

Low-Cost Adaptive Controller for Individuals with Motor Impairments

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ABSTRACT

Individuals with motor impairments face restricted access to digital entertainment, an increasingly central form of interactive multimedia and social participation, due to the high cost and limited adaptability of assistive gaming interfaces. This study presents a low-cost adaptive video game controller for users with unilateral upper-limb limitations. The methodology combined a rapid literature review, a market analysis of commercial adaptive controllers, and prototyping with affordable, open components, including an Arduino Uno, tactile buttons, an HW-504 analog joystick, and 3D-printed parts. Firmware and software resources enabled the prototype to operate as a plug-and-play Human Interface Device, translating analog and digital inputs into standard gaming commands. Preliminary functional checks confirmed the operation of the controller's expected features, and the estimated production cost was lower than the market prices of the surveyed alternatives. These findings suggest the technical and economic feasibility of the proposed controller as an accessible, low-cost assistive technology, while evaluation with target users remains future work to assess its usability, comfort, and potential impact on digital inclusion.

KEYWORDS

Assistive Technology, Motor Impairments, Game Accessibility, Human-Computer Interaction, Inclusive Design

1 INTRODUCTION

Online gaming has expanded rapidly, serving as a powerful medium for cognitive, motivational, and social development.

Evidence indicates that video games can support emotional growth in children and adolescents through cooperative mechanics that foster the acquisition of social skills [1, 8]. In addition, digital games improve attentional precision, spatial processing, and mental rotation, while promoting task persistence and social inclusion [10]. However, individuals with physical disabilities are often unable to fully access these benefits without specialized assistive interfaces [10].

Technologies such as mobile devices and interactive applications play an important role in reducing barriers by enabling personalized and equitable experiences that strengthen social integration [16]. Nevertheless, limited access to appropriate assistive resources frequently restricts participation opportunities for children with disabilities, negatively impacting self-confidence and autonomy [12]. Individuals experiencing partial or total upper-limb loss face additional social and psychological challenges, often intensified by the inability to engage in previously enjoyed leisure activities [11]. In this context, inclusive technologies are essential to ensure meaningful participation in digital environments.

Despite the growing relevance of digital gaming, accessible play options remain limited. Most commercial controllers are designed for bilateral hand use and require coordinated multi-button inputs. In Brazil, approximately 4.63% of the population presents some degree of motor disability, corresponding to more than eight million individuals [9]. Such limitations are associated with reduced opportunities for physical engagement and higher prevalence of sedentary lifestyles compared to individuals without disabilities [9]. Digital games, particularly active video gaming, have demonstrated potential to mitigate these effects by promoting physical activity and supporting overall health [18]. However, this potential can only be realized if interaction devices are accessible. Recent work in WebMedia [3] has investigated alternative input techniques for users with severe motor disabilities, including eye-gaze interaction for hands-free Web navigation.

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Considering this gap between the therapeutic and social potential of digital games and the limited accessibility of existing hardware solutions, a need for cost-effective, adaptable, and ergonomically appropriate interfaces can be observed. In response to this need, this work presents the development of a prototype adaptive video game controller designed as an accessible alternative to proprietary commercial devices. The proposed system is designed to support single-handed interaction through a configurable interface with customizable input mappings, prioritizing affordability and usability within the Brazilian context. By expanding access to digital gaming, the solution aims to support autonomy, improve self-perception, and foster greater social participation. This work approaches digital games as interactive multimedia content whose accessibility is often constrained by input hardware and makes three main contributions: (i) a modular, single-handed adaptive controller built from low-cost, open components; (ii) a market and cost analysis positioning the prototype against commercial assistive controllers in the Brazilian context; and (iii) a design intended for open release, supporting reproducibility and local adaptation. The primary contribution lies in the low-cost integration and one-handed physical configuration of existing open components, rather than in the development of a novel electronic architecture.

2 LITERATURE REVIEW

The research methodology combined a survey of commercially available adaptive video game controllers with a targeted academic search on accessibility in digital gaming. IEEE Xplore, Web of Science, and CAPES were selected for their coverage of peer-reviewed publications and reliable search tools in engineering and health technologies.

Study selection was based on relevance to accessible gaming solutions, emphasizing the technologies used, accessibility challenges addressed, and clinical applicability for users with motor impairments. Search strategies in IEEE Xplore and Web of Science used keywords such as ‘controller’, ‘videogame’, and ‘disability’. CAPES was used to identify additional academic production, following the same methodological criteria and considering articles published between 2006 and 2025.

2.1 Selected works

The study selection process was structured using a flow diagram (Figure 1), which summarizes the screening and eligibility procedures. A total of 109 records were identified and analyzed. After applying the predefined inclusion and exclusion criteria, 10 studies were selected based on their relevance and alignment with the objectives of this work, particularly regarding the technologies, methodologies, and application domains addressed.

Priority was given to articles published in journals or conference proceedings that addressed physical video game controllers designed for users with physical-motor impairments. Studies focusing primarily on cognitive or intellectual disabilities, games exclusively developed for individualized

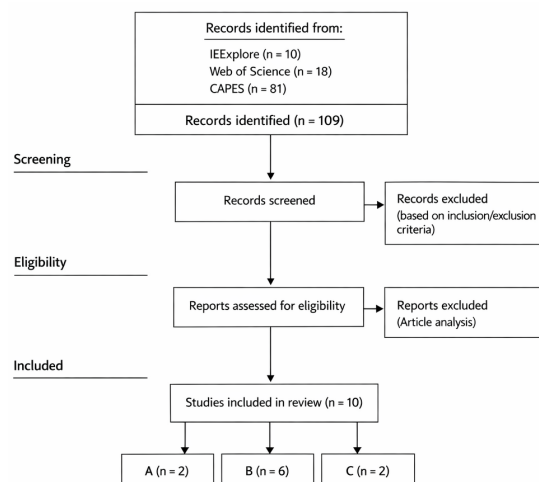


Figure 1: Flow diagram summarizing the study selection process.

physiotherapy, or solutions aimed mainly at promoting physical exercise rather than general entertainment were excluded.

To further characterize the selected literature, the studies were classified according to their degree of relevance to the objectives of this research, as presented in Table 1. Three levels of utility were defined: A (high relevance), B (moderate relevance), and C (low relevance).

Table 1: Utility of Articles Categorized and Chronologically Ordered

Article Reference	Utility Level
Breugelmans et al. [2]	A
Fanucci et al. [6]	A
Eckert et al. [5]	B
Forsberg et al. [7]	B
Malone et al. [13]	B
Mejia et al. [14]	B
Rinne et al. [17]	B
Velasco et al. [21]	B
Shih et al. [19]	C
Standen et al. [20]	C

2.2 Synthesis of Selected Studies

Category C studies [19, 20] investigated the use of commercial Nintendo Wii devices, such as the Nunchuk and Wii Balance Board, as accessible alternatives in assistive and collaborative contexts, showing potential to improve user engagement and task execution. Category B studies [5, 7, 13, 14, 17, 21] addressed digital games and interactive technologies as complementary tools for motor rehabilitation and physical activity, emphasizing accessibility, interface

adaptation, low-cost commercial solutions, sensors, and motion amplification strategies. Category A studies [2, 6] were the most aligned with this work, presenting technically robust adaptive controller solutions, including a console interface for auxiliary devices and a sensor-based controller combining a piezoresistive glove with eye tracking. Together, these studies support the feasibility of adaptable gaming interfaces while highlighting persistent limitations related to cost, command complexity, and dependence on external devices.

3 MATERIAL AND METHODS

The development of the adaptive controller followed a systematic approach focused on accessibility and low-cost implementation. Before the prototyping phase, a requirements analysis was conducted to address different levels of motor impairment, ensuring that the final solution could be tailored to the specific needs of the target audience [2, 21].

3.1 Design Requirements and Target Audience

To define the broader design space, three intervention categories were considered based on user mobility:

- **Category 1 (Severe Impairment):** For individuals with no functional coordination in limbs, solutions based on head or mouth movements are prioritized to enable basic interaction [21].
- **Category 2 (Lower Limb Coordination):** For users with functional legs but no arm coordination, a pedal-based interface is proposed. This design incorporates high-sensitivity actuators, such as piezoresistors and pressure-sensitive buttons, to reduce physical fatigue [2, 13].
- **Category 3 (Unilateral Limitation):** Targeting individuals with only one functional hand, this work proposes an ergonomic adaptation that allows full control through a single-handed interface.

The proposed architecture follows a modular “central hub” concept, similar to the approach discussed by Fanucci et al. [6]. This design allows for the connection of various external peripherals tailored to individual needs while maintaining affordability.

3.2 Hardware Architecture and Electronic Design

The prototype was developed to define an adaptive controller concept inspired by existing commercial models, emphasizing customizable key mapping and cost reduction to enhance accessibility. The implementation was based on the Arduino Uno platform, selected for its flexibility, open-source architecture, and broad availability, which facilitate rapid prototyping and hardware customization.

The system incorporates an embedded module capable of direct communication with a computer, enabling seamless interaction between the hardware and the user. The device acquires signals from integrated sensors, processes the captured data, and translates it into commands interpretable by the host system. This architecture allows the controller to function as an input device for digital gaming environments.

The electronic architecture comprises a central processing unit connected to three tactile push buttons, three 220 Ω pull-down resistors, and an HW-504 analog joystick module for directional control. These components represent a partial implementation of the complete controller and are presented to illustrate the fundamental system structure. The hardware was designed to minimize latency and ensure the accurate translation of user inputs into standardized game commands. Figure 2 schematically illustrates the electronic diagram of the prototype, highlighting the overall system architecture.

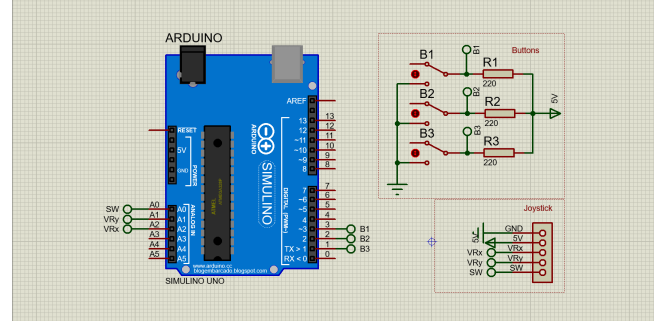


Figure 2: Electronic schematic of the adaptive controller prototype.

3.3 Firmware and Communication Protocol

To enable direct integration with modern operating systems without requiring proprietary drivers, the UnoJoy library [4] was employed, allowing the Arduino firmware to be recognized as a Human Interface Device (HID), specifically as a standard game controller. At the software level, the system incorporates the Pygame, Pynput, and CustomTkinter libraries. These libraries are responsible, respectively, for capturing input signals from the controller, emulating keyboard events, and providing a graphical user interface to support system configuration and operation.

The software implementation was structured into two stages:

- (1) **Data Mapping:** Development of the logic responsible for translating the analog voltage variations from the HW-504 module and the digital signals from the buttons into a data structure compatible with the standard game controller format.
- (2) **Firmware Flashing:** Use of the *Device Firmware Update* (DFU) mode to reprogram the microcontroller’s communication chip, enabling it to operate as a *plug-and-play* joystick.

This configuration prioritizes usability, allowing the assistive device to be recognized as a plug-and-play joystick.

4 RESULTS AND DISCUSSION

The functional assessment of the prototype was structured around two primary criteria: technical responsiveness and economic feasibility. Preliminary tests indicated that the

device was able to translate tactile button activations and analog joystick movements into standard Windows control commands [15]. By implementing the communication protocol described in Section 3, the system was recognized by the operating system as a *plug-and-play* game controller. This native integration supports compatibility with digital gaming environments without requiring proprietary software or additional drivers [6, 22].

4.1 Functional Verification

During preliminary testing, the device showed responsive input behavior suitable for the intended control tasks. Responsiveness is an important characteristic for supporting interaction in recreational and therapeutic gaming contexts involving users with motor impairments [14, 18].

Preliminary functional evaluations also indicated that the integration of the Arduino-based firmware with tactile input components enabled consistent input detection and control, characteristics relevant to effective participation in active video gaming (AVG) environments [15, 18].

4.2 Ergonomic and Assistive Analysis

Figure 3 illustrates the physical configuration of the prototype, which was designed to require minimal hand movement for command activation. In contrast to conventional controllers that demand complex two-handed coordination, the proposed single-handed interface was designed to facilitate a neutral wrist posture, thereby providing a viable solution for users with unilateral upper-limb limitations. However, as the current evaluation did not include target users or biomechanical measurements, aspects such as comfort, wrist posture, and fatigue remain to be investigated in future studies.

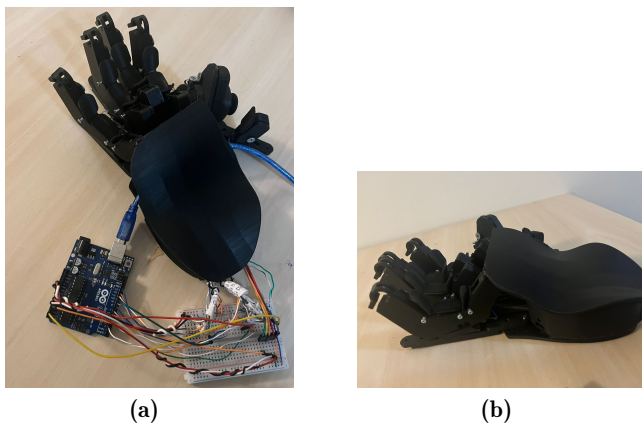


Figure 3: (a) Functional prototype of the adaptive controller featuring an Arduino Uno interface and tactile actuators; (b) Assembled prototype from another angle.

A central feature of the proposed device is the integration of the HW-504 analog joystick module. Unlike digital buttons, which provide binary (on/off) input, this module enables graded control according to the magnitude and direction of the user's movement. In rehabilitation-oriented applications,

this type of input may be relevant for tasks involving fine motor control, as it allows users to perform controlled and directional movements to achieve specific in-game actions.

The resulting interaction between motor input and visual feedback may support motor practice mechanisms commonly explored in rehabilitation-oriented gaming environments [14, 17]. Furthermore, this design choice is consistent with prior studies highlighting the importance of balancing interaction precision and muscle fatigue to support sustained engagement in digital rehabilitation activities [5, 14].

4.3 Cost Analysis and Market Comparison

A comparative cost analysis was conducted between the proposed prototype and commercially available adaptive controllers. While commercial adaptive hubs typically priced around or above USD 100, often excluding specialized actuators, the proposed controller was built using low-cost, open-source components, resulting in substantially lower hardware costs. Table 2 presents the Bill of Materials used in the prototype assembly, based on local market prices for electronic components and 3D printing materials.

Table 2: Detailed Bill of Materials and Production Costs

Component / Item	BRL	USD
Arduino Uno Microcontroller	33.05	6.25
3D Printing Filament (PLA/PETG)	20.00	3.75
HW-504 Analog Joystick	19.01	3.59
Total Material Cost	72.06	13.59
Labor (Manufacturing and Assembly)	320.00	60.49
Final Prototype Cost	392.06	74.08

Note: Exchange rate used: 1.00 USD = 5.29 BRL.

Even when manufacturing and assembly labor costs are included, the total prototype cost remains approximately 26% lower than the least expensive commercial alternative and about 59% lower than professional-grade solutions, such as the Azeron Cyborg, without accounting for import taxes commonly applied to international products in Brazil [6]. This assessment is supported by the survey of adaptive controllers summarized in Table 3.

Table 3: Surveyed Controllers, Manufacturers, and Listed Prices

Controller	Manufacturer	USD
Access Controller	Ben Heck	129.95
QuadStick	Fred Davison	124.00
Single-Handed Xbox One	Ben Heck	285.00
Xbox Adapt. Controller	Microsoft	99.99
Novint Falcon Controller	Novint Technologies	250.00
Cyborg	Azeron	180.00

Note: Prices may vary by region and distributor.

This comparison is limited to estimated production costs and listed acquisition prices, as the surveyed devices differ in functionality, compatibility, target audience, and other factors such as comfort, durability, and user experience.

5 FINAL REMARKS

This work presented the design and preliminary validation of a low-cost, single-handed adaptive game controller for users with unilateral upper-limb impairments, built from open, affordable components. The prototype operated as a plug-and-play device, reliably translating inputs into standard commands, and showed substantially lower material cost than surveyed commercial alternatives. As a proof of concept, validation was limited to functional and economic aspects; future work will evaluate the controller with target users through a structured protocol and the System Usability Scale.

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Generative AI tools were used solely to assist with linguistic revision, and all suggestions were critically evaluated and reviewed by the authors, who remain fully responsible for the final content of the manuscript.

ETHICAL CONSIDERATIONS

This study complies with CNS Resolution No. 510/2016 and did not involve human participants or the collection, use, or analysis of personal data subject to the LGPD.

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