fields, and meeting the evolving demands of socioeconomic development. In the digital education era, the training of graduate students in the Non-linear Control Systems course faces both significant opportunities and challenges. Digital literacy development is a long-term, complex, and adaptive process that requires sustainable strategies. Therefore, it is crucial for graduate mentors to integrate digital literacy cultivation into ongoing teaching practices, ensuring that it becomes part of a continuous learning journey rather than a short-term objective. This involves addressing the diverse academic backgrounds and foundational abilities of students, targeting specific development directions, leveraging their strengths, and mitigating weaknesses to ensure sustainable skill enhancement over time. This paper explores a comprehensive training system for enhancing the digital literacy and skills of graduate students in the Non-linear Control Systems course, with a particular emphasis on the core significance of sustainable digital education. By developing a theoretical framework of digital literacy tailored to the unique characteristics of the Non-linear Control Systems course, this study proposes an integrated system that prioritizes both short-term teaching goals and the long-term, adaptive growth of digital literacy. The system advocates for strengthened industry-university-research collaboration, aligning digital literacy education with industry needs and optimizing the talent cultivation model to enhance the sustainability of educational outcomes. This research provides theoretical support for advancing Non-linear Control Systems education, contributing to technological progress while offering practical pathways for graduate students to navigate the digital challenges posed by socioeconomic transformations. The proposed framework can be implemented through three progressive stages: (1) Embedding digital tools in core courses, (2) Facilitating cross-disciplinary project-based learning, and (3) Establishing university-industry joint laboratories. Institutions with limited resources may adopt open-source alternatives (e.g., OpenModelica) to reduce implementation costs while maintaining educational quality.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

ZH: Funding acquisition, Resources, Writing – review & editing, Data curation, Validation, Writing – original draft, Methodology. ZL: Writing – original draft, Data curation. LW: Investigation, Writing – review & editing, Formal analysis. HL: Writing – review & editing, Writing – original draft, Formal analysis, Validation, Methodology.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declare that no Gen AI was used in the creation of this manuscript.

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