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# Open-Source Robotic Study Companion with Multimodal Human–Robot Interaction to Improve the Learning Experience of University Students

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**Abstract:** Remote, online learning provides opportunities for flexible, accessible, and personalised education, regardless of geographical boundaries. This study mode also promises to democratise education, making it more adaptable to individual learning styles. However, transitioning to this digital paradigm also brings challenges, including issues related to students' mental health and motivation and communication barriers. Integrating social robots into this evolving educational landscape presents an effective approach to enhancing student support and engagement. In this article, we focus on the potential of social robots in higher education, identifying a significant gap in the educational technology landscape that could be filled by open-source learning robots tailored to university students' needs. To bridge this gap, we introduce the Robotic Study Companion (RSC), a customisable, open-source social robot developed with cost-effective off-the-shelf parts. Designed to provide an interactive and multimodal learning experience, the RSC aims to enhance student engagement and success in their studies. This paper documents the development of the RSC, from establishing literature-based requirements to detailing the design process and build instructions. As an open development platform, the RSC offers a solution to current educational challenges and lays the groundwork for personalised, interactive, and affordable AI-enabled robotic companions.

**Keywords:** Robotic Study Companion; open source; social robot; natural language processing; university students; higher education; human–robot interaction; human–AI interaction

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## 1. Introduction

Education trends increasingly favour remote and online study settings [1,2], which have been praised for offering new learning venues and flexibility in location and scheduling [2–4]. Despite these advantages, numerous studies have identified issues students face in such settings, including problems with mental health, motivation, distractions, communication, and time management, as well as technical difficulties [2–7]. The COVID-19 pandemic further emphasised these challenges, underlining the profound impact of isolation on students' learning capabilities and emotional health [7–9]. Social robots as physical artificial-intelligence (AI) agents in human–AI interaction may be a promising approach to facilitating personalised learning experiences, reducing loneliness, and providing academic support.

There are many tools used to facilitate personalised interactive learning, e.g., computer and web-based programs [10–12], smartphone apps [13–15], and robots [16,17]. However, existing research indicates that students learn more and comprehend better with physical robots than with their virtual counterparts [17–20]. Social robots have proven valuable in primary and secondary education, aiding in language learning [21,22] and personalised instruction [17–19] and helping to support special-needs students [23–25]. However, their application in higher education remains largely unexplored [20]. This presents a significant opportunity, especially in university environments, where the focus on self-directed study and lecture-based learning necessitates the use of efficient and self-motivating learning strategies for academic success [20].

Studies with social robots in education predominantly utilise pre-existing robots [26], neglecting the exploration of technical features required explicitly for university students [27]. Additionally, multiple factors impede the integration of social robots into higher education, such as stock limitations due to market disruptions, privacy concerns, limited customisability, and few affordable options [26,28]. One approach to addressing these issues is to develop open-source hardware (OSHW) solutions. According to [29], OSHW projects can enhance teaching methods, foster creativity and engagement, support distance learning, and reduce costs while increasing transparency in design and manufacturing. They also provide broader applicability because they incorporate publicly modifiable solutions for individual needs [30].

Robotic companions are described as consistently helpful, interactive social robots designed to assist human users over extended periods [31]. Thus, these robots have the potential to provide educational support while offering a reassuring physical presence to students [18], especially during isolated study sessions. Robotic companions specialising in study support could aid students in reflecting on and monitoring their progress [32,33], providing feedback through insights into learning strategies and exam preparation [27,33]. They can also enable educators to effectively track student progress, identify areas requiring focus, and support struggling students [34,35].

This paper presents the open-source Robotic Study Companion (RSC), a physical desktop social robot designed for human–AI interaction with learners in higher education (Figure 1). Using cost-effective off-the-shelf components, university students can build and customise their own RSC, enabling them to adapt it to their learning styles. We summarise the contributions of our paper as follows:

- Based on the literature (Section 2), we developed requirements (Section 2.4) for an RSC tailored to the needs of university students and highlight the main design considerations based on the needs of students and educators.
- We designed and implemented the hardware and software for an RSC with multimodal human–robot interaction (Section 3).
- We have documented and released our solution as an open-source hardware project in a public repository on GitHub [36] and invite others to replicate and improve on our solution.

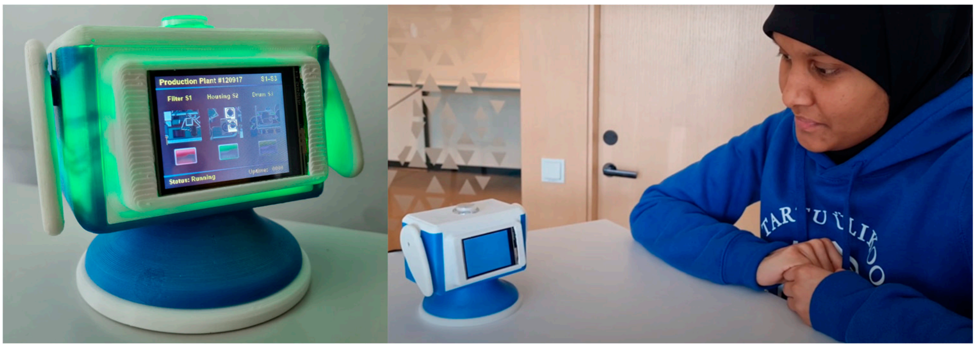

**Figure 1.** Fully assembled 3D-printed open-source Robotic Study Companion (RSC) (**left**) and a learner sitting at a desk with the RSC (**right**).

## 2. Related Works and Requirements

In recent years, social robots have emerged as promising tools for enhancing learning across various educational contexts [17,18,20–24,28,37–39]. These robots can range in design from humanoid to animal-like to abstract or biomimetic designs [26,40]. Some have been primarily researched for classroom use, with researchers focusing on improving educational quality [26,37]. Although most of the research on social robots in education focuses on children [20], studies indicate that many of these robots fail to meet the specific needs and preferences of learners in higher education [27]. The Softbank Robotics' humanoid robot Nao is often used in research and has been praised for enhancing learning experiences [37,41] but is impractically expensive for most students [42]. On the other hand, during the COVID-19 pandemic, student-designed robots like Moody Study Buddy [8] and AMIGUS [9] emerged; these models focus on providing students with emotional support and are built using off-the-shelf components. However, these robots lack features such as adaptive learning, subject-specific assistance, and collaborative learning opportunities for university students [20,27,41]. Furthermore, their development frameworks offer limited avenues for open contributions and customisation, restricting their adaptability to diverse educational needs and settings.

This section further delves into works related to social robots used in education and research, starting with teacher and student perspectives (Section 2.1) on the use of social–educational robots. We review and synthesise the design and interaction modalities of various commercially available social robots (Section 2.2) and natural language processing, along with the potential of generative AI technologies (Section 2.3), to inform the design decisions we made in creating a social Robot Study Companion (RSC). Finally, we conclude this section by formulating a set of requirements (Section 2.4) to aid in guiding the creation of a physical human–AI-interacting RSC prototype for university students.

### 2.1. Teacher & Student Perspectives

Social–educational robots [26,43] enhance learning by providing subject-specific support and serving as personal tutors. A study on German teachers' attitudes [41] showed a preference for robots as individual or small-group tutors. Teachers expect robots to improve motivation, act as information sources, assess progress, and provide support. They also sought classroom-ready robots with voice control. However, they had concerns regarding programming workload, maintenance, acquisition costs, and budget constraints. International studies [34,35,44–46] highlighted the engagement potential of social robots for all students but raised challenges in regard to equitable access, classroom disruptions, privacy, and cross-cultural adaptation.

Reich-Stiebert et al. [27] investigated 116 university students' preferences with regard to educational-robot design, interaction modes, and personality traits. Most preferred a medium-sized (~100 cm), machine-like robot in gender-neutral colours with speech as the primary interaction mode, followed by a touch screen, gestures, and touch. Key desired features included facial and emotional recognition and a display of positive emotions, while negative personality traits like pessimism were viewed unfavourably. The study emphasised the need to consider different learning environments and personal factors, such as motivation, privacy, safety, and ease of handling, in the design of these robots.

Studies indicate that personalised robot tutors enhance task performance and interaction in university settings [17], with their physical presence aiding measurable learning gains [18]. Research on university tutoring revealed that students are interested in exam-preparation assistance and exhibit a preference for more time spent in interaction [20]. These studies suggest significant potential for robot study companions with personalised features to improve learning outcomes, underscoring the role of social robots in higher education.

### 2.2. Design and Interaction Modalities of Social Robots

Jibo, launched in 2014, is a 30 cm tall, 2 kg desktop robot designed for emotional connection through voice interaction, expressive interfaces, and lifelike movements [47]. Despite its multifaceted interaction capabilities [48], Jibo's design has raised concerns about surveillance and limited portability. The company has transitioned to new ownership [49], and acquiring a Jibo remains challenging due to its inconsistent market availability and prohibitive cost. Honda Robotics introduced Haru, a robot akin to Jibo, in 2018.

Haru is a tabletop robot with a minimalist design for emotional and long-term interaction featuring a 22-centimetre base, animated eyes, and an LED display [50,51]. It excels as a multimodal communicative agent [52] but faces challenges in portability and maintainability. Like Jibo, Haru's market unavailability, reliance on proprietary components, and closed-source software limit its customisability and availability to most students, failing to alleviate the concerns of teachers and students regarding affordability and accessibility.

Moxie, a socially interactive robot companion developed by Embodied, was designed to promote social, emotional, and cognitive development in children aged 5–10 [53], particularly those on the autism spectrum [19]. While its endearing design and portability make it appealing, Moxie's high cost, privacy concerns due to built-in cameras and microphones [54], and lack of customizability limit its suitability for use in higher education. Moxie is accompanied by a companion app that provides parents with insights into their child's interactions with the robot; however, its availability is limited to certain countries, which further impedes its global accessibility.

Robots like Anki's Cozmo (released in 2016) and Vector (released in 2018) effectively promote engagement and collaboration in educational contexts with their animated, expressive features [23,55]. However, despite their cute and engaging design and affordability, these closed-source robots are also no longer sold. In contrast, the open-source ElectronBot enables a hands-on approach to building a desktop companion robot using DIY 3D printing [56], providing a more accessible option for students. While it addresses the accessibility concern, it lacks the sophistication and advanced features desired by university students for their educational needs.

The DIY desktop robot Mira [57,58], modelled after 'Pia the robot' [58], and Eilik [59] explore diverse physical forms and interaction modalities for affective (emotional) communication and interactions. Additionally, ElliQ, a robot companion designed to aid older adults in various activities to support their well-being, has achieved commercial success but is primarily tailored for use by older adults [60,61]. These affordable, entertaining desktop social robots offer valuable insights into interactive social human–robot interaction (HRI) [62]. However, their focus on entertainment may limit their suitability for educational purposes, as they lack the features and functionalities necessary for effective subject-specific support and personal tutoring.

Many of the commercial robot platforms listed above [19,49,51,59,61,63] often have limited manufacturing cycles, making them less accessible in the long term. Additionally, many of these platforms [54] are cost-prohibitive and offer limited customisability, even though customisability is essential for meeting the diverse needs of university academic settings [27]. These challenges highlight the need for a new, affordable, open-source platform targeting this demographic.

### *2.3. NLP & GenAI Technologies*

The advancement of Natural Language Processing (NLP) has been pivotal in fostering speech-based human–robot interactions, the most common modality in social robots [26,64]. NLP technologies such as Conversational Intelligent Tutoring Systems (C-ITS) offer tailored instruction and have demonstrated their versatility in various educational domains, including algebra tutoring [65], Scratch programming [66], and serving as an AI-assisted tutor [67]. However, these technologies are intangible and lack the engagement of a physical robot [18,19]. The Google AIY Voice Kit [68] was a notable attempt to combine hardware assembly with voice-enabled applications [69]. However, as of January 2023, this AIY project is now archived and no longer supported for further development.

Generative AI (GenAI) expands on traditional NLP systems by enabling robots and machines to generate coherent, contextually appropriate responses. This advancement empowers not only chatbots, virtual assistants, and conversational agents, but also conversational agents within physical robots, facilitating more natural human–AI interaction.

The deployment of large pre-trained language models such as Generative Pre-trained Transformers (GPT) [70] demonstrates significant potential in facilitating rapid prototyping for physical robot applications [71–74]. This emerging application allows for the integration of APIs like GPT-3 [70,75] into the Robot Study Companion (RSC), transforming it into a personalised physical AI robot capable of enhanced interactions.

### 2.4. Requirements for the RSC

Designing social robots is an involved, multifaceted process spanning physical and functional considerations, brought to life with software. To guide the design, features, and personality of an RSC for university students, we formulated the following requirements (Table 1) based on the literature outlined above. We observe that to establish effective human–AI interaction, the RSC should feature multimodal communication (Req 1 in Table 1) and a portable and customizable design (Req 2), in addition to being readily available (Req 3). These requirements will enable interactive conversation and learning support (Req 4), aligning with the principal role of an RSC, which is to assist and monitor studies, facilitating personalised learning experiences [17,20,33]. Finally, the RSC should be reliable and secure (Req 5, 6).

**Table 1.** Literature-Derived Requirements for Robot Study Companions.

| ID | Requirement | Rationale |
|---|---|---|
| Req 1 | The RSC shall support multimodal Social Interaction. | To ensure diverse, context-aware social interactions and support positive academic results, the RSC should facilitate multimodal communication, primarily through speech [26,27], with additional support for touch, gestures, and visual cues [27]. |
| Req 2 | The Design of the RSC will be User-Centred. | The design of the RSC should be compact and aesthetically pleasing, with a size range between 6 cm and 30 cm. It should feature neutral colours and curves to enhance portability, visual appeal, and ease of handling [41], with a machine-like aesthetic [27,76].<br>The RSC should be accessible, user-friendly, offering adjustable settings and clear, engaging conversations, aiming to improve social interaction and user satisfaction in various study settings (such as individuals or small groups) [20,41], providing support for learners in diverse educational contexts [37].<br>The RSC should support and promote the customisation of peripherals, extending available interaction modalities to accommodate various learning styles and user preferences. This flexibility may address university student preferences [27] regarding personalisation options, which may improve learning outcomes [20]. |
| Req 3 | The RSC should be Obtainable. | The RSC's software, hardware, and documentation should be open-source, and the hardware should be made with readily available parts that are not cost-prohibitive [29,30,41]. |
| Req 4 | The RSC should provide Adaptable Learning Support. | The RSC should analyse student performance, adjust responses based on learning styles, recommend customised study plans, and apply gamification to boost motivation. This approach may enhance engagement and support individual learning needs in diverse educational contexts [17,20,33,37,41].<br>The RSC should personalise learning in line with students' and teachers' perspectives [17,20,27,41]. The RSC should support a variety of subjects or courses to provide host academic institutions curricula or programs [20,43]. |
| Req 5 | The RSC should be Reliable. | The RSC should be performant, delivering high interaction quality by enabling low latency replies to user queries. The RSC should reduce frustration [20,27] with a responsive, robust interface and support long system uptimes without interruptions.<br>The RSC should require minimal specialised expertise to maintain and should feature up-to-date documentation. A low-upkeep approach enhances the user experience and ensures a reliable system [20,33,41]. |
| Req 6 | The RSC must be Secure. | The RSC must safeguard user privacy and confidentiality [27,44].<br>Peer-reviewed threat models and associated security updates should maintain continuous security monitoring with regular updates. |

In summary, the RSC should have a compact, visually appealing design and interact with users through speech while offering additional interaction modalities. It should engage in interactive conversations, support learning, and adapt to individual student needs. Finally, the RSC should be user-friendly, secure, and reliable. In this paper, we document the prototype development of the RSC as a new open-source desktop social robot study companion platform.

## 3. Design and Implementation

The Robotic Study Companion (RSC) presented in this article is an affordable, open-source desktop robot (Table 2; Figure 2) designed primarily to serve as a social and physical AI agent to support learning for university students. Featuring a sleek and friendly design, the RSC is made from off-the-shelf components, supporting reconfigurability and balancing cost and performance. All the custom mechanical components are 3D-printed to ensure scalability, availability, and further customisation of the platform. The RSC aims to enrich learning experiences by facilitating multimodal human–AI interaction including visual, auditory, and tactile communication cues (Table 3). It employs three main feedback modes—light, motion, and sound—to provide subtle, intuitive, and informative cues. This multimodal approach offers diverse ways for users to engage, with the option of activating modalities based on preference, enhancing the study sessions and interactions.

**Table 2.** Overview of open-source RSC hardware specifications.

| Hardware Name | RSC—Robot Study Companion |
|---|---|
| Subject area | Educational tools and open-source alternatives to existing infrastructure |
| Open-source license | CERN-OHL-S-2.0 |
| OSHWA certification | EE000003 * |
| Cost of hardware | ~€240 |
| Project repository | https://github.com/RobotStudyCompanion/RSC2023 (accessed on 25 May 2024) |
| Source files | https://doi.org/10.5281/zenodo.11962698 (accessed on 18 June 2024) |

* https://certification.oshwa.org/ee000003.html (accessed on 25 May 2024).

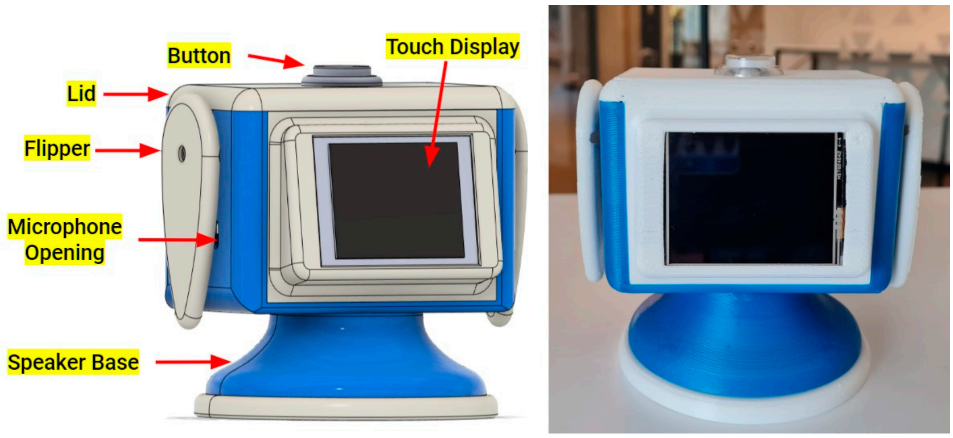


**Figure 2.** Computer-Aided Design (CAD) model (**left**) and fully assembled 3D-printed RSC (**right**). Existing desktop robot-companion solutions (discussed in Section 2.2) inspired the RSC's design. As a result, the RSC's small form-factor tabletop solution features curved edges, circular shapes, and outward shells that are neutral in colour [76]. It houses the speaker within the base and secures the remaining peripherals within its rectangular body.

**Table 3.** Overview of social-interaction modalities.

| Interaction | Description |
|---|---|
| Speech | Employing a speaker and microphones to recognise and respond to audio queries. The RSC uses Speech-to-Text (STT) software to capture user speech and Text-to-Speech (TTS), with a language model generating responses. |
| Gesture | The RSC can communicate using gestures by rotating the flippers, expressing responsiveness. This indicates the RSC is ready to engage; for example, it may greet the student with a waving gesture. |
| Tactile | The top-mounted arcade button provides a direct touch interaction. Pressing it can, for example, start a conversation, which may foster a sense of privacy. |
| Touchscreen | The RSC includes a touch display for adjusting settings and showing information. |
| Light | An RBG LED ring maps colours to device states such as loading, conversing, or an error state. |
| Sound | Audio cues convey internal device states by providing an audible speaker and microphone test. |

To continuously develop the RSC, we adopt the Design Science Research Method [77] to systematically create a purposeful artefact to meet the outlined challenges. We document insights gained throughout the design process in an approach akin to the design thinking model [51], which emphasises rapid design iterations and building on the understanding gained with each implementation. We rely on previous studies and discussions (Section 2) to inform the prototype's creation, aiming to benefit the open-source community and enable future refinements.

### 3.1. Design

This section highlights the design process, files, and features. The mechanical design of the RSC helped bring to life the required features, particularly those relating to verbal and non-verbal social interaction (Table 3). Given the compactness and multimodal-interaction requirements (Req 1), the main challenge was packing several components into a confined space, keeping them protected, and enabling tool-free maintenance access. The RSC (Figure 2) adopts an hourglass-like shape, which sits comfortably in the hand (Req 2). We employed snap-fit assembly to house the internals with the construction parts (Tables 4 and 5).

**Table 4.** Design-file summary; more information in the project's GitHub repository [36].

| Construction Part | File Name | File Format |
|---|---|---|
| Rear panel | back_panel | STEP, 3MF, F3Z |
| Flipper | rsc_flipper | STEP, 3MF, F3Z |
| Front panel | LCD_panel | STEP, 3MF, F3Z |
| Lid | button_neopx_panel | STEP, 3MF, F3Z |
| Pi bracket | Pi_bracket_panel | STEP, 3MF, F3Z |
| Speaker base | speaker_base | STEP, 3MF, F3Z |

The top lid (white) features an arcade button and snaps into place (Figure 3), locking the front and back panels. The front panel, featuring a small screw-mounted touch display, slides into place with the help of guide grooves embedded in the main body (blue, Pi bracket). Similarly, the rear panel, with openings for power-supply connectors, also slides into place using these grooves. On either side of the main (blue) body are two small, flat, conical servo-mounted flippers (white). The servos rotating the flippers are press-fit into the main body. At the base of the RSC is a screw-attached bell shape (blue speaker base) hiding an embedded bottom-firing speaker and ending with a round anti-slip padding detail (white).

**Table 5.** Bill of materials for the RSC.

| Component | Description | Cost [EUR] |
|---|---|---|
| USB-C Power Supply | 15 W 5.1 V USB-C power supply | 10 |
| Raspberry Pi 4B 4 GB | Quad-core CPU compute SBC. All-round I/O options. | 55 |
| AIY Voice Kit *<br>AIY Voice Bonnet v2 HAT<br>Arcade Button<br>Speaker | Microphone: SPH1642HT5H-1<br>Supports far-field voice recognition and extends RPi GPIO I/O.<br>LED Button provides user-friendly interaction.<br>NH 4ohm 3 W 76 mm<br>Connects to the AIY Voice Bonnet. | 60 * |
| Micro SD Card | Capacity: 32 GB<br>UHS Speed Class: 3, Video Speed Class: V30<br>Application Speed Class: A1, Speed Class: Class 10 | 9 |
| 2x SG90 Servo | Basic flipper movement.<br>Connected to the voice bonnet via GPIO pins. | 16 |
| NeoPixel Ring<br>16 × 5050 RGB LED | Features 16 individually addressable LEDs.<br>Offers aesthetic illumination, visual indication, and mood lighting.<br>Connected to RPi and controlled with PWM. | 10 |
| Touch Display | Nextion Enhanced NX3224T024 2.4″ HMI 320 × 240 Touch Display<br>Equipped with a microcontroller and internal memory.<br>Enhances touch modality and displays menus.<br>Connects to RPi, controlled via UART. | 53 |
| Logic Level Shifter | 4-Channel, Bidirectional; translates voltage logic level signals: 5 V (peripherals) to 3.3 V (RPi). Allows RPi to communicate with peripherals. | 3 |
| 3D Printing Filament | White & Blue PLA and White TPU | 20 |

* AIY Voice Kit includes the AIY Voice Bonnet HAT v2, arcade button, and speaker.

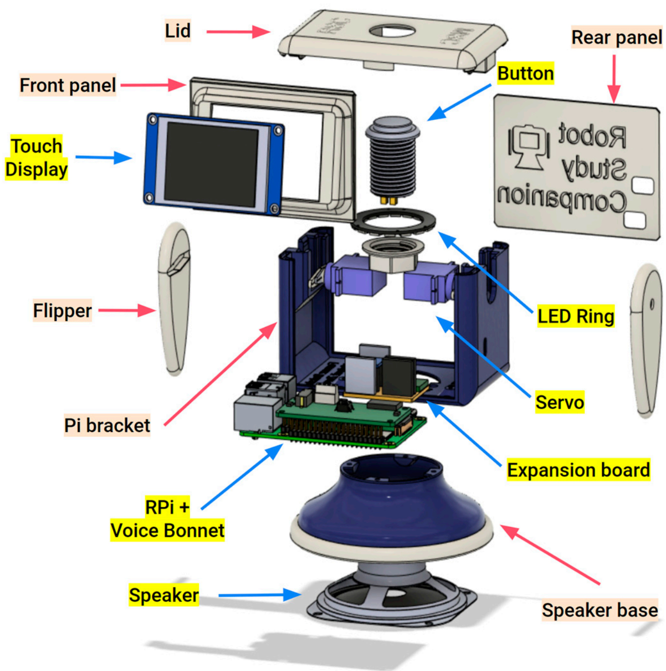


**Figure 3.** Exploded assembly view of the RSC. Components are denoted by yellow highlights and blue arrows, while 3D-printed construction parts are indicated by orange highlights and red arrows. More information on the assembly can be found on the project's GitHub page [36].

The RSC's design overall prioritises a cost-effective, portable solution at ~11 cm high and a weight of ~375 g. Our RSC prototype-development process (Figure 4) helped establish the size, shape, and peripheral placement. The Pi bracket houses bespoke slots that fit servos to actuate the flippers and features openings for both microphones (Figures 2 and 3). In addition to the arcade button, the lid houses an LED ring. We chose a blue-and-white colour palette to give the device a friendly appearance [76], using white and blue polylactic acid (PLA) 3D-printing filament. The base is printed out of white thermoplastic polyurethane (TPU) filament, which improves grip and stability on desktop surfaces.

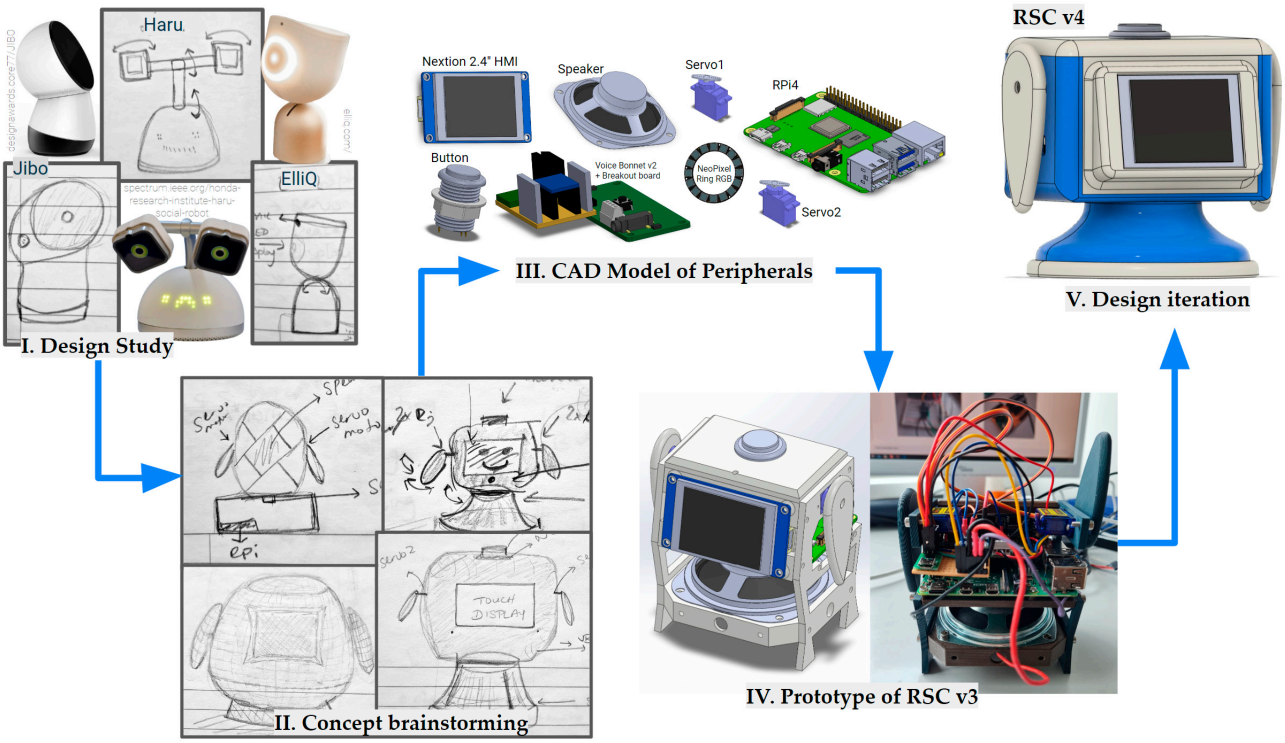


**Figure 4.** Process of design thinking and rapid prototyping development. The progression involves (I.) conducting a design study to investigate features of existing social robots, a step that is followed by (II.) brainstorming and concept sketching. Subsequently, (III.) component modelling is carried out in CAD-enabled layout exploration. The initial prototype design was an open-enclosure test assembly to secure all components (IV.). This test assembly helped document additional design insights. The RSC was ready for further development after identified issues had been addressed and additional features incorporated (V.).

All CAD files for this design are available in the MechDesign repository in our replication package [78] with ready-to-print files and assembly instructions.

### 3.2. Bill of Materials

The Bill of Materials (BOM; Table 5) lists all main components needed to reproduce the RSC, including component names with quantities, descriptions, and associated costs (in EUR). The RSC costs amount to ~240EUR at the time of writing. An extended, up-to-date BOM can be found in the project's repository [36].

### 3.3. Electronics

This section outlines component integration and peripheral communication protocols. To meet the requirements for multimodal, responsive interaction (Req 1), the RSC must be able to hear and playback audio, which is why we chose the AIY Voice Bonnet v2 [68,79]. It features a button connector, a dual speaker terminal, integrated left and right microphones, headers to connect servo motors and serial devices, and documentation with examples of use [80]. The Voice Bonnet's drivers also come pre-packaged with a ready-to-use operating system image [81]. We used a Raspberry Pi single-board computer because it was turnkey and compatible with the AIY Voice Bonnet and drivers. Specifically, we used model 4B with 8 GB RAM [82] (state-of-the-art at the time of development), as it provides shorter compilation times than did previous-generation models.

We integrated several peripheral devices (Figure 5) to meet RSC requirements, using a custom expansion board to power the connected devices (Figures 6 and 7). This board includes a logic-level shifter circuit, ensuring communication with peripherals operating at different voltage levels.

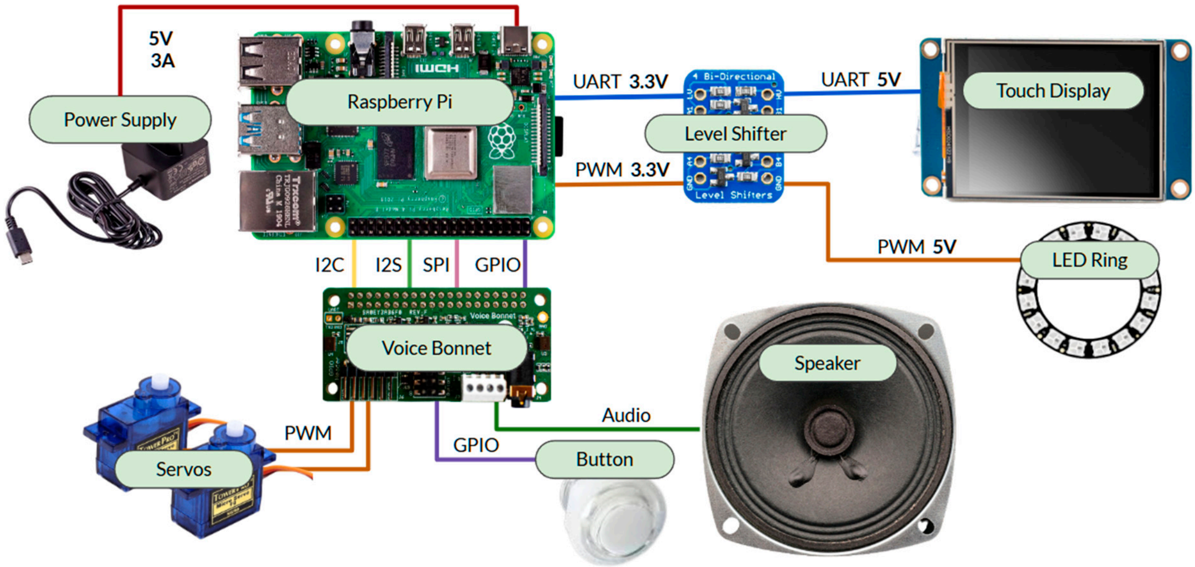


**Figure 5.** Simplified system-communication diagram.

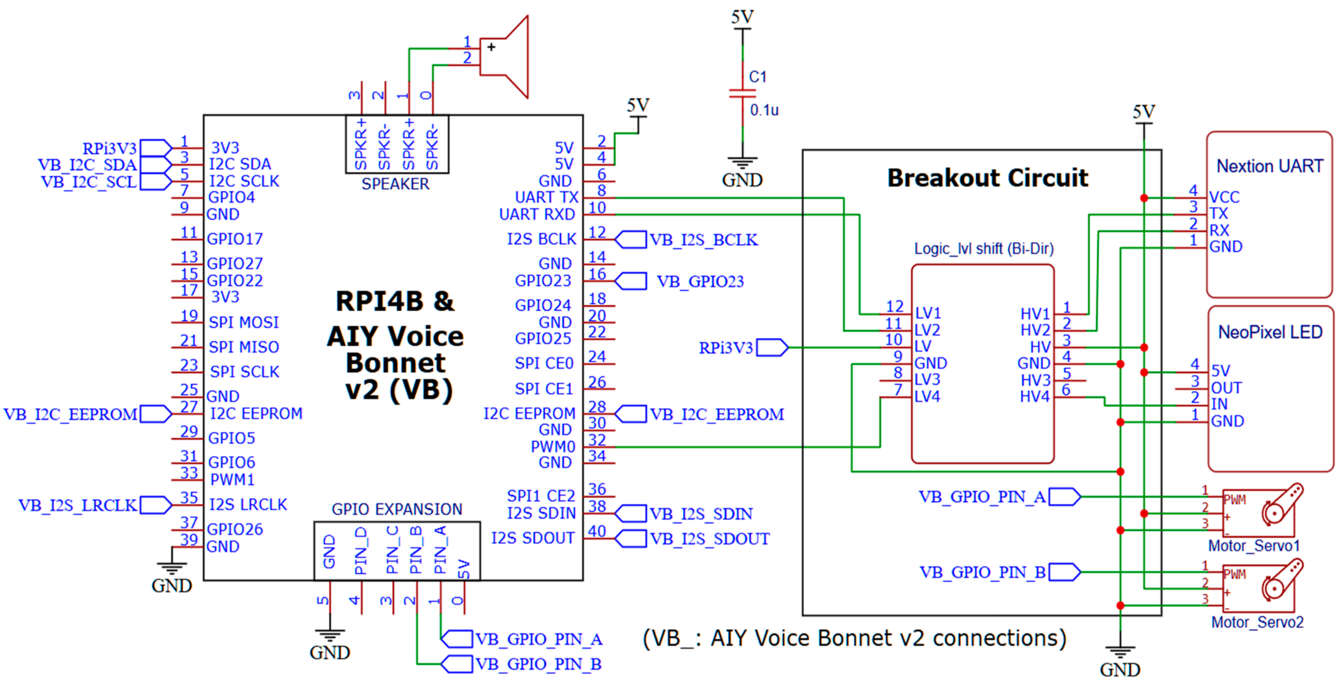


**Figure 6.** RSC Electronics schematic.

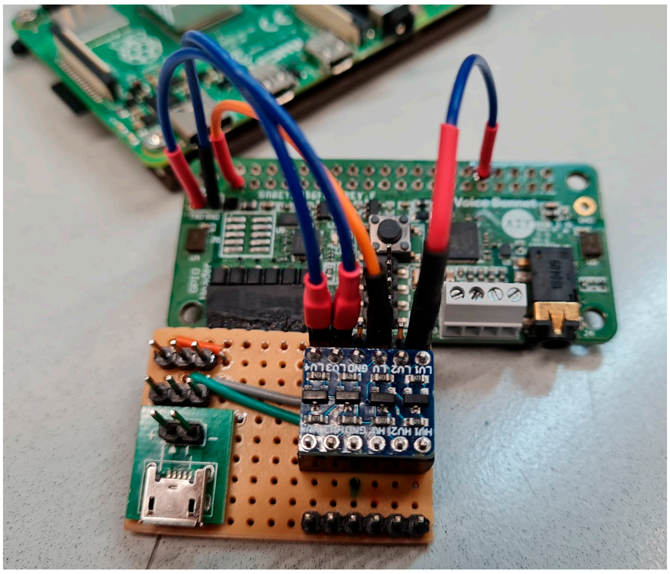

**Figure 7.** Custom expansion board installed in the AIY Voice Bonnet extension header. Depicted on the brown protoboard to the right is a bidirectional logic level shifter (blue). To the left of the protoboard is a USB power-supply connector and two servo pin headers.

The HMI Nextion touch display [83] talks with the RPi using the universal asynchronous receiver transmitter (UART) protocol. It is connected through the expansion board headers and requires logic-level conversion (3.3 V to 5 V). The RGB NeoPixel LED ring [84], connected through the expansion board, also requires logic-level conversion for reliable pulse-width-modulated (PWM) communication. On the other hand, the servo motors [85] work with the 3.3 V level PWM signal from the RPi, routed through the Voice Bonnet to the expansion board, where they connect and receive 5 V power. Finally, the arcade button connects to a dedicated general-purpose input–output (GPIO) header on the Voice Bonnet [79].

This schematic (Figure 6) outlines the connections and layout for a Raspberry Pi 4B integrated with an AIY Voice Bonnet v2, detailing the connectivity for multiple peripherals. It shows direct speaker connections, the expansion board (Figure 7) with a logic level shifter [86] for interfacing between the Raspberry Pi and the Nextion UART touch display and NeoPixel LED at different voltage levels, and two servos controlled via PWM.

Additional files are available in the ElectroCircuits folder of the repository [36,78].

### 3.4. Software Architecture

This section describes the software architecture and libraries in the development process. While the voice bonnet connects the peripherals, the RPi handles the processing. The AIY Voice kit [68] ships with a Debian/Raspbian-based system image [87] and a Python library [79] for working with the Voice Bonnet and connected peripherals. Preparing the RSC prototype involved integrating various components and software libraries to enable its functionality and provide seamless user interaction.

To provide coherent, context-aware text responses that enable engaging, interactive conversations, we selected OpenAI's text_davinci003, a variant of the Generative Pre-trained Transformer (GPT) model [88]. OpenAI's official Python library (v0.27.4) [89] provided a convenient, user-friendly interface for their NLP API.

The RSC, in its current state, engages users using a demo interaction loop (Figure 8) that was written in Python v3.7.3 [90] using compatible speech and language-processing libraries. Multiple speech-processing libraries enable automatic speech-to-text (STT) and text-to-speech (TTS) transcription. 'PyAudio' v0.2.11 [91] helps the RSC listen and speak by accessing the microphones (record audio) and speaker (play audio). The 'SpeechRecognition' library v3.9.0 [92] allows the RSC to interpret spoken user inputs by transcribing spoken language (audio) into written text. The 'pyttsx3' library v2.90 [93] enables the RSC to respond to responses by converting text to speech (audio).

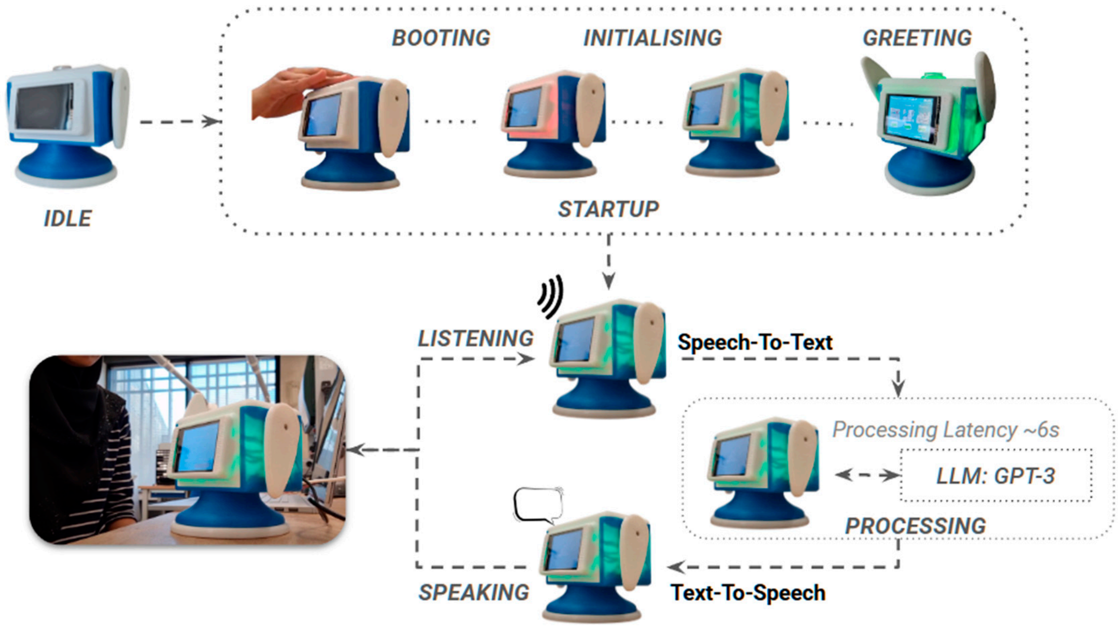


**Figure 8.** Interaction–state loop diagram. After the loop starts, a brief setup phase commences. Once it is ready for user input (question), the RSC listens, transcribes spoken words into text, and sends the question to OpenAI for processing. The RSC then 'speaks' the response from the API to the user.

In addition to audio-related libraries, the RSC also features additional peripherals and their libraries (Figure 9). The 'adafruit-circuitpython-neopixel' library version 6.3.8 [94] integrates and controls the NeoPixel RGB LED ring. It provides an interface for managing the colour and brightness of the 16 individually addressable NeoPixel LEDs on the ring. This level of customizability allows for dynamic lighting effects, contributing to the interactive experience.

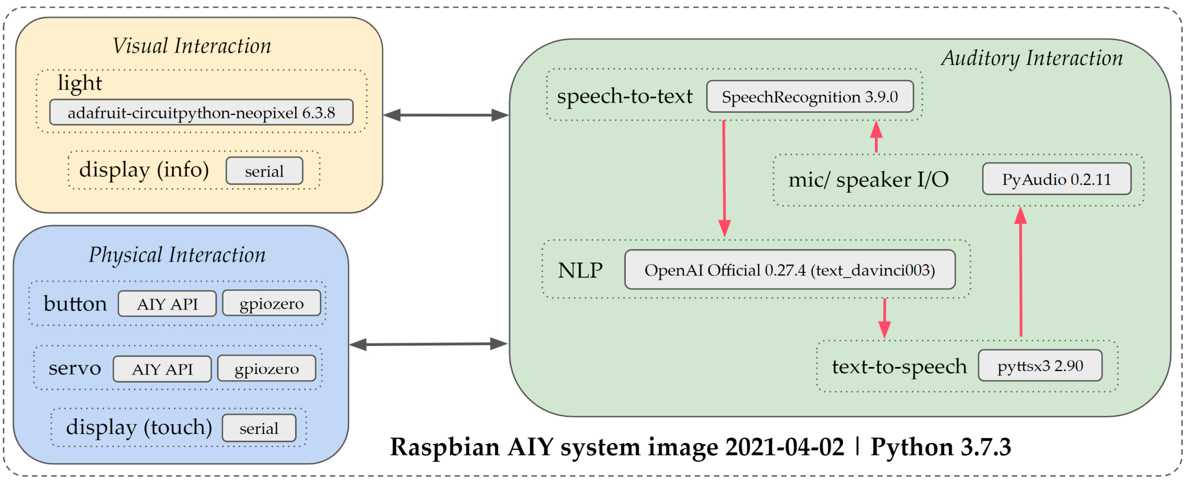


**Figure 9.** HRI block diagram and library flow. Auditory interaction (green, **right**) incorporates preinstalled libraries: AIY (enabling Voice Bonnet I/O access), pyttsx3 (text-to-speech), and pyaudio (audio input/output). We installed OpenAI and SpeechRecognition to facilitate comprehensive auditory interaction. To accommodate physical (blue, **bottom left**) and visual (yellow, **top left**) interactions, we installed the CircuitPy and Adafruit-NeoPixel libraries. Both physical and visual interaction are governed by auditory interaction (NLP).

The 'AIY Voice Bonnet' library [79,87], in addition to providing access to the speaker and microphones, also provides access to servos and buttons connected to the Voice Bonnet. We aimed to establish a basic interactive and functional baseline for the RSC that can be continuously improved and expanded on in an open-source community. The class diagram (Figure 10) illustrates how all the peripherals communicate with their qualities (attributes) and data operations (methods).

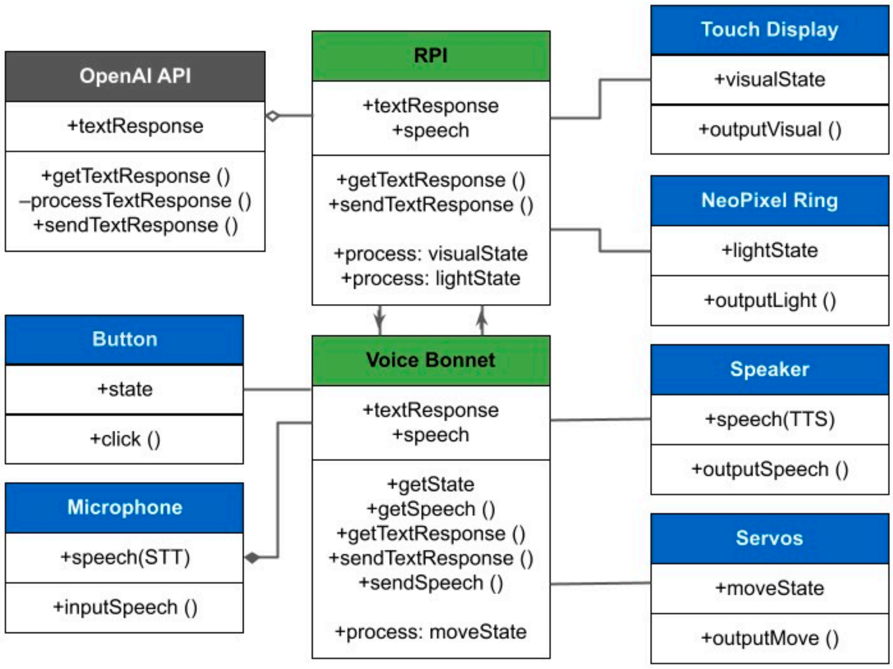


**Figure 10.** Class diagram illustrating all the peripherals of the RSC, including various objects, their attributes, and data operations.

The visibility of an attribute or method sets the accessibility for that attribute or method: a private (−) method cannot be accessed by another class, whereas another class can access a public (+) method. The lines represent the relationship between objects and classes. The empty diamond terminator denotes that OpenAI API operates independently of the RPi because the computation is offloaded to the OpenAI services. Meanwhile, the filled diamond terminator shows that audio input via the microphone depends on the Voice Bonnet.

All code files can be found in the CodeStation folder of the repository [36,78].

## 4. Results and Discussion

This section discusses the ongoing work on the RSC prototype, documents its limitations, and assesses how well it meets our established requirements.

### 4.1. Requirements Analysis

Research indicates that university students can improve their comprehension and learning outcomes by interacting with physical robots rather than virtual human–AI interaction counterparts, especially when these robots feature practical, machine-like designs that are easy to handle and minimise learning interruptions [17–20,27,41]. Building on these and other insights, we derived a set of requirements (Table 1) from related works (Section 2) to guide the development of a Robotic Study Companion (RSC). Table 6 provides an overview of the outcomes of this development process and the extent to which the RSC meets the requirements described in Table 1.

**Table 6.** Analysis of the RSC prototype with respect to requirements.

| ID | Requirement | Review of Outcomes |
|---|---|---|
| Req 1 | The RSC shall support multimodal Social Interaction. | The RSC combines electronics and software to enable multimodal social interaction (Table 3, video demo [95]). The prototype can listen and reply to student voice commands using the AIY voice bonnet microphones and speaker. It can interpret and respond to commands using the open-source, permissively licensed Python speech-recognition library and the OpenAI GPT-3 remote API (deprecated as of January 2024).<br>The NeoPixel LED ring provides visual cues like status updates, and the arcade button offers basic tactile interaction. Meanwhile, the touch display shows runtime information and displays a convenient settings menu. Finally, the servos enable simple gestures, such as 'waving hello' during startup. These integrated technologies enable diverse interactions for students with different learning styles. |
| Req 2 | The Design of the RSC will be User-Centred. | The RSC's rapid prototype development (Figures 2 and 4) took inspiration from existing solutions (Section 2.2). At ~11 cm in height and weighing ~350 g, the RSC is portable. It features a compact, easy-to-handle hourglass-shaped design suitable for transportation in a student's backpack. Inspired by university students' preference for abstract and machine-like aesthetics, the RSC prototype also features a blue-and-white colour palette for a friendlier appearance.<br>Moreover, as the case is 3D-printed, students can further personalise their RSC by choosing their preferred neutral colour combinations. Employing snap-fit construction, the RSC, by design, simplifies assembly and helps to facilitate modifications, including, for example, adding sensors, motors, or a different display.<br>We envision this flexibility, combined with the permissive open-source license, may empower, support, and encourage students to personalise and adapt their RSC to their specific learning environments and user preferences. |
| Req 3 | The RSC should be Obtainable. | Our Bill of Materials (Table 5) uses off-the-shelf components costing ~240 EUR. The RSC is more affordable to a broader audience than existing desktop social robot companions.<br>With the permissive, open-source license, we promote transparent global accessibility, and all files for building the RSC are available on the project's GitHub [36,78]. We focus on personalisation and customisation to enhance support for new components, improve market access, and increase user adoption. |
| Req 4 | The RSC should provide Adaptable Learning Support. | The presented prototype engages users in a conversation with OpenAI's GPT-3 API, which was considered state of the art at the time of prototyping during spring 2023 and deprecated in January 2024. The prototype does not analyse student performance, adjust responses based on individual learning styles, or offer customised study plans. |
| Req 5 | The RSC should be Reliable. | While it was designed for maintenance with low tool-use requirements to simplify upkeep and make it relatively easy to maintain, the prototype's development must advance in several areas to address reliability issues. For example, a noticeable response latency adversely affects the interaction quality. Furthermore, while the prototypes feature many modalities for human–AI interaction, they need further integration to deliver a seamless, responsive, robust, and positive user experience. All features need comprehensive and up-to-date documentation for further development and user maintenance. Finally, the prototype must support long, uninterrupted system uptimes, a crucial reliability aspect. |
| Req 6 | The RSC must be Secure. | The RSC has a physical button that users can press when they want to start a chat. This feature may help address privacy concerns by ensuring no unwanted surveillance or recording occurs. Alternatively, users could opt for a keyword-spotting algorithm instead.<br>The absence of a camera in the design is another deliberate design decision to safeguard user privacy by avoiding any visual data collection that could compromise confidentiality.<br>The use of OpenAI's GPT-3 API to generate responses means that conversations are stored not locally but remotely, meaning the third party can retain potentially sensitive information. Instead, hosting local LLM inferences in future implementations will enhance user privacy. |

The prototype RSC we designed and implemented features a student-centric design and incorporates remote large language model (LLM) services packaged in a visually appealing manner that supports interactive conversations. However, the RSC still needs to deliver a fully personalised learning experience. Videos demonstrating the prototype RSC in action can be found in the Supplementary Materials [95].

The RSC prototype developed in this study successfully implements several user-centred design elements derived from our background literature review (Section 2). However, while the prototype has made significant strides in design, affordability, and open-source availability, there remain challenges in achieving optimal performance, learning support, and reliability, indicating substantial opportunities for continued development.

As an open-source project, the RSC offers global accessibility and the potential for significant market impact without traditional barriers, such as cost or market availability. Teachers' expectations (Section 2.1) were met because the prototypes improve motivation, act as information sources, and are classroom-ready robots with voice control. The multimodal, portable, and modular design was created to empower students, giving them greater autonomy by serving as a study support robot. The RSC distinguishes itself from other existing social robot companions (Section 2.2) by using readily available components to create an open development platform. It can support isolated study sessions where motivation is critical and provide a more engaging and interactive physical presence compared to conventional screen-based methods. This enhances the potential for reflective engagement and supports a richer variety of interaction modes, delivering additional value in educational settings.

### 4.2. Preliminary User Evaluation

Formally assessing the various educational use cases of the RSC is one plan for ongoing work. However, we conducted an informal survey to gather preliminary user impressions during a two-hour student design competition event held in May 2023 at the University of Tartu. We displayed the prototype RSC, and eight ($N$ = 8) students shared their feedback using a Google form after briefly interacting with the prototype (max 5 min). Overall, the feedback was positive, with many supportive comments; for example, students said, "I liked the prototype and I would like to see its further development" and "Very promising prototype with some unfortunate glitches".

Initial comments touching on the aesthetic included descriptions such as "tiny", "cute", "small robot tutor", "geeky", and "interesting". Participants also ranked their preferred interaction modes, with speech and touch as top priorities, followed by gestures, with web/text/chat-based in last place. Their main concerns were privacy and affordability, in line with requirements (Req 3, 6). Participants suggested improving the RSC with remarks such as "make it portable by adding batteries and [add] touch sensors for more interaction" and "use better voice generator [for] more input and output options". One participant shared their screen preference: "I would love to see a bigger screen on it . . .", while another noted they would prefer a more compact, flipper-free design: "I actually don't think the arms are necessary, and it could be made more compact without them".

As we continue to develop the RSC, we are conducting ongoing cross-cultural user evaluations at partner universities to validate the use cases of the RSC. The successful integration and utility of the Robot Study Companion (RSC) hinge on its acceptance and usability, which require comprehensive evaluation through user studies, planned as part of our future research. In designing the RSC, we adhered to the Technology Acceptance Model (TAM) principles [96,97], focusing on perceived ease of use and usefulness—key factors for user adoption. Although empirical validation of the RSC's acceptance and effectiveness is pending, we expect these design considerations to promote platform adoption among university students. We foresee the RSC's utilisation in university settings in individual and group exam-study sessions, in laboratories to store and communicate information, and as a motivational reminder for students during study sessions.

### 4.3. Limitations & Future Work

While developing the RSC prototype, we encountered several limitations that influenced the final prototype and identified areas for future exploration and refinement. These limitations encompassed various domains, including technical constraints, software challenges, and the absence of extensive user evaluations. Regardless, each limitation reveals a unique set of difficulties and learning opportunities.

The prototype's electronic system faces several power-supply challenges. Notably, the absence of an integrated battery restricts the device's portability to areas with power outlets. We initially estimated the peak power draw of all devices could exceed 15W. During development, we included a USB connector to attach a second power supply in case this became a recurring issue. We do not recommend using two separate power supplies due to the risk of ground loops, voltage-level variances and uneven load distribution. An alternative solution for this scenario is to use a higher-rated power supply.

Relying on a custom expansion board means users aiming to build their own RSC must understand the electronics and how to use specialised tools, complicating basic setup and maintenance. Additionally, the wiring in the prototype's internals is highly disorganised (see ElectroCircuits [36]), causing excessive crosstalk and interference. Meanwhile, the end-of-life status of the Voice Bonnet v2 without OEM (Original Equipment Manufacturer) support limits future scalability and hinders maintenance options. Finally, the servos we used produce power-line noise when active due to insufficient power-line filtering, impacting overall system reliability.

Mechanically, the servos emit loud noises due to insufficient sound-dampening measures. We could mitigate this issue by switching to higher-quality servos or alternate motor types, like small brushless direct-current gimbal motors. At the same time, the single degree of freedom of both flippers limits the prototype's expressive motion gestures. Adding encoder-based odometry and perhaps a more sophisticated shoulder joint with more degrees of freedom could substantially enrich the prototype's functionality and expressiveness. Finally, we observed durability concerns with regard to the LCD panel and the lid-panel locking mechanism, which typically lasts ~100 cycles in regular use. These issues indicate a need for design improvements to enhance longevity and the user experience.

One of the significant technical constraints involved optimising the accuracy and reliability of the open-source speech-to-text and text-to-speech systems, particularly concerning handling diverse accents and dialects and ensuring their integration with the RSC. Despite leveraging the pyttsx3 library to enhance voice communication, the generated voice maintained a robotic timbre and presented comprehensibility challenges, indicating a need for further work to provide a more natural and engaging text-to-speech solution to enhance social interaction (Req 1).

Google's archiving of AIY projects and the associated GitHub repositories in February 2023 made finding support and documentation more difficult, slowing overall progress. Integrating OpenAI's NLP API created an additional issue by introducing latency due to the offloading of computation to online services, impacting real-time interactions. For instance, users wait approximately 6 s when starting a conversation and an additional 3 s before receiving a reply to a question. The effect of this delay on overall immersion when studying with the RSC needs to be investigated. At the same time, development should focus on optimising the software and hardware integration to reduce latency and improve the system's overall responsiveness.

During the prototyping phase in spring 2023, we utilised OpenAI's GPT-3 (text_davinci003) API, which was considered state-of-the-art at the time but which was deprecated in January 2024. While this LLM (GPT-3) allows for subject-specific interactions that can be motivating during the conversation, the system does not retain this context-specific engagement after the conversation ends, limiting the RSC's effectiveness in supporting sustained study goals. Future enhancements will focus on developing a functional software stack capable of analysing student interactions. This study engine must include adapting responses to enhance learning experiences through personalisation and gamification to keep users engaged beyond their initial interactions (Req 4).

Another priority of technical future developments (Req 3, 4, 5) should include enhancing system stability to support longer uptimes without interruptions. Updated documentation will remain essential, ensuring all users can easily set up, maintain, and benefit from the RSC without extensive technical knowledge. Lastly, for the RSC to achieve ongoing security and privacy (Req 6), it should adopt a zero-trust-like architecture. With this approach, the RSC must rely on local processing, which should enhance data security. This shift will require substantial changes in how the RSC handles data, including the development of local LLM inference capabilities that do not compromise the functionality or responsiveness of the device.

## 5. Conclusions

This paper addresses the gap in social robotics for university students by developing an open-source Robotic Study Companion (RSC) platform. We derived insights from an extensive literature review that helped us formulate precise requirements, guiding the RSC prototype's design and development. We present the resulting prototype, which was built using off-the-shelf components and integrates OpenAI's conversational API, leveraging its capacity to simplify complex concepts and enhance human–AI interaction.

The RSC embodies a step towards creating accessible, customisable, and cost-effective human–AI learning companions. The RSC has the potential to positively impact the future of education, facilitating more engaging and personalised learning experiences for university students. The RSC platform is under active development, and we welcome external contributions. More information can be found in the project's repository [36], replication package [78], and demo videos [95].

**Supplementary Materials:** The following supporting information can be downloaded at: https://github.com/RobotStudyCompanion/RSC2023 (accessed on 25 May 2024). Our replication package: https://doi.org/10.5281/zenodo.11962698 (accessed on 18 June 2024). Videos: https://doi.org/10.5281/zenodo.11671444 (accessed on 18 June 2024).

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