Journal on Interactive Systems, 2024, 15:1, doi: 10.5753/jis.2024.3534

Interactive rapid prototyping combining 3D Printing and Augmented Reality

Derzu Omaia [**Federal University of Pernambuco** | ***do@cin.ufpe.br***]
Walter F. M. Correia [**Federal University of Pernambuco** | ***walter.franklin@ufpe.br***]
Andre L. M. Santos [**Federal University of Pernambuco** | ***alms@cin.ufpe.br***]

Informatic Center, Federal University of Pernambuco, Av. Jornalista Anibal Fernandes, s/n, Cidade Universitária (Campus Recife), Recife, PE, 50740-560, Brazil.

Received: 10 July 2023 • **Accepted:** 25 October 2023 • **Published:** 01 January 2024

Abstract In the development of new products by the industry, a rapid prototyping stage is recommended so that an initial version of the product can be evaluated. In this way, any necessary corrections can be applied while still in the prototyping stage, preventing design errors from reaching the final product. Augmented Reality (AR) and 3D Printing are techniques that have become ubiquitous in recent years due to the reduction of equipment costs. Several works in the area of rapid prototyping have been developed with one of these techniques in isolation; a few works have tried to unite these two tools. In this work, we propose a new functional rapid prototyping process, combining 3D Printing and AR to create functional interactive prototypes. This process is accomplished by projecting the AR onto the 3D-printed prototype. It interprets the user's gestures on the physical prototype, converting clicks and touches into actions to be executed on the AR virtual prototype, making the prototype functional and interactive. The proposed system is evaluated by means of case studies and the application of the UEQ (User Experience Questionnaire) to users who have tested the system. This way, it is possible to evaluate the relevance of the proposed process.

Keywords: Augmented Reality, Virtual Reality, Interactive Rapid Prototyping, 3D Printing

1 Introduction

The manufacturing of a product by industry is increasingly automated, thus less dependent on human intervention. However, during the development of a new product there is usually a prototype testing and evaluation stage [Noorani, 2006] which requires human mediation. Some users test and evaluate an initial version of the product and the results are used to make any necessary corrections, preventing design errors from reaching the final product. The cost of the prototype development stage is proportional to its duration, which can take days or months, therefore it is essential to shorten its length to reduce the final cost [Teixeira *et al*., 2016; Gibson *et al*., 2014].

Rapid prototyping can be classified into: structural, functional, and structural and functional. In structural, appearance, shape, and fit are evaluated. In Functional, product functionality is considered, which can be mechanical, electrical, or digital. Structural and functional prototypes have combined characteristics of the two categories mentioned above [Baxter, 1995; Zorriassatine *et al*., 2003; Alexander *et al*., 2009].

The structural prototyping process is the simplest process because it requires only the 3D model of the product, which is built with design aid software (Computer-Aided Design - CAD) and physically produced using some digital manufacturing technique. The size and shape of the prototype must be equivalent to the final product [Alexander *et al*., 2009].

The purely functional prototypes can be physical or virtual. If physical, functionalities must be present, but their size and shape do not need to match the final product. If virtual, they can make use of Virtual Reality (VR) or Augmented Reality (AR) for interaction and display of their functionalities [Zorriassatine *et al*., 2003; Alexander *et al*., 2009].

Structural and functional prototyping is the most costly because functionalities need to be added to a physical prototype. These functionalities can be mechanical, electrical, or digital. For mechanical functionalities, the digital prototype manufacturing process has separate parts, which must be fitted together to finalize the prototype [Zorriassatine *et al*., 2003; Alexander *et al*., 2009]. If functionalities are electrical or digital, specific processes must be applied to complete the prototype. Katakura and Watanabe [2018] use hollow buttons, where clicks generate sounds that are detected by a circuit. Simon [2012] uses RFID sensors in control interfaces. Macdonald *et al*. [2014] uses 3D printing to produce the prototype integrated into a circuit, allowing the prototype to have electrical functionalities such as lights. For digital functionalities, VR and AR can be used.

VR is the simulation of a 3D environment by computer systems so that it is possible to visualize and manipulate 3D models in these environments. In rapid prototyping, VR is used mainly for prototype generation and visualization; however, some works, e.g. Balcisoy *et al*. [2000], use VR in functional prototyping, where it is possible to interact with these prototypes using some interaction device, such us mouse or keyboard [Balcisoy *et al*., 2000; Zorriassatine *et al*., 2003].

AR is a mechanism for viewing, directly or indirectly, in real-time, a natural physical environment over which computer-generated virtual information is added. AR aims to enrich the user's experience by integrating virtual elements with the real world view, increasing the user's perception and interaction with the environment [Furht, 2011; Khan *et al*., 2019]. It can be used in the most diverse areas and applications, and has been widely used in industry, for which several works have being proposed in the prototyping area [Choi and Chan, 2004; Simões *et al*., 2016; Porter *et al*., 2010; Abulrub *et al*., 2011].

In AR, the 3D model of the prototype can be integrated into the real environment using AR visualization devices, such as glasses, visors, or special helmets. The prototype can then be positioned somewhere in the surroundings or in the user's hands, although it is only virtually present. The drawback is that most of the time, this type of visualization of the prototype grants limited manipulation, allowing only basic operations such as rotation and scaling of the 3D model, therefore the prototype remains non-functional. Nevertheless, it is possible to add functionalities to the prototype in AR, thus generating functional prototypes [Tziouvara, 2012].

Another tool for rapid product prototyping is 3D printing. This method has become popular in recent years due to the decrease in the costs of acquiring 3D printers and their inputs [Gibson *et al*., 2014; Leite *et al*., 2016]. One of the advantages of this method is that a physical 3D object is generated in the real environment; the user can interact visually and with the sense of touch. The acceptability of the prototype depends heavily on the tactile and haptic sensation that the user feels when interacting with the prototype [Simon, 2012]. The prototypes generated are usually only structural; however, moving parts can be added by printing them separately and then fitting them together, making the prototype structural and functional. The inconvenience of most popular printers, which use Fusion Deposition Modeling (FDM) technology, is that they usually print in a single color, not allowing surfaces to be printed in their original colors, causing some details of the object to be missed [Gibson *et al*., 2014].

One problem encountered in the prototyping stage is that most prototypes used are only structural, not allowing a detailed product evaluation. Structural and functional prototypes are a minority, and those produced generally do not cover all the product's functionalities, many being restricted to mechanical functionalities only. Thus, some design errors may not be noticed at this stage and will only be detected in the final product [Zorriassatine *et al*., 2003; Alexander *et al*., 2009]. Few works propose to develop structural and functional prototypes covering most of the product functionalities [Park *et al*., 2009]. Thus, this type of prototype is still little explored by the industry because the proposed techniques are not simple to implement and do not cover the product functionalities completely.

After the 3D model of the prototype has already been designed, the cost of prototyping using AR or 3D printing is minimal. It is possible to combine the two methods, taking advantage of both. This way, the user can touch the 3D printed physical object, have the sense of touch immersed in the experience, and benefit from the AR features, which allows the prototype to have an appearance and interactive behavior like a final product. However, few works have been developed combining these two areas [Fernandes *et al*., 2015; Gieser *et al*., 2016; Simões *et al*., 2016]. Using AR and 3D Printing to generate functional and interactive prototypes were found only the works of Park *et al*. [2009] and Verlinden [2014]. Therefore, this is a promising research area that has several challenges to be explored.

The work of Park *et al*. [2009] presents a rapid prototyping system for portable products using physical models and AR. The physical model is 3D printed and the AR model is positioned to overlap the physical model. It is possible to interact with the model using a physical pointer which has a marker to be perceived in AR. Using the pointer the user performs clicks and touches on the 3D model, and the result of these actions is displayed in the AR. The visualization of the system is done on a PC, and a webcam is positioned on the user's head. The main contribution is interacting directly with the physical prototype and in the AR. The inconvenience is the need to use a pointer [Park *et al*., 2009].

Verlinden [2014] work proposes an AR prototyping methodology, where AR is superimposed on a physical prototype using a projector. Powered by a camera, the system locates the prototype and projects some texture onto it. It is possible to interact with the prototypes by moving them directly on the table or using a touch screen controller [Verlinden, 2014].

The two cited works above contribute with approaches that generate structural and functional prototypes. There are, however, several points to be improved - such as the need for physical pointers for interaction, the use of more than one device in the testing environment, among others - aiming for a more comprehensive solution to the problem of experimenting with a functional prototype in industry.

The present work fills gaps found in related works. It presents a new process of rapid prototyping in which the generated prototypes are structural and functional, allowing functionalities of the final product to be tested while in the initial prototyping phase.

The general goal of this work is to propose a cyclic process of interactive, functional, and structural rapid prototyping (CYPIRP) for product development, exploring the isolated advantages of AR and 3D Printing and combining them to generate a synergistic process.

To accomplish this, a structural and functional prototype is produced. Initially, the physical prototype is 3D printed; the functionalities are implemented in AR; then the prototype is tested by the user according to the experiment protocol. Finally, the results are analyzed, and, if necessary, all these steps can be redone until obtaining the prototype with the expected behavior.

This work has as main contribution the development of a cyclic process of rapid interactive prototyping. This allows new products to be planned, developed, and evaluated in a shorter prototyping time, in order to reduce the final cost. A secondary contribution is the Prototyping experiment system, based on the proposed process, on a single device with a single video camera, creating a simple to use and easy-to-configure system. Also, the interaction with the prototype is realized directly by the user's fingers without the need for gloves or special markers.

This paper is organized as described below. In this first section the Introduction of the work was presented, in Section 2, Related Work, techniques related to the present work are presented. In Section 3, Methodology, the proposed process and the methodology used are presented. In Section 4, Results, the results obtained are presented. Finally, in Section 5, Conclusion, the conclusion and future work are presented.

2 Related Work

The most relevant works on process development dealing with rapid interactive prototyping have been analyzed and identified. Our research will address the following question: What initiatives have been undertaken to develop interactive rapid prototyping processes? These initiatives must be based on 3D Printing, VR, or AR.

A comparative summary of the main contributions of the works is presented below and in chronological order.

Balcisoy *et al*. [2000] propose an AR framework for generating interactive virtual prototypes controlled by a virtual avatar. The prototype and avatar are positioned in a VR environment or an AR environment. A virtual user performs actions on the prototype; these actions are preconfigured, the AR user watches without directly participating in the interaction [Balcisoy *et al*., 2000].

The work of Balcisoy *et al*. [2000] has as its main contribution that it was the first work proposed in rapid interactive prototyping using VR and AR. They presented as future work an analysis of the comfort and possible injuries that the user could suffer when interacting with the proposed product. However, this proposed future work is not explored in this work.

In Lee and Park [2005], a system is proposed to help designers test their prototypes. A 3D object is modeled, and then its physical model is generated by a CNC (Computer Numerical Control) machine using polyurethane foam as the base material. A marker is placed on the physical model, enabling the same 3D model to be projected onto the physical model via AR, allowing color and texture to be changed and tested Lee and Park [2005].

The work of Lee and Park [2005] has as main innovation the projection of the model in AR onto the physical model. As future work, they suggest improving the marker tracking that the AR uses by accepting partially occluded markers. These two features were implemented in the present work.

Park *et al*. [2009] present a rapid prototyping system for portable products using physical models and AR. The physical model is 3D printed; then, the AR model is positioned to overlap the physical model. It is possible to interact with the model using a physical pointer which has a marker that allows it to be perceived in AR. With the pointer, it is possible to perform clicks and touches on the 3D model, and the result of the actions is presented in the AR. The visualization of the system is done on a PC, and a webcam is positioned on the user's head [Park *et al*., 2009].

The main contribution of Park *et al*. [2009] is the possibility of interacting directly with the physical prototype. However, it is necessary to use a physical pointer to interact with the AR. They propose as future work the interaction without the pointer, directly with the fingers, and the use of HMD devices for visualization. These two proposals have been implemented in the present work.

A work by Akaoka *et al*. [2010] presents a rapid prototyping workbench that projects functional interfaces onto physical prototypes. The projection is carried out using multimedia projectors (data show), allowing the user to visualize the AR without the need of glasses or HMD. The physical prototypes are monochromatic and reused real objects such as cans, globes, and boxes painted a solid color. Interaction is performed through finger touches; however, it is necessary to stick a marker on the finger to be recognized. The projection of the AR onto the physical prototype is achieved using a projector. The test environment has eight cameras that detect the markers and two projectors that project the interface onto the prototype [Akaoka *et al*., 2010].

In Porter *et al*. [2010], multimedia projectors (datashow) are used to integrate AR with the real world. The goal is to evaluate car dashboard prototypes. The image of the car dashboard is projected on a flat surface. A finger detection module is used to detect the user's movements and allow interaction with the prototype. The finger detection requires the user to wear an orange thimble on the index finger. A questionnaire is applied to evaluate the User Experience (UX) [Porter *et al*., 2010; Marner *et al*., 2011].

In Akaoka *et al*. [2010] and Porter *et al*. [2010], the main innovation is the use of projectors for an interactive prototyping system. Akaoka *et al*. [2010] propose as future work improving tracking with partially occluded markers, enhancing the quality of the cameras and projectors used, interaction without the need for markers on the fingers, and simplifying the configuration environment of the proposed workbench [Akaoka *et al*., 2010]. Porter *et al*. [2010] suggest a faster interaction process between the user and the prototype as future work. The present work uses a simple configuration of the interaction environment, interaction with fingers without markers, and the application of questionnaires to validate the proposed process.

In Stöcklein *et al*. [2010], MiReAS, an interactive prototyping framework in a mixed reality environment, is presented. This framework has an iterative refinement system based on the Model-View-Control-Environment (MVCE) pattern. A case study was conducted with an indoor airship controlled by remote control, and virtual obstacles can be added to the scene to test the airship's mobility [Stöcklein *et al*., 2010].

The main innovation in the work of Stöcklein *et al*. [2010] is the use of the MVCE (Model View Controller Environment) design pattern [Stocklein *et al*., 2009] in the iterative refinement stage of the prototype. It is proposed as future work a standardization in describing the models used in the rapid prototyping process [Stöcklein *et al*., 2010]. The present work proposes a cyclic process of prototyping that includes an iterative refinement stage as well.

The IRIS rapid prototyping method [Zampelis *et al*., 2012] allows interactive screens in static prototypes. The case study used a static prototype with some buttons; these buttons send commands via Bluetooth to a computer, where the interactive screen is located. One of the problems with this system is that the screen is separated from the prototype, which can cause a bad UX. It was suggested as future work to increase the resolution of the screen used [Zampelis *et al*., 2012]. No features from the work of Zampelis *et al*. [2012]

were explored in work proposed in this paper.

In Simon's (2012) Ph.D. Thesis, IntelliTIO (Intelligent Tangible Input Object), a rapid prototyping system in an AR environment for control panels, is proposed. The interaction with the user is performed via tangible input objects, such as physical control panels, which also have an AR version. Sensors are attached to these panels, enabling to obtain data from the natural environment. The sensors communicate via RFID (Radio-Frequency Identification) with the interaction system. As future work, Simon suggests using different models of antennas to capture the signal and optimize the RFID system [Simon, 2012].

Verlinden [2014], in his doctoral thesis, proposes a five-stage methodology of prototyping in AR: modeling, preparation, deployment, review, and reflection. In the modeling stage, the 3D model is generated through a CAD tool or by scanning an existing object; in preparation, the intended interactions with the model are configured; in deployment, the environment where the 3D model will be in the AR is prepared; in review, the experience is tested, and modifications may be proposed; in reflection, the interactions are re-analyzed, and decisions about the design may be changed. A case study is conducted in which some 3D printed objects are arranged on a table, and AR is applied by a projector. Powered by a camera, the system located the objects and projected some texture onto them. It is possible to interact with the prototypes by moving them directly on the table or using a touch screen controller [Verlinden, 2014].

In Verlinden [2014] work, the main innovation is the cyclical prototyping process. As future work he proposes integrating all the functionality of the prototyping experiment into a single device such as a tablet, and also to produce physical prototypes based on malleable materials such as clay [Verlinden, 2014]. The present work uses a cyclical process, and the experiment is performed on a single device.

In the work of Simões *et al.* [2016], two rapid prototypes of different natures are generated for the same product. The first is a physical prototype printed in 3D, and the second is a virtual prototype in AR. These two prototypes are compared and undergo tests and questionnaires with lay users and prototyping experts. The experiences are evaluated, and the advantages and disadvantages of each prototype are pointed out for an application in the analysis phase of a product design [Simões *et al.*, 2016].

The main highlight of the work of Simões *et al.* [2016] is the comparison between physical and AR prototypes for the analysis of a product. It is proposed as future work the execution of the experiments with a sample of testers more representative of the consumer market, the prototyping of products not yet known by users, and the use of AR without traditional markers (fiducial or QR code) [Simões *et al.*, 2016]. In the present work, AR is used without conventional markers.

An *et al.* [2017] propose a workflow for prototyping named CEPVR. The process is interactive and allows the creation of 3D models from sketches. The sketch is tested and evaluated in an AR environment. The process is collaborative, and more than one person can participate in the interaction. A case study was conducted for a car in which the steering of the vehicle was designed and tested, two users interacted: the driver and a passenger [An *et al.*, 2017].

The main highlight of An *et al.* [2017] work is using multiple users for testing the prototype and the possibility of experiments with large products, such as cars. Given the complexity of the experiment, future work should include a focus on aiding the human helpers of testers [An *et al.*, 2017]. None of the highlights and future work were applied in the present work.

Katakura and Watanabe [2018] propose a rapid prototyping process using 3D printed and interactive prototypes called ProtoHole. The interactivity is realized through an electrical and acoustic system installed inside the printed object; holes in the object are used as buttons. It is possible to detect the holes that the user closes by detecting the different sound frequencies. The system was tested using a few objects such as a joystick, lamp controller, and a toy dog [Katakura and Watanabe, 2018]. Each closing of a hole generates a different action depending on the object.

The main differential of Katakura and Watanabe [2018] work is the use of holes as buttons and the use of sound sensors in the prototype to trigger a click. Future work proposes changing the shape of each hole so that the sound resonated by them is sufficiently different to make it easier to detect which hole was closed [Katakura and Watanabe, 2018]. Neither the differential nor the future work was applied in the present work.

Arrighi and Mougenot [2019] introduce a tool that allows end-users to visualize the virtual prototype of the product in 3D and participate in the design process by manipulating and modifying it directly in an intuitive way. The interaction with the prototype is accomplished through blocks with markers; the manipulation of the block generates an action in the virtual environment. The blocks can be repositioned, generating a repositioning of the virtual object within the environment. A case study is conducted to decorate a room, where each block is a piece of furniture, which can be moved around the scene [Arrighi and Mougenot, 2019].

The main innovation of Arrighi and Mougenot [2019] work is applying the method in the field of architecture and interior design. As future work, it was proposed to evaluate the usability of the experiment and its impact on the environment design process [Arrighi and Mougenot, 2019]. The present work uses a UX evaluation process through questionnaires.

Morozova *et al.* [2019] propose Mixed UX, a framework that combines 3D models with 2D interaction interfaces, like mobile device screens. The intention is to facilitate interaction with the prototype through the interaction screen. The demonstrated case study projected the 3D model using AR at a fixed location. A mobile device is positioned over the projection; the interactions on the mobile are reflected in the projected 3D model. Microsoft HoloLens was used as the AR display device, and the interaction screen is an ordinary cell phone with a touchscreen [Morozova *et al.*, 2019].

Morozova *et al.* [2019] highlight the interaction screen, which allows simple interaction with the prototype. Future work proposed interactions with other parts of the prototype and not just the interaction screen [Morozova *et al.*, 2019]. Neither the highlighting nor the future work was applied in the present work.

2.1 Highlights

The positive and negative points of the cited articles were examined. The present work tries to solve the shortcomings identified in the analyzed works, implementing some points suggested as future works by the authors. The main elements and features that need to be improved or added are listed below and are incorporated into the method proposed in the present work.

- Projection of the prototype model in AR onto the physical model [Lee and Park, 2005].
- Tracking of partially occluded markers [Lee and Park, 2005; Akaoka *et al*., 2010].
- Interaction of the system user with the prototype [Park *et al*., 2009].
- Visualization of the interaction using HMD devices [Park *et al*., 2009].
- Interaction with the prototype using the fingers, without the need for a pointer or marker [Park *et al*., 2009; Akaoka *et al*., 2010].
- Application of questionnaires to validate the proposed process and UX [Porter *et al*., 2010; Arrighi and Mougenot, 2019].
- Test environments with simple configuration [Akaoka *et al*., 2010].
- Test standardization scheme for different models [Stöcklein *et al*., 2010].
- Cyclic prototyping process [Verlinden, 2014].
- Prototyping experiment on a single device [Verlinden, 2014].
- AR tracking without traditional markers [Simões *et al*., 2016].

These points show that the research area in rapid interactive prototyping still has many issues to be ameliorated, and the present work aims to fill most of these gaps. All these points highlighted in this review were implemented in the current work, aiming to develop a complete and robust prototyping process.

3 Methodology

The investigation into rapid prototyping methods provided an understanding of this area and its processes. Procedures that had been little explored were located, and possible improvements detected. Thus, a new cyclical, structural, functional, and interactive rapid prototyping process was proposed. The process was implemented through a system, allowing various products to be configured and prototyped.

A case study was developed to validate the process and the system to prove theoretical and practical feasibility. The case study was applied to users who experienced the process through the system developed. They then answered the UEQ questionnaire to evaluate their experience of using the system.

The proposed interactive rapid prototyping process, the implementation of its system, the case study, and its form of evaluation are all included in this section.

3.1 Cyclic Process of Interactive Rapid Prototyping - CYPIRP

The present work proposes a cyclic process for the rapid development of structural, functional, and interactive prototypes combining AR and 3D Printing. This process has been designated as Cyclic Process of Interactive Rapid Prototyping (CYPIRP). We recognize an interactive prototype when it is possible to perform actions on the prototype that generate reactions referring to its functionalities. In this way, a user can interact with the prototype exploring its functionalities more naturally.

The proposed process is based on the product development cycle proposed by Noorani [2006]; however, some steps were grouped, others partitioned, some modified. Figure 1 shows the process proposed by Noorani, and the equivalence between Noorani's approach and the method presented in this paper is indicated. Noorani's first three steps, Design Conception, Parametric Design, and Analysis and Optimization, were grouped into the Product Specification step of CYPIRP. Noorani's Rapid Prototyping step was changed to Structural and Functional Prototype Creation and encompassed the creation of the functional prototype and the production of the physical prototype. The Prototype Test and Evaluation step was segmented into two steps: Prototype Experimentation and Prototype Evaluation.

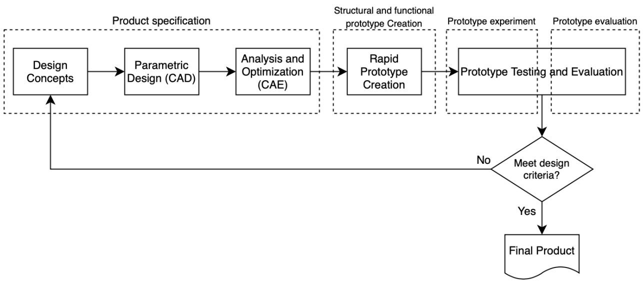


Figure 1. Product development cycle. It is adapted from Noorani [2006]

Given these equivalences, the proposed process architecture is shown in Figure 2, consisting of four steps, each of which is composed of several modules. The initial stage is Product Specification, where the product is designed and specified, and the 3D model is generated as output. The Functional and Structural Prototyping stage receives, as input, the 3D model of the product. The functionalities to be tested are then defined, a functional virtual prototype is generated, and the physical prototype is also produced. Next is the Prototype Experiment stage, where the structural and functional prototype is tested through a system that allows interaction with the prototype. Finally, there is the Evaluation and Revision stage, where the prototype is evaluated, and adjustments and changes can be proposed. This process is cyclical and must be repeated as long as the question: "Does it meet the design criteria?" is negative; when it is positive, the prototype is ready to go to the assembly line, and the final product can be produced.

This cyclical process is already used similarly in works such as those by Stöcklein *et al*. [2010], Marner *et al*. [2011] and Verlinden [2014], so it does not represent innovation in isolation; however, the innovation proposed in this work is in the stages of Structural and Functional Prototype Cre-

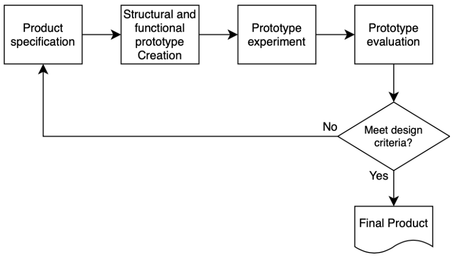


Figure 2. Proposed cyclical process (CYPIRP).

ation, Prototype Experimentation, and the CYPIRP system as a whole.

The CYPIRP stages, and their internal modules, are detailed below.

3.1.1 Product Specification

.

The Product Specification stage comprises the first three stages of the product development cycle proposed by Noorani [2006]: Design Conception, Parametric Design, and Analysis and Optimization. At the end of these steps, a 3D model of the product is generated and used by the following steps of CYPIRP. Figure 3 shows the flowchart of this step.

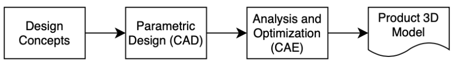


Figure 3. CYPIRP Product Specification Stage.

In the Design Concept step, general configurations of the product to be developed are defined. The product design is specified and described in the Parametric Design stage, usually using a Computer-Aided Design (CAD) Program. The third stage is Analysis and Optimization, where the design is analyzed and, if possible, optimized, usually using a Computer-Aided Engineering (CAE) program. These three steps are unchanged compared to the Noorani [2006] proposal and should follow the specific processes of each industry.

3.1.2 Structural and Functional Prototyping Creation

.

The Structural and Functional Prototype Creation stage must generate a structural and functional prototype in the Prototype Experiment stage. Figure 4 shows the flowchart of this step; it receives as input the 3D Model of the Product, generated in the Product Specification step, which is used in the two main modules, namely Digital Fabrication and Functions Definition.

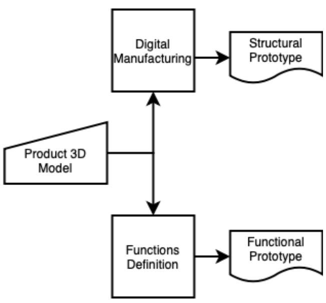


Figure 4. CYPIRP Structural and Functional Prototype Creation Stage.

In Digital Manufacturing, the 3D model is sent to some Digital Manufacturing equipment to generate a structural prototype of the 3D model received. In this work, a 3D printer was used; after printing the model, which usually takes several hours, the printed structural prototype is ready to be used by the system. The artifact produced in this module is one of the outputs of this stage.

In the Functions Definition module the entire UX must be planned. At this stage the product functionalities are defined and tested, and the actions and reactions that can be performed on the interactive prototype are configured. Each prototype function must be divided into pairs of actions and reactions that can happen on the prototype, and each action and reaction must be associated with a spatial region in the 3D model. In this way, each area of the 3D model amenable to some interaction must be defined along with the expected action and reaction. The action to be performed can be a click or a moving touch on the object. The object can react to the actions with the following reactions:

- Animations and Movements;
- Change of color or lighting;
- Sound playback;

These actions and reactions must be configured to generate a functional prototype using AR. In the present work, the prototype was configured using the development tool Unity Engine [Unity, 2022]. The procedure for producing this prototype varies depending on the functionality involved and will be presented along with the case study developed.

The design of actions and reactions is specific to each product. In this project, the possibilities of actions to be performed on a children's car toy were analyzed. In this way, the actions of opening and closing, turning and moving were planned to generate the equivalent reactions, adding sound to each action. More details are given in the case study in section 3.1.1.

After the Structural Prototype and Functional Prototype are generated, they are used and combined into a single Structural and Functional prototype in the Prototype Experiment stage.

3.1.3 Prototype Experiment

The Prototype Experiment stage is responsible for experimenting with the structural and functional prototype. This stage receives the outputs of the Structural and Functional Prototyping Creation stage, the structural and functional prototypes. These will be combined to generate a single structural and functional prototype.

For the execution of the experiment, an architecture for an Interactive Prototype Experiment system is proposed, which is presented in Figure 5 and uses a portable radio as an example prototype to be manufactured and evaluated.

The Functional Prototype with its actions and reactions is sent to the Central Controller module. This module manages the AR Controller and the Gesture Detector. It interprets the gestures and generates the commands that the AR Controller must execute.

The AR Controller module is responsible for generating and controlling the AR information and displaying it on a

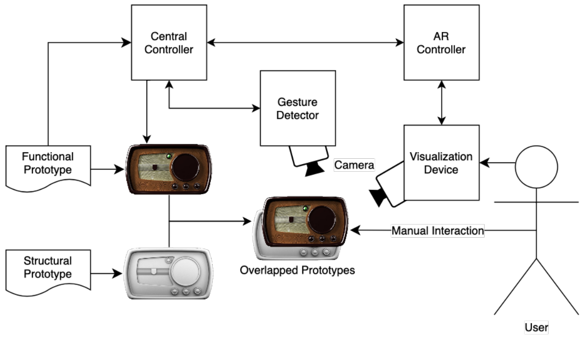


Figure 5. Architecture of the Prototype Experiment stage of the CYPIRP.

Display Device. The core of this module is an AR library or engine; in the present work, the Vuforia AR library was used [Vuforia, 2020]. The AR Controller module receives the 3D model of the functional prototype, renders it, and, together with an AR Visualization Device, projects the rendered 3D model onto an AR marker located on the Structural Prototype so that the Functional Prototype and the Structural Prototype are overlapped with the same rotation and scale settings. This process is possible because the AR Controller and the AR Visualization Device, which has a video camera, can track the object of interest and detect its position.

The Visualization Device has three essential components, a visualization screen, a sound system, and a video camera. The visualization can be either through an Optical see-through device or a Video see-through device, allowing the user to visualize the AR in the real environment. The sound system will enable sounds resulting from interaction with the prototype to be heard. The video camera captures the real environment and allows the AR Controller to track the point of interest. In the present work, a video direct vision device is being used, a cell phone with a sound system and a video camera integrated.

This configuration of the experiment allows the user, when holding the Printed Structural Prototype (monochrome), to see the prototype rendered in color and manipulate it traditionally, with the basic operations of rotation and scale, moving it closer or further away.

To enable the prototype's functionalities to be activated interactively, a camera films the user's interaction with the Structural Prototype; this camera can be the AR Visualization Device's camera or another external camera. The captured images are processed in the Gesture Detector module that will recognize the movements made by the user's hand on the printed object to recognize touches and clicks. These movements are passed to the Central Controller module that converts them into actions to be applied on the Functional Prototype according to the possible actions that the prototype can perform. Once identified, the AR Controller executes the actions in the Functional Prototype, and the user will perceive them through AR.

The most diverse actions can be executed; for example, if an action to turn on the radio is executed, a green light will be turned on in the functional radio prototype, and a sound from some broadcaster will start playing.

The architecture presented allows the four modules in this step to be integrated into a single device, with a single camera or configured in separate devices using 1 or 2 independent cameras. In the present work, they are integrated into a single device.

The hand gesture detector module is responsible for identifying the movements made by the user's hands and converting them into clicks or touches to be performed on the prototype. In this way, it is possible to interact with the prototype without using gloves or markers on the hands or fingers. This module can be implemented using some specific algorithm for hand and gesture recognition [Shen *et al*., 2011] or using some tool available in the development platforms. In this work, the Vuforia virtual button-tool was used [Vuforia, 2020].

Vuforia's virtual button [Vuforia, 2020] works by occluding parts of the marker with one's finger or some other object that is interacting with the marker. This process has some limitations if the marker is very simple, or if the interacting object is small. However, in the experiments carried out in this work, the virtual button performed satisfactorily.

3.1.4 Prototype Evaluation

The last stage of CYPIRP is the Prototype Evaluation. The user who experimented with the Structural and Functional Prototype must report the failures or needs perceived during the use of the prototype. This information must be passed on to and analyzed by the prototype development team so that refinement can be performed with the suggestions generated by the user, which can be accepted or not, and, if necessary, the prototype will be adapted, developing a new prototype and all the steps are performed again.

This step is part of the Noorani [2006] macro step Test and Evaluation of the Prototype, and the Evaluation part follows without changes compared to the Noorani [2006] proposal and must follow processes specific to each industry.

After this step, one must answer the question: "Does it meet the evaluation criteria? If it does not, the prototype must be adjusted, and the steps must be performed again. If it does, the prototype is ready to go to the assembly line, and the final product can be produced.

3.2 Evaluation of the CYPIRP process

The proposed process needs to be evaluated. One way to do this is through case studies applied to users who try out the system and evaluate it.

User experience (UX) is the combination of what the user feels, perceives, thinks, and how he reacts physically and mentally before and during the use of a given product or service [Punchoojit and Hongwarittorrn, 2017]. Understanding user needs and expectations is essential for successful product design. A common way to analyze UX is through questionnaires; however, it is vital to recognize that participants are not always objective.

3.2.1 Questionnaire definition

Mantova *et al*. [2016] study the various metrics for applying questionnaires for multiple purposes. Among the metrics presented, the ones that most fit the character of the research in question are the Software Usability Measurement Inventory (SUMI) [Kirakowski and Corbett, 1993] and the

AttrakDiff. The SUMI is recommended for any organization that wishes to measure the perceived quality of software use. The AttrakDiff [Hassenzahl *et al*., 2003] is recommended to measure the attractiveness of an interactive product through pairs of opposing adjectives [Mantova *et al*., 2016].

Sauro and Lewis [2016], in the same direction as the first investigated authors, present possible options for applying standardized questionnaires, stating that these are intended to assess participants' satisfaction with the perceived usability of products or systems during or immediately after usability testing. In the authors' words, a standardized questionnaire should be designed for repeated use, usually with a specific set of questions presented in a specified order using a previously defined format, with particular rules to produce metrics based on respondents' answers [Sauro and Lewis, 2016].

Aligned with Mantova *et al*. [2016], Sauro and Lewis [2016] also consider the previously mentioned SUMI as one of the most widely used standardized usability questionnaires for evaluating usability perceptions at the end of a study (after completion of a set of test scenarios). Among others cited for this purpose, the authors present the Post-study System Usability Questionnaire (PSSUQ) [Lewis, 2002] as a revised and updated option for the former, as well as the Software Usability Scale (SUS) [Brooke, 1996], the latter recommended by the authors for application in the case of post-study.

After analyzing the questionnaire models proposed by Sauro and Lewis [2016] and Mantova *et al*. [2016], we considered for the choice of model to be applied in the present research, the following parameters: applicability, ease of interpretation by users, and quality of information generated from the answers.

Given this need, we analyzed the then most recent User Experience Questionnaire (UEQ) developed by Laugwitz *et al*. [2008] for a German software company based on a theoretical model of UX described by Marc Hassenzahl [Hassenzahl *et al*., 2003].

The UEQ is intended to assess user perception in the light of the product's distinction between "perceived ergonomic quality and perceived hedonic quality" [Laugwitz *et al*., 2008]. For this case, ergonomic and hedonic aspects express two aspects of software product quality. The former concerns aspects related to accomplishing tasks and goals efficiently and effectively, while the latter focuses on the aesthetic quality of the interface [Laugwitz *et al*., 2008].

According to Hassenzahl [Hassenzahl *et al*., 2003], ergonomic quality is related to product usability, which addresses the human need to be safe and in control of the situation. The hedonic quality refers to qualitative dimensions and thus addresses the human need for change or novelty and social power, which presents itself in visual design, an innovative interface, or new features [Hassenzahl *et al*., 2003].

Although the SUS [Brooke, 1996] has been recommended for its popularity, efficiency, and speed in obtaining answers, and the PSSUQ [Lewis, 2002], in its Third version (2002), with sixteen items, has also proven effective for the objective proposed in the present study, the UEQ was chosen here. The latter was selected for application in the work presented here for being considered more current, intuitive, and contemplating aspects necessary for the evaluation of the proposed model from questions referring to the effectiveness and efficiency of the software and aesthetic quality of the interface, ergonomic and hedonic characteristics, respectively, as advocated by the author above. As recommended by [Rauschenberger *et al*., 2013], the UEQ was applied to a sample of thirty users in order to obtain a valid impression in the face of the diversity of people investigated and the range of possible answers.

The hypothesis that will be verified is whether the process of rapid interactive prototyping proposed in this work helps us to understand the product in subjective parameters and information beyond the physical model, thus facilitating the interpretation of data for production. The questionnaire aims to verify user satisfaction and the relationships established between the user and the interactive prototyping system.

3.2.2 Evaluation Experiment Setup

The Research Ethics Committee of UFPE authorized the experiment, and all volunteers signed the Free and Informed Consent Term (FICT). The project is registered in Plataforma Brasil with the title: "Rapid interactive prototyping combining 3D Printing and AR" with the Certificate of Presentation of Ethical Appreciation (CAAE) identification code: 52200121.5.0000.5208. The performance of the CYPIRP as an experiment followed the ethical precepts of Resolution 466/12 or 510/16 of the Brazilian National Health Council.

This section presents how the participants were recruited and the procedures for applying the experiment.

The experiment was carried out at the Informatics Center - UFPE; the questionnaire was applied at the same place.

The recruitment of volunteers was done through public calls in the e-mail lists of the Informatics Center (CIn) and the Arts and Communication Center (CAC) of UFPE. Volunteers were also recruited directly from passers-by at the Informatics Center, who were approached and invited to participate in the experiment.

The characteristics needed for the participants to be included or excluded from the research are described below.

Inclusion criteria - The target population will be students, employees, and professors from the Informatics Center (CIn) and the Arts and Communication Center (CAC) at UFPE, aged between 18 and 60.

Exclusion criteria - Those who do not know how to handle a smartphone basically and those over 60.

In order to carry out the experiment, the necessary equipment includes a VR goggles, a smartphone, and a 3D printed physical prototype of the case study being investigated.

Paper-printed questionnaires were used for data collection, answered with a pen after the experiment had been carried out.

The following procedures will be performed:

- Sanitizing the user's hands.
- Explaining to the user with instructions on how to perform the experiment;
- Equipping the VR glasses on the face and positioning the physical prototype in the hands.
- Executing the experiment, by manipulating the physical prototype and visualization in AR of the functional prototype.

- Applying of the UEQ questionnaire after the experiment.

The instructions on how to perform the experiment vary depending on the case study.

3.2.3 Analysis and Interpretation of Experiment

The experiment was conducted with a sample size of 30 subjects. The distribution of the mean is close to the normal distribution from sample sizes of 30, obtaining a statistically reliable result [Sauro and Lewis, 2016]. This sample size is also the value recommended by Rauschenberger *et al.* [2013] and Schrepp *et al.* [2017].

The result obtained will be analyzed through graphs. Initially, the 26 properties of the UEQ were divided into two groups, namely the group where the optimal outcome is the value seven and the group where the optimal result is one. Each of these groups was left with 13 properties. After this division, two graphs are generated for each group.

The first chart used is the Boxplot, which shows the minimum value, maximum value, first quartile, third quartile, and median (second quartile) [Montgomery and Runger, 2021]. This graph will be generated based on the 13 properties in each group, analyzing the seven possible values that can occur. In this way, the properties that received a better score and those that received a worse one will be visible.

The second graph is the histogram, which displays the frequency of occurrence with which each possible score value occurred [Montgomery and Runger, 2021]. In this way, the number of times each score (from 1 to 7) occurred in each group of 13 properties is displayed. It will be visible whether most of the scores were close to or far from the optimal expected value.

The properties with a low score will be analyzed to see whether any changes can be made to the proposed system to improve this result.

According to the founders of UEQ [Schrepp *et al.*, 2017], the 26 pairs of UEQ opposite adjectives can be segmented into six groups, which are listed below:

- Attractiveness. Overall impression of the experience. Did users like it or not? Is it attractive, pleasant, or enjoyable? Six pairs are in this category: Annoying/Enjoyable, Good/Bad, Unlikable/Pleasing, Unpleasant/Pleasant, Attractive/Unattractive, and Friendly/Unfriendly.
- Perspicuity. Is it easy to become familiar with experience? Is the experience clear and easy to understand? Four pairs are in this category: Not Understandable/Understandable, Easy to Learn/Difficult to Learn, Complicated/Easy, and Clear/Confusing.
- Efficiency. Can users solve the tasks without unnecessary effort? Is the interaction efficient and rapid? Does the experience respond quickly to the user? Four pairs are in this category: Fast/Slow, Inefficient/Efficient, Impractical/Practical, and Organized/Cluttered.
- Dependability. Do the users feel in control of the interaction? Can they predict the system's behavior? Do they feel safe during the experience? Four pairs are in this category: Unpredictable/Predictable, Obstructive/Supportive, Secure/Not Secure, and Meets Expectations/Does not Meet Expectations.
- Stimulation. Is the experience stimulating and motivating? Is it fun? Four pairs are in this category: Valuable/Inferior, Boring/Exciting, Not Interesting/Interesting, and Motivating/Demotivating.
- Novelty. Is the experience innovative and creative? Does it catch the users' attention? Four pairs are in this category: Creative/Dull, Inventive/Conventional, Usual/Leading Edge, and Conservative/Innovative.

UEQ provides on its website [Schrepp *et al.*, 2022] a data analysis tool, in spreadsheet format, that analyzes user responses by scoring the result according to the listed groups [Schrepp *et al.*, 2017].

This tool has a standard reference table (benchmark), with the averages of the answers of 21175 volunteers in 468 papers, in the current version used [Schrepp *et al.*, 2022]. This makes it possible to compare the results obtained in this work with those cataloged in the benchmark [Schrepp *et al.*, 2017].

The UEQ response values range from 1 to 7; however, the data analysis tool transposes these values so that they are in the range of -3 to +3. The pairs of opposite adjectives that had the positive value in response 1 were reversed so that all the optimal positive responses were in the +3 value and all the optimal negative responses were in the -3 value.

The results available in the tool are divided into five quality scales:

- Excellent item: The evaluation of the experiment is between 10% of the best results.
- Good: 10% of the results in the benchmark is better than the evaluated experiment, and 75% of the results are worse.
- Above average: 25% of the results in the benchmark are better than the evaluated experiment, and 50% of the results are worse.
- Below average item: 50% of the results in the benchmark is better than the evaluated experiment, and 25% of the results are worse.
- Bad: The evaluation of the experiment is among the 25% of the worst results.

The tool itself generates a Stacked Columns chart with the results of these comparisons. Thus, the results obtained were also analyzed using this chart.

3.3 Case Study

This section presents a case study used to validate the proposed process. It was performed with a children's toy car with several possible interactions.

It is possible to open and close the car door; the windows have moving parts that go up and down and make noise. In the trunk, a bird can be moved from side to side and makes a sound. The wheels turn as if the car were moving.

The CYPIRP process was applied to this case study, and each of the four steps is detailed in the following topics.

3.3.1 Product Specification

This step defines which product will be developed, its characteristics, and its 3D model are elaborated.

The product defined for this case study was a children's toy of a car. The colorful 3D model of the vehicle was developed in a traditional CAD application; in this case, the Blender [Lee, 2008] application was used. All moving parts of the toy, such as the car door, windows, wheels, and trunk, were modeled separately and then positioned on the main block of the model. No optimization was done in Computer-Aided Engineering (CAE). The 3D model of this car is shown in Figure 6.

Figure 6. 3D model of the car toy

The output of this step is the 3D model of the product, which is used in the Structural and Functional Prototyping step.

3.3.2 Structural and Functional Prototyping Creation

To produce the structural prototype, the 3D model of the product is used in the Digital Fabrication module, which physically makes the prototype. We used a monochrome Fused Filament Fabrication (FFF) 3D printer in this case study. The structural prototype was 3D printed in one solid color, a shade of purple, in a single block, with no moving parts, as shown in Figure 7.

Figure 7. Structural Prototype of the car toy

To create the functional prototype, the actions and reactions that should happen during the interactions with the user were defined. The interaction regions were determined, and these are activated through touch actions. Each area has its reaction, and these are listed in Table 1.

The functional prototype was implemented in Unity Engine [Unity, 2022], and each action and reaction was configured. The touch actions were developed using the Box Collider feature, which must be set to cover the entire region where a specific action can be performed. The reactions were set up with the Animator feature. When a collision occurs, the response of the corresponding area is activated.

Table 1. Region and Reaction

Region	Reaction
Front/Back Wheels	The wheels are rotated counterclockwise as if the car were moving forward.
Door	Rotating movement to open or close the door, and a door creaking sound.
Front window	It has disks that move vertically up and down.
Back window	Vertical translation movement up and down the window.
Luggage rack	Horizontal translation movement, allowing lateral movements.

Using the animations, it is possible to define basic translation and rotation movements. For each moving part of the prototype, an animation corresponding to the expected reaction was configured. A rotation animation from zero degrees up to 110 degrees was configured for the car door. Figure 8 shows the result of this animation, from its initial state, through the 45 degrees angle until the end of the animation at 110 degrees.

After the structural and functional prototypes are set up, we move on to the Prototype Experiment stage.

3.3.3 Prototype Experiment

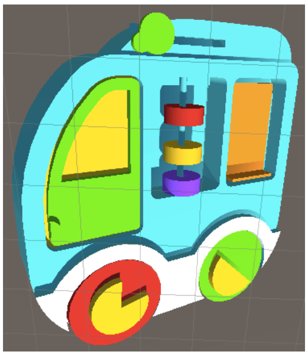
The proposed CYPIRP process architecture (Figure 5) has been configured to allow a simple experiment environment on a single device. Each module of the architecture configured for this case study is presented below.

The AR Controller module used is the AR library Vuforia [Vuforia, 2020], which works integrated with the Unity Engine [Unity, 2022].

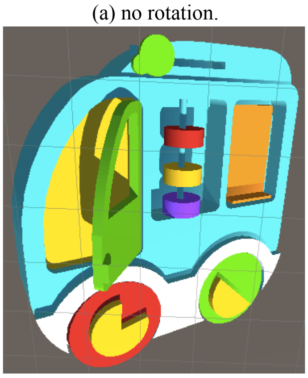
To enable the overlapping of the prototypes, the AR Target feature of the Vuforia library is used [Vuforia, 2020]. The marker used was the structural prototype itself; for this Image Target type marker was used, and the image used is a picture of the structural prototype; this image is presented in Figure 9. In this way, the marker is practically imperceptible to the user, functioning as an invisible marker [Park and Park, 2010]. The functional prototype, which is only visible in AR, is associated with this physical marker. When the marker is detected in the field of view of the display device, the functional prototype is displayed over the physical marker. The functional prototype should be positioned so that it overlaps with the marker. In this way, when the marker is detected, the functional prototype is presented to cover up the structural prototype.

The Gesture Detector module was implemented using the Virtual Buttons feature from the Vuforia library [Vuforia, 2020]. The Virtual Buttons detect touches over specific regions of the Image Marker. Each virtual button was positioned over the marker's region that corresponds to a user interaction region. Figure 9 shows the areas of the virtual buttons on the image marker. It is possible to notice that they are precisely in the areas where the actions and reactions of the functional prototype take place.

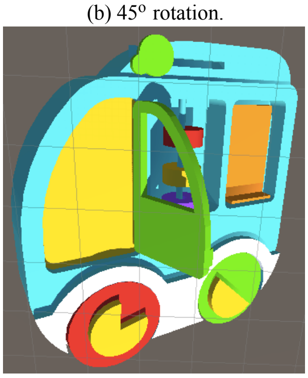
The Central Controller module was developed in C# on Unity Engine [Unity, 2022] and managed the actions re-



(a) no rotation.



(b) 45º rotation.



(c) 110º rotation.

Figure 8. Animation of door rotation.

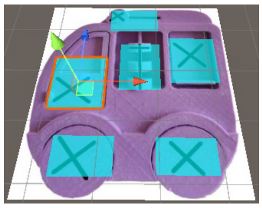


Figure 9. Image marker and the virtual buttons

ceived from the Gesture Detector module and generated the reactions on the functional prototype.

All modules were embedded in a single mobile application, developed in Unity Engine [Unity, 2022]. The application was tested on the Android platform.

The Visualization Device uses a VR goggle with an Android phone attached as a screen, enabling AR through Video see-through. The Viewer Device and the Gesture Detector module use the cell phone's camera.

The user taking the test is instructed to follow these instructions:

1. Put the AR glasses on;
2. Hold the prototype with your hands;
3. Perform the following tasks on the prototype:
    - Open and close the car door;
    - Rotate the wheels of the car;
    - Raise and lower the car windows;
    - Move the luggage rack sideways;

In Figure 10, you can see the structural and functional prototype being tried out on the CYPIRP system. It can be seen that the car door was being opened as the user put his hand on the door of the structural prototype.

Figure 10. The structural and functional prototype being tested.

A demonstration video on this case study has been made available on YouTube [Omaia, 2023a]. The source code of this Unity project was made available at GitHub [Omaia, 2023b].

3.3.4 Prototype Evaluation

After the prototype experimentation has been performed, the user is invited to suggest adjustments that can be made to the prototype. The suggestions were documented and are presented in Section 4 (Results). However, no new development cycle was run with the recommendations made.

After the case study is completed, the user is invited to answer the UEQ questionnaire.

4 Results

The process proposed in this paper was applied in the case studies presented. An experiment was conducted with 30 users to test and evaluate the system developed.

The proposed case study was applied to a group of 30 volunteers, and each volunteer answered UEQ [Laugwitz *et al.*, 2008] questionnaires. The volunteers are undergraduate students and university employees, all over 18 years old.

4.1 Children's Car Toy

Right after the execution of the experiment of the child's toy car, the volunteers were asked to answer the UEQ [Laugwitz *et al.*, 2008] questionnaire about their experience of manipulating the functional prototype. The results are presented below.

Table 2 shows the table with the unified result of the answers of the 30 users. In the seven possible answers of each opposite pair, the number of volunteers that gave that same answer is shown. For example, in the Annoying/Enjoyable pair, eleven volunteers answered value 7, ten volunteers answered value 6, four volunteers answered value 5, and five volunteers answered 4. The values 1, 2, and 3 were not represented.

Table 2. Complete UEQ Result

	1	2	3	4	5	6	7	
Annoying	0	0	0	5	4	10	11	Enjoyable
Not Understandable	0	0	0	0	4	6	20	Understandable
Creative	18	8	3	0	0	0	1	Dull
Easy to Learn	24	3	0	2	0	1	0	Difficult to Learn
Valuable	10	7	4	7	1	1	0	Inferior
Boring	0	0	0	2	6	14	8	Exciting
Not Interesting	0	0	0	0	2	9	19	Interesting
Unpredictable	1	0	3	8	4	6	8	Predictable
Fast	8	8	6	5	2	1	0	Slow
Inventive	14	9	7	0	0	0	0	Conventional
Obstructive	0	0	1	3	10	6	10	Supportive
Good	19	11	0	0	0	0	0	Bad
Complicated	0	0	0	2	4	3	21	Easy
Unlikable	0	0	0	0	4	8	18	Pleasing
Usual	0	1	1	12	6	8	2	Leading Edge
Unpleasant	0	3	2	2	4	12	7	Pleasant
Secure	24	3	2	0	1	0	0	Not Secure
Motivating	17	8	3	1	1	0	0	Demotivating
Meets Expectations	18	8	4	0	0	0	0	Does not meet Expectations
Inefficient	0	0	1	3	2	12	12	Efficient
Clear	12	10	5	2	1	0	0	Confusing
Impractical	0	0	0	0	5	2	23	Practical
Organized	22	8	0	0	0	0	0	Cluttered
Attractive	16	8	5	1	0	0	0	Unattractive
Friendly	21	8	1	0	0	0	0	Unfriendly
Conservative	0	0	0	3	6	8	13	Innovative

Of the 26 pairs of opposing adjectives, those considered positive for the evaluation were colored green, and the non-positive adjectives a shade of yellow. Of the 7 possible responses, values 1, 2, and 3 indicate a tendency toward the first adjective, and values 5, 6, and 7 have a tendency toward the second adjective. Value 4 indicates either neutrality or that the volunteer did not know how to define the indicated adjective correctly.

Table 2 was reorganized, aiming at a better understanding of the results. For this purpose, the number of responses for each item was normalized, some columns were grouped, and the rows were reordered. The new table is shown in Table 3.

The normalization was performed by obtaining the quantity of each response, which varies between 0 and 30 and dividing it by the maximum quantity of responses, i.e., 30. Thus, $normalized\_value = quantity\_responses/total\_responses$. The grouping of the columns was done based on each column's trends; thus, columns 1, 2, and 3 and columns 5, 6, and 7 had their contents grouped and summed. Each row of the table was rearranged. Initially, the 13 pairs of adjectives, where the optimal adjective is value 1, were at the beginning of the table (Optimal Group 1), and the 13 pairs where the optimal adjective is value 7 were at the end of the table (Optimal Group 7). The pairs of adjectives in Optimal Group 1 were then arranged in descending order according to the answers 1, 2, and 3; and the pairs in Optimal Group 7 were arranged in descending order according to the column of answers 5, 6, and 7.

Table 3. Ordered Simplified Result of UEQ

	1,2,3	4	5,6,7	
Inventive	1,00	0,00	0,00	Conventional
Good	1,00	0,00	0,00	Bad
Meets Expectations	1,00	0,00	0,00	Does not meet Expectations
Organized	1,00	0,00	0,00	Cluttered
Friendly	1,00	0,00	0,00	Unfriendly
Creative	0,97	0,00	0,03	Dull
Secure	0,97	0,00	0,03	Not Secure
Attractive	0,97	0,03	0,00	Unattractive
Motivating	0,93	0,03	0,03	Demotivating
Easy to Learn	0,90	0,07	0,03	Difficult to Learn
Clear	0,90	0,07	0,03	Confusing
Fast	0,73	0,17	0,10	Slow
Valuable	0,70	0,23	0,07	Inferior
Not Understandable	0,00	0,00	1,00	Understandable
Not Interesting	0,00	0,00	1,00	Interesting
Unlikable	0,00	0,00	1,00	Pleasing
Impractical	0,00	0,00	1,00	Practical
Boring	0,00	0,07	0,93	Exciting
Complicated	0,00	0,07	0,93	Easy
Conservative	0,00	0,10	0,90	Innovative
Inefficient	0,03	0,10	0,87	Efficient
Obstructive	0,03	0,10	0,87	Supportive
Annoying	0,00	0,17	0,83	Enjoyable
Unpleasant	0,17	0,07	0,77	Pleasant
Unpredictable	0,13	0,27	0,60	Predictable
Usual	0,07	0,40	0,53	Leading Edge

After these changes, it is possible to see in Table 3, that the positive adjectives always got more responses than the negative adjectives and were also higher than the number of neutral responses (value 4) for all 26 pairs of adjectives.

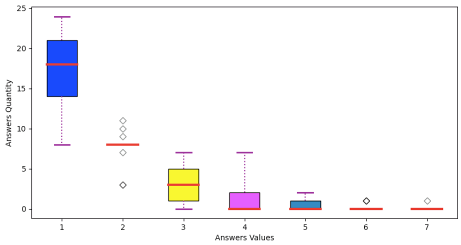
It is also possible to note that of the 26 positive adjectives, only 2 (Predictable and Leading Edge) were less than 70% of the responses obtained, and even in two, the positive responses were still higher, followed by the neutral responses (value 4) and the negative responses.

The pairs that received the most neutral responses (value 4) were: Valuable/Inferior, Unpredictable/Predictable, and Usual/Leading Edge. This indicates that the volunteers were in doubt regarding these points; however, even in these pairs, the number of responses referring to positive adjectives was still higher.

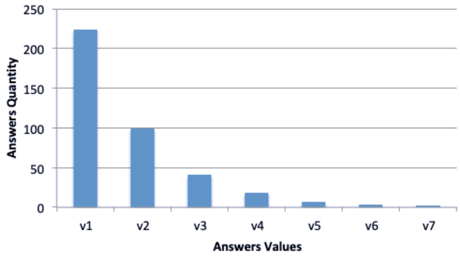
Of the 26 pairs of adjectives, in 12 of them, the rate of positive responses was greater than 95%. The adjectives that received more responses than 95% were: Inventive, Good, Meets Expectations, Organized, Friendly, Creative, Secure, Attractive, Understandable, Interesting, Pleasing and Practical.

For each group (Optimum 1 and Optimum 7), the Boxplot and Histogram plots were generated. For the Optimal 1 group, these 2 graphs are presented in Figure 11.

It can be seen in Figure 11 that the two graphs for the Optimal 1 group indicate a more significant amount of responses for values 1 and 2 than for the other values. In the Box Diagram graph (Figure 11.a) several metrics can be obtained. With regard to response 1, it received the maximum value of 24 responses (adjectives Secure and Easy to Learn); the

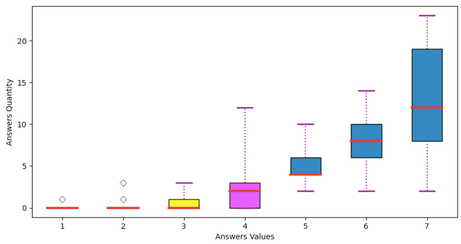


(a) Box plot.

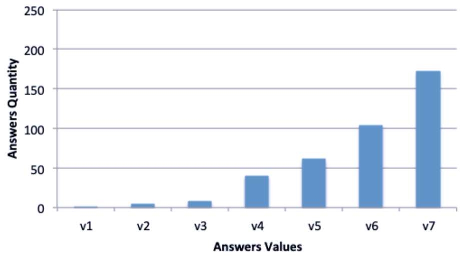


(b) Histogram.

Figure 11. Graphs Optimal Group 1.



(a) Box plot.



(b) Histogram.

Figure 12. Graphs Optimal Group 7.

third quartile received the value of 21 responses (adjective Friendly); the median was 18 responses (adjective Meets Expectations); the first quartile was 14 responses (adjective Inventive), and the minimum value received in response 1 was 8 responses (adjective Fast).

The histogram graph (Figure 11.b) indicates the number of responses received for each response on the 13 adjectives in the group in question. Response 1 received 223 responses from a maximum of 390 answers. This total of possible responses value is calculated by multiplying the number of volunteers by the number of pairs. This way: $total = numberPairs * numberVolunteers$, that is, $total = 13 * 30 = 390$.

Figure 12 presents the Box plot and Histogram plots for Optimal Group 7. The behavior of the results is inversely proportional to that of Optimal Group 1, indicating a more significant amount of responses for values 6 and 7. However, in Optimum Group 7, values 6 and 7 represent positive adjectives for the experiment.

The UEQ data analysis tool was used to compare the results obtained with the standard reference table (benchmark) made available [Schrepp *et al.*, 2017, 2022]. The mean values obtained in the responses of the present work were calculated for the six groups (Attractiveness, Transparency, Efficiency, Control, Stimulation, Innovation) [Schrepp *et al.*, 2017]. These mean values are presented in Table 4.

Table 4. Average responses for the experiment.

Scale	Mean	Comparison to benchmark
Attractiveness	2,22	Excellent
Perspicuity	2,38	Excellent
Efficiency	2,19	Excellent
Dependability	1,98	Excellent
Stimulation	2,08	Excellent
Novelty	1,86	Excellent

Using the data analysis tool, the Stacked Columns chart of the averages for the six groups of the possible [Schrepp *et al.*, 2017] responses were also generated. This graph is displayed in Figure 13 and presents the benchmark averages for each group and the comparison with the average obtained in the proposed experiment, which is highlighted by the black line between the columns. From both the graph and Table 4 it is possible to notice that the result obtained was in the excellent range in the 6 analyzed groups. The excellent result means that the result is in the range of the 10% best results.

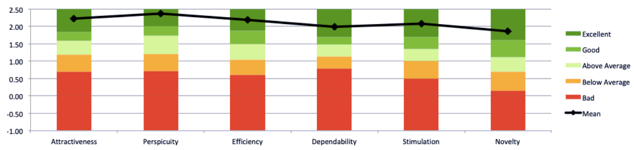


Figure 13. UEQ result based on the categories

4.2 Results Conclusion

In Optimal 1 group, most answers were for the values 1, 2, and 3. In Optimal 7 group, most answers were for the values 5, 6, and 7. These results indicate that most of the volunteers selected answers with positive adjectives to the experiment, thus indicating that the experience was positive overall.

The comparison with the benchmark is an indicator of whether the proposed process offers a UX sufficient to be successful in the market [Schrepp *et al.*, 2017]. As the results obtained were considered excellent in all six groups, we can infer that the proposed process would be well accepted in the market.

5 Conclusion

This section presents the final considerations on the main topics addressed in this paper, including the contributions achieved and indications for future work.

5.1 Main Contributions

The present work proposed a new structural, functional, and interactive rapid prototyping process (Cyclic Process of Interactive Rapid Prototyping (CYPIRP)) for product development, exploiting the advantages of AR and 3D Printing. An architecture for an interactive prototyping system was also proposed and implemented. This process was considered innovative for combining these two techniques (AR and 3D Printing), generating a structural, functional, and interactive prototype using a process that had not yet been applied in the literature.

To validate and address these contributions, a systematic literature review was conducted on works in interactive rapid prototyping that use AR and 3D Printing.

The secondary contributions are listed below:

- Interaction through hand gestures, allowing manipulation of the prototype using the fingers, without needing gloves or special markers.
- Prototyping experiment on a single device, with a single video camera, generating a test system of simple configuration.
- Tracking the object of interest without the need for traditional AR markers. That is, the 3D-printed object itself was used as a marker.

Of the proposed objectives, all were achieved, among them:

- Defining the architecture of the proposed prototyping system;
- Developing the proposed prototyping system;
- Developing a case study
- Analyzing the case study through the application of questionnaires
- Validating and testing the process;

Validation of this system was performed through user testing. A group of 30 users tried out the system, and after the experiment, they answered the UEQ [Schrepp *et al.*, 2017] questionnaire. The answers were analyzed, and it can be inferred that the process had a good receptivity, achieving excellent averages of satisfaction in the UEQ benchmark, among the top 10% of results.

5.2 Future Works

To continue the research work described here, this section lists proposals for future work.

- Conduct more case studies.
- Experiment on a group of industry volunteers.
- Apply the process to large products, not just manual products.

5.3 Concluding Remarks

The present work has met expectations, demonstrating that the proposed system is applicable due to its high receptivity, making the industrial prototyping phase faster, more rapid, efficient, and concise.

References

Abulrub, A. H. G., Attridge, A. N., and Williams, M. A. (2011). Virtual reality in engineering education: The future of creative learning. In *2011 IEEE Global Engineering Education Conference (EDUCON)*, pages 751–757. DOI: 10.1109/EDUCON.2011.5773223.

Akaoka, E., Ginn, T., and Vertegaal, R. (2010). Displayobjects: Prototyping functional physical interfaces on 3d styrofoam, paper or cardboard models. In *Proceedings of the Fourth International Conference on Tangible, Embedded, and Embodied Interaction*, TEI '10, pages 49–56, New York, NY, USA. ACM. DOI: 10.1145/1709886.1709897.

Alexander, C. *et al*. (2009). *Value proposition development of early stage computational fluid dynamics analysis in automotive product development*. PhD thesis, Massachusetts Institute of Technology.

An, S.-G., Kim, Y., Lee, J. H., and Bae, S.-H. (2017). Collaborative experience prototyping of automotive interior in vr with 3d sketching and haptic helpers. In *Proceedings of the 9th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*, AutomotiveUI '17, pages 183–192, New York, NY, USA. ACM. DOI: 10.1145/3122986.3123002.

Arrighi, P.-A. and Mougenot, C. (2019). Towards user empowerment in product design: a mixed reality tool for interactive virtual prototyping. *Journal of Intelligent Manufacturing*, 30(2):743–754. DOI: 10.1007/s10845-016-1276-0.

Balcisoy, S., Kallmann, M., Fua, P., and Thalmann, D. (2000). A framework for rapid evaluation of prototypes with augmented reality. In *Proceedings of the ACM symposium on Virtual reality software and technology*, pages 61–66. ACM.

Baxter, M. (1995). Product design: A practical guide to systematic methods of new product development.

Brooke, J. (1996). Sus: a 'quick and dirty' usability. *Usability evaluation in industry*, 189.

Choi, S. and Chan, A. (2004). A virtual prototyping system for rapid product development. *Computer-Aided Design*, 36(5):401 – 412. DOI: http://dx.doi.org/10.1016/S0010-4485(03)00110-6.

Fernandes, A. S., Wang, R. F., and Simons, D. J. (2015). Remembering the physical as virtual: Source confusion and physical interaction in augmented reality. In *Proceedings of the ACM SIGGRAPH Symposium on Applied Perception*, SAP '15, pages 127–130, New York, NY, USA. ACM. DOI: 10.1145/2804408.2804423.

Furht, B. (2011). *Handbook of augmented reality*. Springer Science & Business Media.

Gibson, I., Rosen, D., and Stucker, B. (2014). *Additive manufacturing technologies: 3D printing, rapid prototyping, and direct digital manufacturing*. Springer.

Gieser, S. N., Gentry, C., LePage, J., and Makedon, F. (2016). Comparing objective and subjective metrics between physical and virtual tasks. In Lackey, S. and Shumaker, R., editors, *Virtual, Augmented and Mixed Reality: 8th International Conference, VAMR 2016, Held as Part of HCI International 2016, Toronto, Canada, July 17-22, 2016. Proceedings*, pages 3–13, Cham. Springer International Publishing. DOI: 10.1007/978-3-319-39907-2$_1$.

Hassenzahl, M., Burmester, M., and Koller, F. (2003). *AttrakDiff: Ein Fragebogen zur Messung wahrgenommener* *hedonischer und pragmatischer Qualität*, pages 187–196. Vieweg+Teubner Verlag, Wiesbaden. DOI: 10.1007/978-3-322-80058-$9_1$9.

Katakura, S. and Watanabe, K. (2018). Protohole: Prototyping interactive 3d printed objects using holes and acoustic sensing. In *Extended Abstracts of the 2018 CHI Conference on Human Factors in Computing Systems*, CHI EA '18, pages LBW112:1–LBW112:6, New York, NY, USA. ACM. DOI: 10.1145/3170427.3188471.

Khan, T., Johnston, K., and Ophoff, J. (2019). The impact of an augmented reality application on learning motivation of students. *Advances in Human-Computer Interaction*, 2019:7208494. DOI: 10.1155/2019/7208494.

Kirakowski, J. and Corbett, M. (1993). Sumi: The software usability measurement inventory. *British journal of educational technology*, 24(3):210–212.

Laugwitz, B., Held, T., and Schrepp, M. (2008). Construction and evaluation of a user experience questionnaire. In Holzinger, A., editor, *HCI and Usability for Education and Work*, pages 63–76, Berlin, Heidelberg. Springer Berlin Heidelberg.

Lee, S. S. (2008). Blender. US Patent App. 29/305,015.

Lee, W. and Park, J. (2005). Augmented foam: A tangible augmented reality for product design. In *Proceedings of the 4th IEEE/ACM international symposium on mixed and augmented reality*, pages 106–109. IEEE Computer Society.

Leite, J. V. d. F., Teixeira, J. M. X. N., and Teichrieb, V. (2016). *Optimizing 3D Object Visualization on the Web*, pages 287–298. Springer International Publishing, Cham. DOI: 10.1007/978-3-319-39907-$2_2$7.

Lewis, J. R. (2002). Psychometric evaluation of the pssuq using data from five years of usability studies. *International Journal of Human-Computer Interaction*, 14(3-4):463–488.

Macdonald, E., Salas, R., Espalin, D., Perez, M., Aguilera, E., Muse, D., and Wicker, R. B. (2014). 3d printing for the rapid prototyping of structural electronics. *IEEE access*, 2:234–242.

Mantova, A. R., Ferreira, A. C. M., da Cruz Landim, P., and Marar, J. F. (2016). Escala dos questionários para análise da experiência do usuário: Estudo preliminar. *Blucher Design Proceedings*, 2(9):1130–1137.

Marner, M. R., Smith, R. T., Porter, S. R., Broecker, M. M., Close, B., and Thomas, B. H. (2011). Large scale spatial augmented reality for design and prototyping. In *Handbook of Augmented Reality*, pages 231–254. Springer.

Montgomery, D. C. and Runger, G. C. (2021). *Estatística aplicada e probabilidade para engenheiros (7nd ed.)*. LTC, Rio de Janeiro (RJ.

Morozova, A., Rheinstädter, V., and Wallach, D. (2019). Mixedux: A mixed prototyping framework for usability testing in augmented reality. In *Companion Publication of the 2019 on Designing Interactive Systems Conference 2019 Companion*, DIS '19 Companion, pages 41–44, New York, NY, USA. ACM. DOI: 10.1145/3301019.3325146.

Noorani, R. (2006). *Rapid prototyping: principles and applications*. John Wiley & Sons Incorporated.

Omaia, D. (2023a). 3d car toy prototype using the cypirp. `https://www.youtube.com/watch?v=q7QNOgbb04Q`.

Omaia, D. (2023b). 3dcar-cypirp. `https://github.com/derzu/3DCar-CYPIRP`.

Park, H., Moon, H.-C., and Lee, J. Y. (2009). Tangible augmented prototyping of digital handheld products. *Computers in Industry*, 60(2):114–125.

Park, H. and Park, J.-I. (2010). Invisible marker–based augmented reality. *International Journal of Human-Computer Interaction*, 26(9):829–848. DOI: 10.1080/10447318.2010.496335.

Porter, S. R., Marner, M. R., Smith, R. T., Zucco, J. E., and Thomas, B. H. (2010). Validating spatial augmented reality for interactive rapid prototyping. In *2010 IEEE International Symposium on Mixed and Augmented Reality*, pages 265–266. DOI: 10.1109/ISMAR.2010.5643599.

Punchoojit, L. and Hongwarittorrn, N. (2017). Usability studies on mobile user interface design patterns: A systematic literature review. *Advances in Human-Computer Interaction*, 2017:6787504. DOI: 10.1155/2017/6787504.

Rauschenberger, M., Schrepp, M., Pérez Cota, M., Olschner, S., and Thomaschewski, J. (2013). Efficient measurement of the user experience of interactive products. how to use the user experience questionnaire (ueq). example: Spanish language version. DOI: 10.9781/ijimai.2013.215.

Sauro, J. and Lewis, J. R. (2016). *Quantifying the user experience: Practical statistics for user research*. Morgan Kaufmann.

Schrepp, M., Hinderks, A., and Thomaschewski, J. (2017). Construction of a benchmark for the user experience questionnaire (ueq). *International Journal of Interactive Multimedia and Artificial Intelligence*, 4:40–44. DOI: 10.9781/ijimai.2017.445.

Schrepp, M., Hinderks, A., and Thomaschewski, J. (2022). User Experience Questionnaire (UEQ). `https://www.ueq-online.org`. [Online; accessed 30-June-2022].

Shen, Y., Ong, S. K., and Nee, A. Y. C. (2011). Vision-based hand interaction in augmented reality environment. *International Journal of Human–Computer Interaction*, 27(6):523–544. DOI: 10.1080/10447318.2011.555297.

Simões, F., Bezerra, M., Teixeira, J. M., Correia, W., and Teichrieb, V. (2016). A user perspective analysis on augmented vs 3d printed prototypes for product's project design. In *2016 XVIII Symposium on Virtual and Augmented Reality (SVR)*, pages 71–80. DOI: 10.1109/SVR.2016.22.

Simon, T. (2012). Tangible spatial augmented reality in rapid prototyping: Multiple and differential tangible object manipulation and interaction.

Stocklein, J., Geiger, C., Paelke, V., and Pogscheba, P. (2009). Poster: Mvce - a design pattern to guide the development of next generation user interfaces. In *2009 IEEE Symposium on 3D User Interfaces*, pages 153–154. DOI: 10.1109/3DUI.2009.4811232.

Stöcklein, J., Pogscheba, P., Geiger, C., and Paelke, V. (2010). Mireas: A mixed reality software framework for iterative prototyping of control strategies for an indoor airship. In *Proceedings of the 7th International Conference on Computer Graphics, Virtual Reality, Visualisation and Interaction in Africa*, AFRIGRAPH '10, pages 27–36, New York, NY, USA. ACM. DOI: 10.1145/1811158.1811164.

Teixeira, J. M., Barros, G., Teichrieb, V., and Correia, W. F. (2016). 3d printing as a means for augmenting existing surfaces. In *2016 XVIII Symposium on Virtual and Augmented Reality (SVR)*, pages 24–28. DOI: 10.1109/SVR.2016.15.

Tziouvara, I. (2012). Integration of 3d tracking systems for interaction in spatial augmented reality. DOI: uuid:acc16325-1c25-445d-ac3c-02c3e89170d4.

Unity (2022). Unity real-time development platform | 3d, 2d vr & ar engine.

Verlinden, J. (2014). *Developing an Interactive Augmented Prototyping Methodology to Support Design Reviews*. urn:nbn:nl:ui:24-uuid:253876ef-b158-4aa1-b39a-7d35fd76f753, TU Delft, Delft University of Technology.

Vuforia (2020). Vuforia developer portal.

Zampelis, D., Loudon, G., Gill, S., and Walker, D. (2012). Iris: Augmented reality in rapid prototyping.

Zorriassatine, F., Wykes, C., Parkin, R., and Gindy, N. (2003). A survey of virtual prototyping techniques for mechanical product development. *Proceedings of the institution of mechanical engineers, Part B: Journal of engineering manufacture*, 217(4):513–530.