Echo-Teddy: Preliminary Design and Development of Large Language Model-Based Social Robot for Autistic Students

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Abstract. Autistic students often face challenges in social interaction, which can hinder their educational and personal development. This study introduces Echo-Teddy, a Large Language Model (LLM)-based social robot designed to support autistic students in developing social and communication skills. Unlike previous chatbot-based solutions, Echo-Teddy leverages advanced LLM capabilities to provide more natural and adaptive interactions. The research addresses two key questions: (1) What are the design principles and initial prototype characteristics of an effective LLM-based social robot for autistic students? (2) What improvements can be made based on developer reflection-on-action and expert interviews? The study employed a mixed-methods approach, combining prototype development with qualitative analysis of developer reflections and expert interviews. Key design principles identified include customizability, ethical considerations, and age-appropriate interactions. The initial prototype, built on a Raspberry Pi platform, features custom speech components and basic motor functions. Evaluation of the prototype revealed potential improvements in areas such as user interface, educational value,

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and practical implementation in educational settings. This research contributes to the growing field of AI-assisted special education by demonstrating the potential of LLM-based social robots in supporting autistic students. The findings provide valuable insights for future developments in accessible and effective social support tools for special education.

Keywords: large language model · agentic flow · social robot · autism education

1 Introduction

Autistic students often face significant challenges in social interaction, a core aspect of their educational experience [28,38]. These difficulties can lead to isolation and hinder their academic and personal development [41]. Recognizing this issue, researchers have increasingly focused on the potential of social robots as companions to help autistic students navigate social interactions [18,22,24,33].

While previous studies have explored various approaches to developing social robots for autistic students, these efforts have encountered several key limitations. Many existing solutions rely on rule-based or scripted chatbots [4,15], which lack the flexibility to adpt the unique communication needs of autistic individuals. The design of these systems often fails to consider the varied ways autistic students process and respond to social cues, leading to unnatural and ineffective interactions [14,42]. Additionally, the robots used in previous research tend to be expensive and difficult to mass-produce or distribute widely, limiting their accessibility and potential impact [3,35]. High development and production costs remain a major obstacle, restricting the scalability and widespread adoption of social robots in educational settings.

Recent advancements in artificial intelligence (AI), particularly in Large Language Models (LLMs), have created new opportunities to enhance social robot interactions. While LLMs are commonly used in education as chatbots [1,21], there is a growing trend toward their use in more autonomous, adaptive, and decision-making roles [19]. Unlike traditional chatbots, which rely on predefined scripts and responses, LLM agents can maintain conversational context, adapt dynamically to user input, and make decisions based on real-time interactions. This agentic approach is increasingly being integrated into robotics research, enabling social robots to engage in more natural, context-aware, and personalized interactions [12,17,40].

To address the limitations of existing research and leverage these advancements, we introduce Echo-Teddy, an LLM agent-based social robot designed specifically for autistic students. Unlike conventional chatbot-driven robots, Echo-Teddy integrates verbal and non-verbal communication cues, allowing for more responsive and meaningful interactions. By implementing LLM agents, Echo-Teddy maintains conversational context, adapts to individual student needs, and makes nuanced decisions in real-time. Additionally, we prioritize cost-effectiveness by utilizing affordable hardware such as Raspberry Pi, ensuring that Echo-Teddy remains a scalable and accessible solution in educational robotics.

Our study focuses on two primary research questions:

- RQ1: What are the design principles and initial prototype characteristics of Echo-Teddy as an LLM agent-based social robot?
- RQ2: How can the initial prototype of Echo-Teddy be improved based on developer reflection-on-action and expert feedback? (Fig. 1)

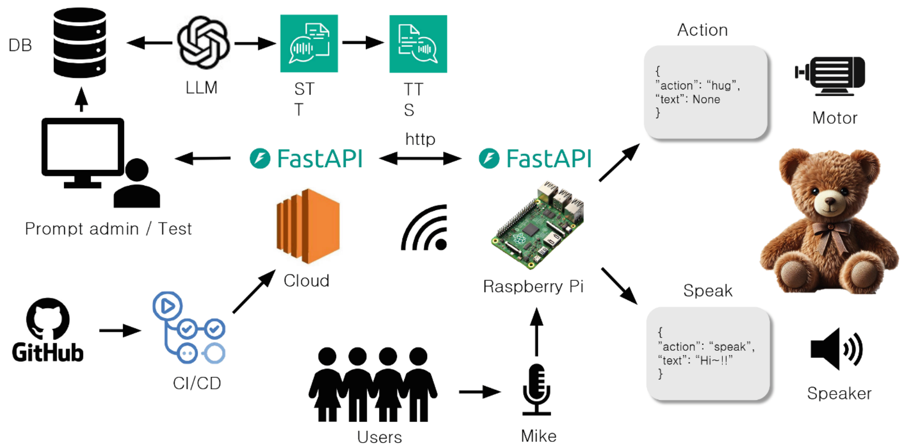

Fig. 1. System architecture of echo teddy.

2 Related Work

2.1 Social Robotics for Autistic Students

Robotics has been actively explored to support learning and social communication in autistic children, using both physical and virtual robots [29]. Socially Assistive Robotics (SAR) emphasizes aiding users through social, not physical, interaction [10,26,34]. SARs vary in form—humanoid, animal-like, and machine-like—and notable examples include KASPAR, ZENO, Probo, and ZECA. Commercial robots like Nao and Pepper have also been used in autism interventions [9,20]. However, due to limitations in existing platforms, many researchers have created custom robots for targeted interventions.

Studies report positive outcomes, such as increased eye contact, verbal communication, imitation, emotional response, and reduced stereotypical behavior [31]. Yet, most research focuses on short-term effects, with few examining long-term use in real-world contexts [8,37]. Future research should assess long-term adaptability, demographic inclusiveness, and practical scalability [29].

2.2 Large Language Model for Robotics

Large Language Models (LLMs), such as GPT-4, are increasingly integrated into robotics to enhance perception, planning, and interaction [17,40,43]. Models like RT-1, SayCan, and PaLM-E demonstrate LLM-enabled manipulation, contextual planning, and multimodal reasoning using text and visual inputs [2,5,11]. These systems generalize across tasks and environments [39,44].

Commercial applications, including humanoid robots from Figure AI and Tesla, show growing industry interest in LLM-enhanced robotics [13,36]. In education, LLMs have supported robotics learning through interactive tutoring and personalized dialogue [16,32], though direct integration into educational robotics is still nascent. This area presents significant opportunities for research into personalized, adaptive learning with intelligent robots.

3 Methodology

3.1 Research Procedure

This study followed a systematic process to design and evaluate Echo-Teddy, an LLM-based social robot for autistic students. The research progressed through three phases: literature review, prototype development, and expert evaluation.

First, a comprehensive review of studies on social interaction support and robot-assisted interventions for autistic students informed the design principles. These included context-aware dialogue using an LLM, voice-based interaction, non-verbal cues for engagement, and cost-effective hardware for scalability.

Based on these principles, a prototype was built using Raspberry Pi, integrating LLM-driven voice dialogue and basic non-verbal gestures. The system processed voice input and responded via synthesized speech, supporting multimodal interaction.

Finally, the development team conducted reflective reviews and semi-structured interviews with five special education experts. Feedback focused on response time, physical form, non-verbal behavior, and educational value. Qualitative analysis highlighted key improvements, guiding the next iteration of Echo-Teddy for better classroom integration and alignment with autistic students' needs.

3.2 Research Tools

Hardware and Software. Echo-Teddy combines hardware and software to support interactive communication for autistic students. The hardware is centered on a Raspberry Pi 5, connected to a microphone, speaker, and motor for voice input, audio output, and basic gestures. These are embedded in a soft, child-friendly teddy bear exterior, offering comfort and durability. The use of affordable, widely available components supports cost-effectiveness and scalability (see Appendix 1 for details).

The software integrates cloud-based AI services to enable real-time interaction. AWS handles Speech-to-Text, while GPT-4o-mini generates context-aware responses. For Korean Text-to-Speech, Naver Clova Voice is used. A prompt management module ensures socially appropriate, personalized interactions. The backend, built with FastAPI and hosted on AWS, ensures low-latency communication between the robot and cloud services.

Interview Questionnaire. The interview questionnaire for Echo-Teddy evaluation covered four categories: *Affordance*, *Usability*, *Instructional Design*, and *Instructional Usefulness*. *Affordance* assessed initial perceptions and understanding of the tool's functions, while *Usability* focused on satisfaction, functionality, and interactive features such as sound and movement. *Instructional Design* explored educational contexts, use scenarios, and expected learning outcomes. *Instructional Usefulness* examined effectiveness in achieving goals, learner suitability, and potential benefits. This structured approach enabled a comprehensive evaluation of Echo-Teddy's technical performance and educational value, informing future improvements to better support autistic students (Table 1).

Table 1. Interview Questions for Echo-Teddy Evaluation

Category	Aspect	Question
Affordance	Use intention	What did you think you would want to do when you first saw the tool?
	Function understanding	Explicit vs. implicit function understanding?
Usability	Satisfaction	Overall satisfaction with the tool?
	Functionality	Is the functionality appropriate?
	Design	Is the visual design appropriate?
	Sound/Voice	Is the sound/voice of the tool appropriate?
	Movement	Is the movement of the tool appropriate?
Instructional Design	Use context	Where can the tool be used?
	Alternative methods	Other ways to achieve the learning goal?
	Learning process	What is the ideal learning process with the tool?
	Behavior outcome	What behavior change should occur?
	Knowledge outcome	What key knowledge should be learned?
	Skill outcome	What skills should be learned?
	Affective outcome	What attitudes or thoughts should change?
	Information format	How should the tool present information?
Instructional Usefulness	Learning process	What should the learning process look like?
	Behavior outcome	What behavior change will occur?
	Knowledge outcome	What knowledge will be learned?
	Skill outcome	What skills will be learned?
	Affective outcome	What attitudes or thoughts will change?
	Validity	Is the tool effective in achieving goals?
	Generality	Is the tool appropriate for all learners?
	Usefulness	Does the tool have any benefits?
		- What intended benefits are there?
		- What unexpected benefits are there?
	Improvements	What needs improvement and why?

4 Result

4.1 RQ1: What Are the Design Principles and Initial Prototype Characteristics of Echo-Teddy?

Design Principles of Echo-Teddy. The design principles of Echo-Teddy focus on four key themes: *Potential User*, *Ethical Consideration*, *Customization*, and *Usage*, aiming to support the social and emotional development of autistic children. Designed as both a peer and assistant, Echo-Teddy accommodates neurodiverse traits such as gaze aversion, preference for structure, and sensory sensitivity, creating an engaging and supportive interaction experience.

Its speech and behavior follow autism support best practices, using age-appropriate language and evidence-based strategies to reinforce target behaviors while minimizing disruptive ones. The soft, non-humanoid design reduces anxiety and enhances comfort for users sensitive to realistic robotic appearances.

Ethical considerations are central, with dynamic positive reinforcement to maintain comfort and engagement. Customization allows caregivers and educators to tailor interaction styles, content, and even the robot's appearance to individual needs and goals.

Echo-Teddy is also designed for practical usability—durable, water-resistant, and capable of autonomous operation without constant adult supervision. Through neurodiverse-friendly design, ethical safeguards, adaptability, and robustness, Echo-Teddy offers a responsible and effective tool for enhancing communication skills in autistic children (Table 1).

Initial Prototype of Echo-Teddy. The hardware design of Echo-Teddy is built on a Raspberry Pi platform, chosen for its cost-effectiveness, scalability, and ability to support real-time interaction. The system efficiently transmits audio files and action commands between the Raspberry Pi and the server, ensuring low-latency communication for natural conversations. To further reduce production costs, the microphone and speaker were assembled using custom-purchased components and soldering techniques (Fig. 2). This approach allowed for greater flexibility in hardware integration while maintaining affordability for broader implementation.

During the production process, it was observed that placing the Raspberry Pi inside the plush doll led to heat buildup, which caused performance degradation. To address this, a backpack-style enclosure was designed to house the Raspberry Pi externally, allowing for better heat dissipation without compromising portability (Fig. 3). This design also improves ease of maintenance and accessibility for future hardware upgrades.

The initial prototype version integrates attached motors to enable basic movements, such as nodding, providing simple nonverbal communication cues. Currently, the range of motion is limited to head movements and facial expressions, which are displayed using a dot matrix (Fig. 4). These features are intended to enhance emotional expressiveness and engagement in interactions with users.

For connectivity, the system utilizes the built-in Wi-Fi module of the Raspberry Pi, ensuring stable access to cloud-based services. Additionally, mobile

Table 2. Design principle for Echo-Teddy.

Themes	Categories	Design Principles
Potential User	Purpose of the Robot	This robot should mainly improve the social/socio-emotional skills of autistic children by performing social communication and interaction. The robot should act like a facilitator, including peers and assistants.
	Characteristics of autistic students	The robot should be designed considering the neurodiverse characteristics of autistic children. (gaze aversion, pattern recognition, perceptual processing, and exceptional focus for particular topic).
	Output of the robot (Verbal)	Keep the utterance style and length appropriate to a child of the same age as the user. The robot should activate verbal teaching strategies to induce positive behavior and reduce interfering behaviors. The robots should be able to elicit the target verbal behavior in children with autism.
	Output of the robot (Behavioral)	The robot should activate behavioral teaching strategies to induce positive behavior and reduce interfering behaviors. The robots should be able to elicit the target behavior in children with autism.
	Appearance of the robot	The appearance of the robot should be non-humanoid.
Ethical Consideration		Avoid frustration by using positive feedback. Reflect the unique needs of the user in your speech and actions. Minimize stress sources and make the participants comfortable.
Customization	Preference of the robot	The preference of the robot should be customized by the caregiver or instructor of the user.
	Output of the robot (Verbal)	The subject of the communication should be customized.
	Output of the robot (Behavioral)	The set of behaviors to be stimulated in the child should be customized by the caregiver or the instructor.
	Appearance of the robot	The appearance of the robot should be customizable.
Usage		Consider the context of use to ensure appropriate sturdiness and prevent damage from shocks or water; the user environment must be considered. The robot should not need additional human support during use.

phone tethering is available as an alternative network solution, enabling portability across different settings, including classrooms, therapy environments, and home use. This flexible connectivity setup ensures that Echo-Teddy remains accessible and functional in diverse user environments.

The server system of Echo-Teddy integrates advanced cloud-based technologies to ensure efficient, scalable, and personalized interactions for autistic students. At its core, the system relies on OpenAI's API for dialogue generation and natural language processing, allowing for context-aware and adaptive conversational interactions. To enhance flexibility and control over language model interactions, a prompt management module has been implemented, enabling LLM administrators to easily update and manage prompt texts for fine-tuned responses.

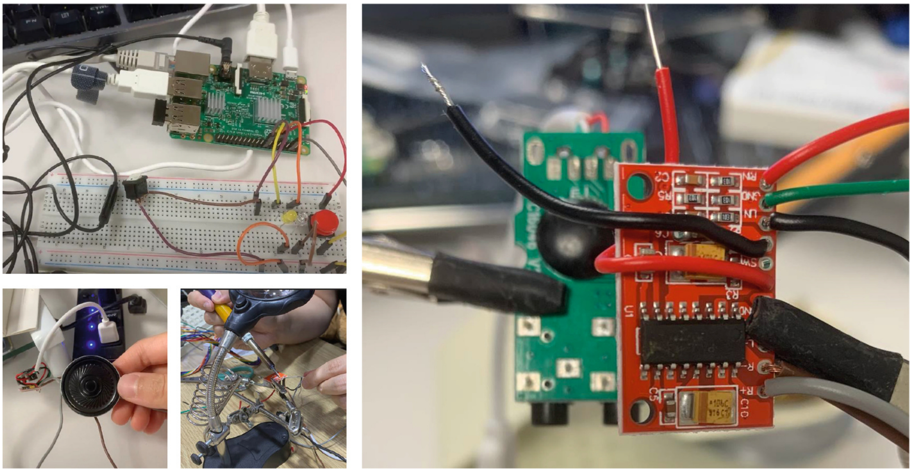

Fig. 2. To reduce costs, we purchased microphone and speaker components separately and assembled them using soldering techniques.

Fig. 3. To prevent the heat buildup, we made backpack to contain the Raspberry Pi.

For speech processing, Echo-Teddy employs AWS Transcribe for Speech-to-Text (STT) functionality, ensuring accurate and efficient transcription of user input. Text-to-Speech (TTS) is handled by both AWS Polly and Naver Clova Voice, with Naver Clova Voice specifically incorporated to support Korean-speaking users. This multi-engine approach ensures high-quality, natural speech synthesis across different languages and user preferences.

Fig. 4. We used dot matrix to express the emotions of Echo-Teddy.

The server infrastructure is built using FastAPI, following RESTful API principles, and is hosted on AWS EC2 to maintain reliable and scalable operations. To streamline development and deployment, the system integrates a CI/CD pipeline using GitHub Actions, enabling automated testing, integration, and deployment, reducing maintenance overhead and improving system stability. A key feature of the backend is its ability to transmit audio files along with structured action commands in JSON format, allowing for synchronized multimodal interactions. This ensures that Echo-Teddy's speech output is coordinated with its physical gestures, enhancing engagement and communication effectiveness.

By leveraging this comprehensive cloud-based system architecture, Echo-Teddy provides a stable, adaptive, and scalable interaction platform designed to support the diverse communication needs of autistic students. The integration of modular and configurable components further ensures that the system remains flexible and customizable, meeting the evolving demands of special education applications.

4.2 RQ2: What Improvements Can Be Made to the Initial Prototype of Echo-Teddy Based on Developer Reflection-on-Action and Interviews with Experts?

Reflection-on-Action of Developers. This section reflects on the design and implementation of the Echo-Teddy prototype, identifying key challenges and provisional solutions to inform future refinements for supporting autistic students' social and emotional development.

A primary challenge was enhancing nonverbal expressiveness. The prototype supported seven basic facial expressions, but to increase emotional nuance, adding movable eyebrows was proposed. This would allow for more dynamic, context-sensitive expressions and richer interaction.

Another improvement area was caregiver monitoring. Experts emphasized the value of tracking interaction histories to inform individualized interventions. They recommended optimizing the web interface for mobile or developing a dedicated app to facilitate easy access to communication logs.

Ensuring reliable emotional responses was also critical. Emotional feedback must be accurate and contextually appropriate to support self-awareness and empathy development. Following Rawal et al. [25], emotional outputs generated from new data should undergo continuous validation to maintain credibility.

Appearance adaptation was equally important. Ricks and Colton [27] found that autistic children often prefer non-humanoid robots. Offering customizable designs (e.g., different animals or textures) could enhance comfort and engagement based on sensory preferences.

These reflections underscore the need for future work on improving real-time expressiveness, refining caregiver tools, validating emotional outputs, and broadening customization. Such efforts will ensure Echo-Teddy evolves into a more adaptive and effective educational tool.

Results of Interview with Experts. The interview involved special education experts who evaluated the early prototype of Echo-Teddy, an LLM-based social robot for autistic students. Their insights were organized into seven key themes: *(1) response speed*, *(2) physical form*, *(3) interaction goals*, *(4) nonverbal communication*, *(5) target student characteristics*, *(6) generalizability*, and *(7) cost and scalability.*

1. Response Speed: Experts stressed that the 6–10 s delay in STT and TTS processing hindered communication, as autistic students require immediate, predictable feedback. Suggestions included upgrading to faster local hardware (e.g., Jetson Nano) or streaming audio in smaller segments for quicker synthesis.

2. Physical Form: The soft teddy bear design was generally well received for its sensory safety, but experts recommended offering modular alternatives (e.g., dinosaur shapes) to accommodate diverse preferences. Opinions were mixed on emphasizing eye contact; while visual focus cues like eye placement can help, forcing eye contact could induce stress in some students.

3. Interaction Goals: Beyond one-on-one caregiver sessions, experts encouraged designing Echo-Teddy to mediate peer interactions in inclusive classrooms. While this could promote social participation, challenges include the risk of novelty wear-off or overdependence on the robot.

4. Nonverbal Communication: Gestures like nodding, waving, and gaze shifting were recommended to model social cues. However, some behaviors (e.g., hugging) may be inappropriate or cause discomfort. Experts debated whether praise like "Good job!" should be immediate or integrated naturally into conversation flow.

5. Target Student Range: Initially targeting high-functioning autistic students was advised, but extending support to AAC users was strongly recommended. Echo-Teddy should recognize electronic voices and alternative inputs to include nonverbal communicators.

6. Generalizability and Practical Considerations: Experts warned that skills learned with robots must transfer to real-life human interactions. The robot should model core social behaviors, while caregivers reinforce them. Durability, hygiene, and reliable connectivity were also highlighted for sustainable use.

7. Cost and Scalability: Given financial constraints in special education, experts suggested an open-source model, enabling DIY customization for appearance, voice, and features to meet local needs and budget limitations.

5 Discussion

Expert interviews offered valuable guidance for refining Echo-Teddy's design to better support social communication in autistic students. Key themes included the need for real-time responsiveness, adaptable behavior, goal-oriented interaction, and scalable implementation.

First, experts emphasized that minimizing response delays is crucial. A 6–10 s lag from cloud-based STT and TTS processing can disrupt interaction and increase anxiety. Immediate, predictable feedback is essential for engagement. Prior research [6] supports that reducing latency enhances communication and reduces behavioral issues. To address this, edge computing or optimized pipelines should be explored.

Second, the robot's form and behavior must flexibly accommodate diverse sensory preferences while modeling appropriate social cues. Subtle gestures like head nods and gaze shifts can support peer interaction in inclusive settings, but overgeneralized behaviors may backfire. Experts stressed the importance of tailoring reinforcement—verbal or nonverbal—to each child's comfort and context. Personalized interaction, as highlighted by Lee and Park [23] and Cano et al. [6], enhances both engagement and learning outcomes.

Third, Echo-Teddy must support skill generalization beyond controlled environments. Transfer to real-life social interactions with peers and adults is vital. Structured progression—from guided caregiver use to peer interaction—can aid this transition [7]. For broader adoption, the robot should support AAC compatibility, stable connectivity, and durable design [30]. These factors are essential for practical use in classrooms and homes, enabling Echo-Teddy to become a scalable and effective educational tool.

6 Conclusion

Expert interviews on the Echo-Teddy prototype identified four key areas for improvement: minimizing response time and ensuring stable interaction, refining physical form and nonverbal behaviors to suit autistic children, developing adaptive interaction scenarios and reinforcement strategies, and addressing practical issues for distribution and maintenance. These insights highlight the need to extend Echo-Teddy's role beyond controlled settings into inclusive classrooms, therapy, and home environments.

Future work will focus on improving technical performance (e.g., response time, motion control, recognition), tailoring interactions to autistic students' social-emotional needs, and supporting AAC-based multimodal communication. Modular design variations will also be explored to boost user preference and engagement.

Longitudinal studies in real-world classrooms will evaluate Echo-Teddy's effectiveness in promoting peer interaction and communication skills among autistic students. Ultimately, Echo-Teddy aims to be a practical, scalable tool supporting inclusive education and everyday communication.

Appendix 1: Component Specifications

Category	Component Type	Model Name	Company Model Name	Specifications
Echo-Teddy Speaker	Sound Card	-	IN-U71CW (IN NETWORK)	USB Virtual 7.1 Channel
Echo-Teddy Speaker	Digital Amplifier Module	PAM8403	SZH-AMBO-006 (SMG)	2 x 3W
Echo-Teddy Speaker	Speaker Module	-	FQ-024 (SMG)	40 mm 8Ω 2W Magnetic Speaker
Microphone	Pin Microphone	-	P5HD (Joytron)	USB
Push Button	Push Button	-	ZAS-BU-003 (PRC)	12 × 12 mm 4-Pin, SMD Type
Dot Matrix	Dot Matrix Module	MAX7219	SZH-DMBN-002 (SMG)	8 × 8 LED Matrix
Motor	Servo Motor	-	MG995 (SMG)	Size: 40.7 × 19.7 × 42.9 mm
LED	LED	-	5BB4SC00 (DAKWANG)	5 mm LED, Red Color
Single Board Computer	Raspberry Pi	-	Raspberry Pi 5	RAM 4 GB, Quad-Core CPU

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