

**DEVELOPMENT OF A DIGITAL LEARNING SYSTEM BASED ON
INTERACTIVE 3D SIMULATIONS AND NON-STANDARD ASSESSMENT
IN ASTRONOMY EDUCATION (CASE STUDY OF THE ASTRONOVA
PLATFORM)**

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Abstract: This paper examines the problem of insufficient formation of students' conceptual understanding of spatial and dynamic cosmic phenomena in astronomy education. The limitations of traditional two-dimensional (2D) visualizations and reproductive assessment methods are critically analyzed. To address this issue, the study proposes the "AstroNova" digital platform, which integrates interactive three-dimensional (3D) simulations with non-standard assessment techniques. The findings indicate that this approach significantly improves students' level of understanding and reduces conceptual misconceptions in learning complex astronomical concepts.

Keywords: astronomy education, interactive simulation, 3D modeling, non-standard assessment, digital assessment, conceptual misconceptions, interactive learning technologies, AstroNova

INTRODUCTION

The integration of digital technologies into the educational process has become a global trend in modern education systems. Recent studies confirm that interactive and immersive learning environments have a significant impact on students' deep understanding of subject matter (Radianti et al., 2020; Makransky & Petersen, 2021). In particular, learning environments based on virtual and three-dimensional (3D) simulations enhance students' engagement, motivation, and level of comprehension (Makransky & Mayer, 2022).

At the same time, one of the key challenges in astronomy education remains the explanation of complex spatial and dynamic phenomena. The use of static two-dimensional (2D) representations to explain inherently three-dimensional cosmic processes often leads to the formation of misconceptions, which negatively affects students' conceptual understanding (Radianti et al., 2020).

Furthermore, contemporary educational research indicates that traditional assessment systems are limited in their ability to evaluate higher-order thinking skills (Bond et al., 2020). The effectiveness of learning in interactive environments depends not only on visualization but also on the implementation of appropriate assessment mechanisms. Therefore, the integration of instructional and assessment processes is essential.

A review of existing studies shows that instructional technologies and assessment systems are typically examined separately, while their integration into a unified educational framework remains insufficiently explored.

In this context, interactive 3D simulations can be considered an effective tool, as they enable students to observe and analyze cosmic processes in real time. At the same time, non-standard assessment methods provide a more effective approach for evaluating students' analytical and logical thinking skills.

To address this research gap, the present study proposes the "AstroNova" digital platform, which integrates interactive 3D simulations with non-standard assessment methods. The study analyzes the conceptual model, methodological foundations, and functional capabilities of the proposed system.

The scientific novelty of this research lies in the development of a comprehensive approach that integrates interactive 3D simulations with a multi-level assessment system within a unified digital environment, aimed at identifying and reducing students' conceptual misconceptions.

LITERATURE REVIEW

Recent studies in modern education highlight the growing importance of interactive technologies in enhancing the effectiveness of the learning process. In particular, research on virtual and immersive learning environments demonstrates that such approaches significantly contribute to students' deep understanding of complex subject matter.

Radianti et al. (2020), in their systematic review, examined the integration of immersive virtual reality (VR) technologies in education and found that these environments positively influence student motivation and learning outcomes. Their findings suggest that VR is particularly effective for teaching complex and spatial concepts, where traditional instructional methods often fall short.

Makransky and Petersen (2021) proposed the Cognitive Affective Model of Immersive Learning (CAMIL), which explains how immersive environments affect learners' cognitive and emotional processes. According to this model, interactive environments enhance attention, increase engagement, and support deeper

cognitive processing. However, the authors also emphasize the potential risk of cognitive overload, which may reduce learning effectiveness if instructional design is not carefully implemented.

Further advancing multimedia learning theory, Makransky and Mayer (2022) introduced the “immersion principle,” arguing that well-designed immersive environments can significantly improve learning outcomes. At the same time, they highlight that poorly designed simulations may negatively impact comprehension, underscoring the importance of methodological rigor in developing interactive learning systems.

In parallel, Bond et al. (2020) focused on assessment practices in digital education, demonstrating that traditional assessment methods are often limited to evaluating reproductive knowledge. Their study emphasizes the need for assessment approaches capable of measuring higher-order thinking skills, which are essential in contemporary education.

Despite the substantial contributions of these studies, a critical limitation remains: instructional technologies and assessment systems are typically examined in isolation. The integration of interactive learning environments with comprehensive assessment mechanisms within a unified digital framework remains insufficiently explored.

Addressing this gap, the present study proposes the integration of interactive 3D simulations and non-standard assessment methods within a single digital platform. The “AstroNova” platform is designed as a comprehensive and innovative solution aimed at improving conceptual understanding and systematically identifying and reducing students’ misconceptions.

Thus, while existing research confirms the effectiveness of interactive technologies in education, the lack of integrated approaches combining instruction and assessment highlights the relevance and novelty of the present study.

METHODOLOGY

This study develops an integrated approach aimed at improving students' understanding and identifying as well as reducing conceptual misconceptions in astronomy education. The research is based on the design-based research (DBR) methodology, which combines iterative design, implementation, and evaluation processes. The study is structured around the integration of technological, pedagogical, and functional components.

1. Technological Framework

The “AstroNova” digital platform was developed using modern web technologies. The front-end architecture was implemented with Next.js and React frameworks, ensuring modularity, high performance, and scalability of the system.

Interactive 3D simulations were created using the Three.js library, enabling real-time visualization of astronomical objects and processes. The platform was designed with a responsive interface to ensure usability across different devices. A component-based architecture and modern state management approaches were employed to manage user interactions efficiently.

Local storage mechanisms were utilized for temporary data handling and processing of assessment results, ensuring system responsiveness and continuity of user activity.

2. Pedagogical Model

The platform incorporates a multi-level assessment model designed to evaluate different cognitive levels of student learning:

- Level 1 (Fundamental Knowledge): identification of basic concepts, facts, and terminology;
- Level 2 (Understanding): interpretation and differentiation of content;
- Level 3 (Analytical Thinking): analysis of cause–effect relationships and complex problem-solving.

In addition, non-standard assessment tasks such as matching, sequencing, visual identification, and simulation-based responses were integrated to enhance student engagement and cognitive activity.

3. Interactive Simulation Model

Interactive 3D simulations serve as the core component of the learning process. The following simulation modules were developed within the platform:

- Modeling of Moon phases;
- Simulation of solar and lunar eclipses;
- Dynamic representation of the Earth–Moon–Sun system.

These simulations allow users to observe processes from multiple perspectives, control temporal parameters, and independently explore causal relationships, thereby supporting deeper conceptual understanding.

4. Research Methods and Evaluation Criteria

The study employed the following research methods:

- Theoretical analysis – review and synthesis of scientific literature;
- Comparative method – comparison of traditional and interactive approaches;
- Modeling – development of 3D simulation-based learning environments;
- Observation and analysis – evaluation of students' interaction with the platform and learning outcomes.

The evaluation criteria included:

- improvement in students' level of understanding;
- reduction in the number of conceptual misconceptions;
- development of analytical thinking skills.

5. Scientific Significance of the Methodology

The proposed methodology enables the integration of teaching and assessment processes within a unified system, allowing for more objective and in-depth evaluation of student learning. The combination of interactive 3D simulations and

non-standard assessment methods serves as an effective pedagogical tool for identifying and reducing conceptual misconceptions, while also providing a scientifically grounded framework for digital learning system design.

ASTRONOVA PLATFORM: SYSTEM ARCHITECTURE AND FUNCTIONAL DESCRIPTION

Within the framework of this study, the “AstroNova” digital platform was developed to support an interactive approach in teaching astronomy. The platform is designed as a comprehensive system aimed at supporting the educational process through visual, interactive, and analytical components.

To provide a clearer understanding of the structural and functional organization of the AstroNova platform, its system architecture is presented in Figure 1.

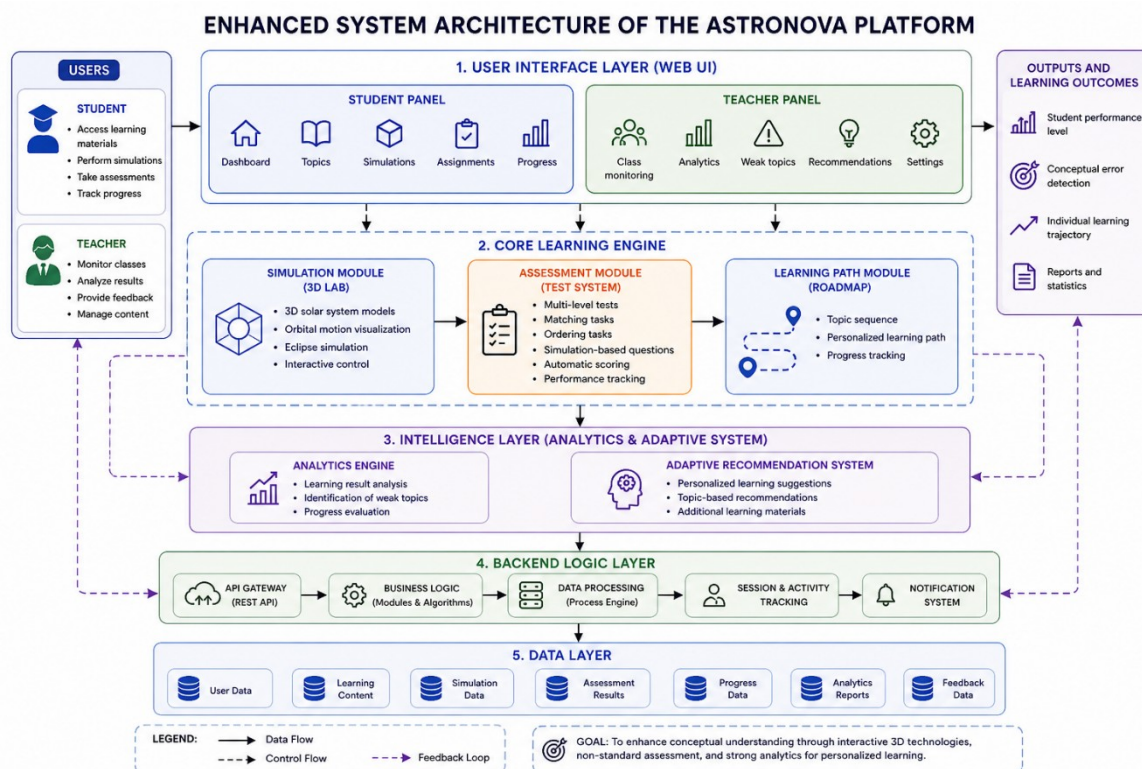


Figure 1. Enhanced system architecture of the AstroNova platform

As shown in Figure 1, the AstroNova platform is not merely a conventional electronic resource for delivering learning materials, but rather an integrated system that unifies teaching, assessment, and analytical processes within a single digital environment. Within the platform, learners acquire knowledge through interactive simulations and tasks, while the assessment module evaluates their level of understanding. The obtained results are processed by the analytics module, enabling teachers to identify students' strengths and weaknesses.

This architecture contributes to identifying conceptual errors, implementing individualized learning approaches, and enhancing students' spatial thinking skills.

Figure 1. Enhanced system architecture of the AstroNova platform

1. System Architecture

The AstroNova platform is developed based on a modular architecture approach and consists of the following key components:

- User Interface — provides an intuitive and user-friendly environment for both students and teachers;
- Simulation Engine — visualizes 3D astronomical processes in real time;
- Assessment Module — evaluates students' knowledge through multi-level testing;
- Analytics Module — processes results and assesses the level of learning achievement.

This architecture enables the integration of teaching and assessment processes into a unified and coherent system.

RESULTS AND ANALYSIS

Within the framework of this study, the impact of the developed “AstroNova” digital platform on the educational process was analyzed based on theoretical foundations and modeling results. The findings indicate that the platform offers several didactic advantages over traditional approaches in teaching astronomy.

The key differences between traditional (2D) and AstroNova-based interactive (3D) approaches are presented in Table 1.

Table 1. Comparison of traditional (2D) and interactive (3D) teaching approaches

No.	Indicator	Traditional (2D) approach	AstroNova-based interactive (3D) approach
1	Visual representation	Static images and diagrams	3D simulations (Moon phases, eclipses, orbital motion)
2	Explanation of spatial processes	Indirect and abstract explanation	Direct observation and interactive manipulation
3	Student engagement	Predominantly passive	Active participation (rotation, observation, time control)
4	Assessment of understanding	Standard tests (reproductive)	Multi-level and non-standard tasks
5	Detection of conceptual errors	Limited	Identified through simulations and assessments
6	Result analysis	General evaluation by teacher	Automated analysis and monitoring
7	Individualization	Limited	Adaptive learning based on student performance

The results presented in Table 1 clearly demonstrate the differences between traditional and interactive approaches. In particular, interactive 3D simulations enable students to directly observe and manipulate astronomical processes, providing a more accurate and stable understanding of spatial and dynamic phenomena compared to conventional 2D representations.

Furthermore, the findings indicate that in traditional approaches students mainly act as passive recipients of information, whereas in an interactive environment they become active participants. The ability to manipulate objects and control time parameters within simulations significantly enhances students' independent analytical thinking.

The assessment component also reveals substantial differences. While traditional testing methods are primarily limited to evaluating reproductive knowledge, the multi-level and non-standard tasks implemented in the AstroNova platform allow for the assessment of deeper understanding and analytical thinking skills. In particular, simulation-based tasks encourage students to comprehend processes rather than merely select correct answers.

In addition, the platform's analytics module enables systematic identification of student errors and their analysis across different topics, thereby supporting the implementation of individualized learning strategies.

Based on the conducted analysis, the following key findings were identified:

- interactive 3D simulations enhance spatial thinking skills;
- visual modeling reduces conceptual errors;
- multi-level assessment enables deeper evaluation of knowledge;
- non-standard tasks improve analytical thinking;
- the analytics module supports personalized learning;
- the interactive environment increases student motivation.

At the same time, the results reveal certain limitations. In particular, effective implementation of the platform requires adequate technical infrastructure (computers and stable internet access), as well as sufficient digital competencies among teachers.

The presented findings are primarily based on theoretical analysis and conceptual modeling; therefore, future research should focus on empirical validation of the platform's effectiveness.

Overall, the integration of interactive 3D simulations and non-standard assessment methods significantly enhances the effectiveness of astronomy education, promotes deeper conceptual understanding, and reduces the occurrence of conceptual errors.

CONCLUSION AND RECOMMENDATIONS

This study analyzed the conceptual model of the “AstroNova” digital platform, developed based on the integration of interactive 3D simulations and non-standard assessment methods in astronomy education. The results of theoretical analysis and modeling indicate that the integration of interactive technologies into the educational process has a positive impact on students' deep understanding of knowledge and their comprehension of complex spatial phenomena.

Based on the findings of the study, the following conclusions were drawn:

- Interactive 3D simulations facilitate the development of students' spatial thinking by providing dynamic and visual representations of astronomical phenomena;
- A multi-level assessment system enables evaluation beyond the reproductive level, allowing the identification of students' understanding and analytical thinking skills;
- Non-standard assessment tasks enhance student engagement and promote independent thinking and problem-solving abilities;
- The integration of teaching and assessment processes into a unified system is an effective approach for identifying and reducing conceptual errors.

At the same time, the study has certain limitations. In particular, the effectiveness of the platform was evaluated mainly based on theoretical analysis

and conceptual modeling, while large-scale empirical validation has not yet been conducted. This indicates the need for further experimental studies to refine and validate the proposed model.

Based on the results of the research, the following recommendations are proposed:

- To widely implement interactive 3D simulations in astronomy education;
- To integrate non-standard assessment methods alongside traditional testing systems;
- To provide professional development for teachers in the effective use of digital educational technologies;
- To test the developed AstroNova platform in real educational environments and evaluate its effectiveness through empirical research;
- To explore the potential adaptation and extension of the platform for other academic disciplines.

In general, the integration of interactive simulations and non-standard assessment approaches represents an effective strategy for improving the quality of astronomy education, enhancing students' interest in science, and developing their modern competencies.

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