



# Physical Display for Visualization of Three-Dimensional Surfaces

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## Abstract

This project is a technological innovation that aims to develop a reconfigurable device of elevation and depth data. In this way, a physical display in 16:9 resolution is created, which will make it possible to display information in three dimensions with the use of elevation data through the implementation of an application that controls 144 servo motors available in a 16x9 matrix, as well as implementing applications to control this display. Based on an Engineering Method, the project consists of a wooden structure with 144 coupled servo motors. Above the table, there is a white knitted fabric, on which the servo motors are attached and perform vertical movements, pulling and lifting the fabric. Attached to the wooden structure, there is another structure in which a projector is attached and projects the images to be displayed over the fabric. This project can have numerous multidisciplinary applications. With the final result of this project, some goals were achieved, such as the development of interactive applications and the way this project can be applied in several different contexts, from school teaching to industrial application.

**Keywords:** Innovation; 3D visualization; Tangible Display

## 1. Introduction

With the computational advances of the last decades, there are new ways of displaying data, making data visualization more interactive, dynamic, understandable and accessible. Thus, this project aims to develop an innovative tool directioned to the tangible three-dimensional visualization of data.

### 1.1. Problem Presentation

Currently, several three-dimensional terrain models and mathematical models can be found in simulations designed for computer screens, Cave Automatic Virtual

Environment (CAVE), stereoscopic glasses and screens with three-dimensional (3D) visualization. As an example, the visualization of spatial data has revolutionized the concept of map, no longer associating the map exclusively to a graphic document printed on paper. However, the display of digital data in a tangible and not purely virtual way is still scarce. Therefore, it is necessary to research different modes of data visualization.

### 1.2. Objectives

Due to the scarcity of 3D altimetric data visualization, the present work aims to build a reconfigurable device for viewing elevation data and depth data. The objective



was to implement a display of physical shapes that can become a multidisciplinary tool. The physical display can be applied in schools, where topographic images and 3D mathematical graphics can be viewed in a more attractive and easily interpreted way by students. Interactivity will help students to understand content, both geographical (study of the topography of a region) and mathematical (3D graphics, bar graphs). Another mode of applying this prototype is associated with the oil market, since this project is also able to simulate and visualize terrain and surfaces digital models. In this way, using the developed display, technical reports can be generated, demonstrating likely regions of new oil deposits and better locations for installations of oil exploration and production equipment. Furthermore, in the social field, this project can bring benefits in the study of risk landslide cases, as well as in prevention, with possible containment works. In short, the final objective was to create a device that, considering the cost-benefit, makes it possible to display information in three dimensions with depth data through the implementation of an application to control 144 servo motors available in a 16x9 matrix, as well as implementing applications to control this display. That said, this article presents the state of the art that inspired and served as the basis of this project, a description of the hardware used and how the applications were implemented, an analysis of results and discussions, and finally a conclusion with future work.

## 2. State of the art

With the advent of technology, new modes of visualization are created to better expose information and facilitate the understanding of this information. In this way, the perception of information does not come only from sight and hearing, but also from touch and the sensation of reality. According to Marieb and Hoehn (2012) as cited in Geng (2013), almost 50% of the human brain's capacity is dedicated to processing visual information. Therefore, when data is associated with visual information, the human brain can be better used to obtain knowledge or understanding of the phenomenon studied. Thus, scientific visualization techniques, that allow the representation of data, increasingly become attractive, causing different techniques to be studied so that more data can be understood and visualized. In conjunction with computational advances, new ways of display devices are being developed for greater perception, not only visual, but also tangible.

### 2.1. 3D Visualization and its Limitations

Since the 1940s, when the first television was created, displays have advanced little. Often the screens that are found on the market cause ambiguity and confusion when it comes to presenting dimensional data or graphical representations, due to the lack of depth information. As good as 3D rendering

techniques and software are, the human's mental capacity to visualize becomes unreliable when depth information is lacking. Schlick, Ziefle, Park, and Luczak (2008) state that alternative ways can be taken for 3D objects to be displayed on 2D screens, such as shutter glasses or polarizing glasses associated to CAVEs, but one of the limitations of such stereoscopic displays is that motion parallax, as one of the depth cues, is not provided automatically. So, it is necessary for a growing development of 3D screens. As an example, Maurits Cornelis Escher, known as the artist of impossible constructions, addresses the problem of representing the real world on 2D canvases. Due to the lack of depth information, Escher deliberately causes confusion when trying to interpret his images. In Figure 1 this problem can be seen.



Figure 1. Belvedere

### 2.2. Tangible Visualization

The Graphical User Interface (GUI) is the most popular and used interface in the world. However, it is limited to its two-dimensional screen and limited in transmitting data to its users. People have developed sophisticated abilities to sense and manipulate their physical environments. However, most of these skills are not employed in interacting with the digital world today. A Tangible User Interface (TUI) builds on these skills and situates the physically embedded digital information in a physical space. (Ishii and Ullmer, 1997; Ullmer and Ishii, 2000, as cited in Ishii, 2008). In this way, Ishii (2008) points out that the TUI has advantages over the GUI, since the interactions with pixels in these GUI screens are inconsistent with our interactions with the rest of the physical environment in which we live. The GUI, tied to the screen, windows, mouse and keyboard, is totally divorced from the way interaction takes place in the physical world. TUIs aim to take advantage of these haptic interaction skills, which is a significantly different approach to the GUI.

The key idea of TUIs is to give physical shapes to digital information. Physical shapes serve as representations and controls for their digital counterparts. TUI makes digital information directly manipulable with our hands and perceptible through our peripheral senses, physically embedding it. Thus, for the construction of the physical display of this present work, it was necessary to research new concepts and similar projects already built or in progress. The idea of new modes of visualization is not new. Next, we will present the four main projects taken as the basis for our development.

#### 2.2.1. *inFORM*

*inFORM* is a project by members of the Tangible Media Group, a group belonging to the MIT Media Lab. In this project, a dynamic shape display was built and it can render 3D content physically, so that users can interact with digital information in a tangible way. According to Leithinger, Follmer, Olwal, and Ishii, (2015) it is possible to physically visualize abstract data in mathematics teaching, in which students can modify equation parameters and see changes on the surface by intuitively finding maximum and minimum locations, as an example.

#### 2.2.2. *AR Sandbox*

*AR Sandbox* (University of California Campus Davis, 2021) is a project on informal science education for freshwater lake and watershed science. The *AR Sandbox* is an example of a 3D environment in which different types of topography can be observed and studied. The project combines 3D visualization applications with a hands-on sandbox display to teach earth science concepts. The augmented reality (AR) sandbox allows users to create topography models by shaping real sand, which is then augmented in real-time by a color map of elevation, topographic contour lines, and simulated water.

#### 2.2.3. *FEELEX*

Another reference project is *FEELEX*. The word is derived from the conjunction of the words *FEEL* with the word *FLEX*. The device consists of a flexible screen, an array of actuators and a projector. The flexible screen is deformed by the actuators to simulate the shape of virtual objects. An image of the virtual objects is projected onto the flexible screen surface. Screen warping converts the projector's 2D image to a solid image. This configuration allows users to touch the image directly using any part of their hand, simultaneously providing visual and haptic sensations, using a single device that does not require the user to use any extra equipment (Iwata, 2008). The actuators are equipped with force sensors to measure the force applied by the user. The hardness of the virtual object is determined by the relationship between the measured force and its position on the screen. If the virtual object is soft, a large deformation is caused by a small force.

#### 2.2.4. *Gemotion Screen*

Niiyama and Kawaguchi (2008) proposed a 3D display system, called *Gemotion Screen*, to present 3D environments and recreate the shapes of all types of 3D objects on a screen. *Gemotion Screen* allows the dynamic expression of 3D worlds not simply as visual illusions, but as a physical object that can be touched. In addition, multiple people can view the screen at the same time, and the system can be applied to large-screen applications.

### 3. Materials and Methods

In this section, the project to be built, the methodology applied, the techniques, tools and materials adopted for the construction of the project will be described. Finally, it will be reported how the device will work with all its components. The project was divided into two main parts which are: the physical part, also referred to as *Hardware*, and the programming part, also referred to as *Software*. In the development of *Hardware* and *Software*, it was also important to divide each part of the project into specific tasks, so that problems could be solved and did not affect the development of other stages. Briefly, the device is a table with mechanisms attached to it and on this table there is a white fabric. The complete set forms the physical display. In this project, reliefs will be formed in this white fabric and images related to these reliefs will be projected on the same fabric. Attached, under the white fabric, there are 144 rods that will move in the vertical direction, pulling or pushing the mesh fabric. The set of movements of these rods will shape the relief in the mesh. To control the physical display, four applications were developed that communicate with the physical display and send data to control the relief shapes. Figure 2 shows the physical display.



Figure 2. Physical Display

### 3.1. Hardware

The physical part of the project consists of a wooden table, servo motors coupled to the connecting rod-crank system, servo motor control modules, the projector and computers that generate and send the images to the projector and send control signals to the modules. The servo motors together with the connecting rod-crank system are responsible for making the rods lift and form the relief in the mesh. For the construction of this project, it was necessary to research different types of materials, equipment and tools that best fit the project requirements, taking into account the cost-benefit.

#### 3.1.1. Servo Motors

The servo motor is an electromechanical device that converts electrical energy into mechanical energy, being used in applications where control and precision of a movement is required. Servo motors have an axis that makes a rotational movement from  $0^{\circ}$  to  $180^{\circ}$ . Each type of servo motor has a scale of numerical values that controls the angulation of its axis. The position of the servo motor is determined by this angulation.

#### 3.1.2. Connecting rod-crank system

In this project, the linear servo motor could have been chosen to perform the vertical movement of the rods. But the choice of the satellite dish servo motor was based on cost-effectiveness, as it is much cheaper and easier to find than the linear servo motor. Thus, it was necessary to think of a system that was coupled to the servo motor, of simple construction and operation and that could convert the circular movement of the servo axis into linear movement of the rods. Thus, the connecting rod-crank system was chosen.

#### 3.1.3. Control modules

One of the computers used in the project is dedicated and runs the software for controlling the position of the servos. To control the height of the rods it is necessary that the servo motor receives a control signal that adjusts the position of its rotational axis. Thus, a control module is needed to act as an intermediary between the servo motor and the second computer. In this project, the SD84 module is used.

#### 3.1.4. Wooden structure

A wooden structure was built to support the number of servo motors, measuring 124 cm long by 73 cm wide and 81 cm high from the ground. The size was dimensioned according to the minimum necessary spacing between each servo motor, forming a 16x9 matrix of servo motors. The structure is formed by two planes made of wood. The plane below is thicker than the plane above. In the wooden foreground, which is thicker, the servo motors are fixed by a fixing bracket, made of aluminum. Each fixing bracket has two holes

and is 14 cm high. This height is necessary to suit the movement and size of the connecting rod-crank system. The second plane is thinner and serves only to guide the rods, both being planes with the same area.

#### 3.1.5. Computers and Projector

In this work, two computers were used. The first computer generated the elevation data for the control module and the second computer acted as a server that received the data and communicated with the SD84 module. The first computer had to be more robust as it would process large images, convert them to grayscale, reprocess them, encode as elevation data, and finally send them to the second computer via Wi-Fi. In addition, the first computer also sent the original images to the projector, which were processed in order to be projected onto the white knitted fabric above the servo motor matrix. The second computer acts as a server, always waiting for any message containing height data to arrive from any device that connects to it via Wi-Fi. Once the elevation data arrived, the second computer would convert this data into a format that the SD84 module could understand and send this data to the module. The projector used in the project is a Samsung brand with 7.9 cm high, 27.9 cm wide and 22.9 cm long. This projector has 2500 lumens among its features, and projects images in HD in 4:3 or 16:9 scale. This projector was fixed by an aluminium stand, which is movable and allows projects directly on the physical display. With the stand, the projector reaches a height of 180 cm above the white mesh. This height is required so that the image projected onto the white grid is exactly 116.8 cm long by 65.7 cm high. In this way, images are projected in the 16:9 scale.

### 3.2. Software

The programming part of this project was developed in Visual Studio whose programming language is C-Sharp (C#), in Processing whose programming language is its own, in MATLAB which has its own language and finally it was also developed in Android Studio whose language is Java aimed at Android system. All programming languages were chosen because they are high-level languages. For a better usability of the prototype, an application was developed dedicated to control the servo motor modules. Through this dedicated application, any other application developed in a different programming language in another computer can communicate and control the physical display, making the implemented solution being agnostic. In order for the second computer to be dedicated to communication with the SD84 module, an application was developed, also in Visual Studio, that would work as a server, in which different programming languages would communicate and control the servo motors. The application dedicated to communicating with the control modules is called the server and the programs that generate the data and communicate

with the server are the clients. For this communication between client and server, the UDP protocol is used.

### 3.2.1. Maps Application

The application that converts 2D topographical maps into 3D maps was developed in Visual Studio, using the C# language. The initial idea of the software for this project was to develop an application that would open any map images, regardless of content and format (BMP, Jpg, Gif, PNG and Tiff), convert the colors of these maps into proportional elevation values and send these values to the control module. To make a direct association between colors and the control of the rotation of the servo motors with consequent elevation of the rods for relief formation, color maps were converted into shades of gray, based on their colormaps, since different maps can have different colormaps. After converting to grayscale, the images are resized to a 16x9 resolution, corresponding directly to the servo motor matrix, where each pixel of the image and its grayscale color will be converted to the rotation of the corresponding servo motor in the matrix. Finally, the grayscale values of the pixels that vary between 0 and 255 are proportionally converted into the servo motor rotation value, between 0 and 180°, with the consequent elevation of the rod coupled to the servo motor in the connecting rod-crank system. Figure 3 shows the layout of the Maps Application and Figure 4 shows the 3D display.

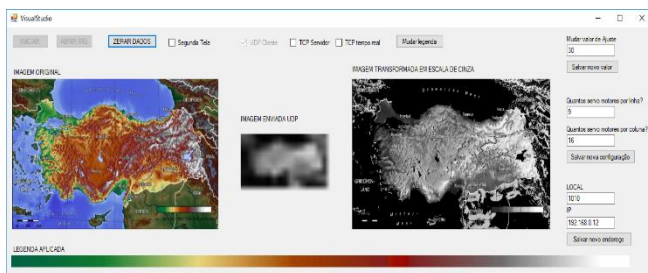


Figure 3. Maps Application Layout



Figure 4. Maps Application

### 3.2.2. Dynamic Applications using Processing

Increasingly, the presence of technological tools allows communication in real time, through video, audio or document sharing. However, there is a limitation regarding physical interaction with other participants. One of the goals of this application is to enable physical interaction between remote participants. Thus, an application was developed in Processing that creates telepresence using Kinect, a Microsoft device originally created for games, but which can be used in different applications. Processing was chosen because it is an open source programming language aimed at visual development, in addition to having a library for applications with Kinect, making it easier to obtain data and use the information that the Microsoft device can make available. Kinect provides depth information that varies between a minimum of 0.7 m and a maximum of 6 m and provides an image with a resolution of 320x240 and each pixel of the image assumes values between 0 and 2047. This information is used in the code using a grayscale image and a vector containing each pixel being represented by a depth value. After obtaining the pixel information, the image is scaled down to have the same resolution as the physical display, which is 16x9. For the process to be dynamic, each image generated is sent to the server at a rate of 4 frames per second. In addition to developing the telepresence application in Processing, an application that simulates sine waves was also developed. This application is dynamic and has an attractive visual effect. The Figure 5 shows the Physical Telepresence application. The Figure 6 shows the sine waves application.



Figure 5. Physical Telepresence application

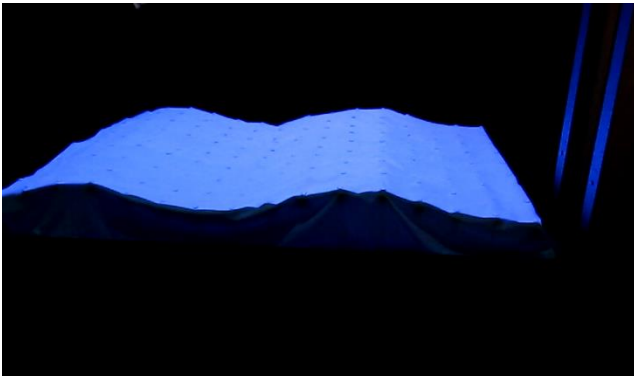
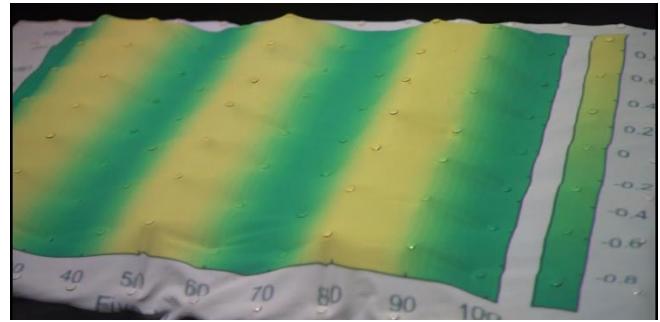
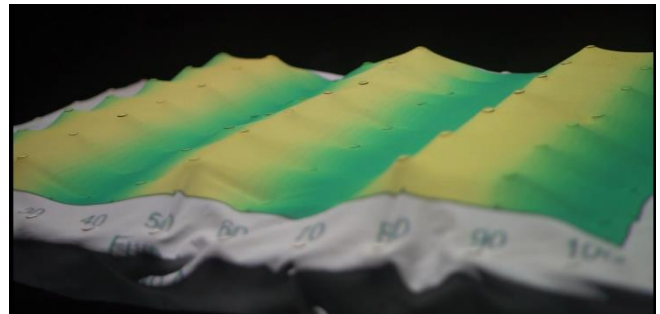


Figure 6. Sine waves Application

### 3.2.3. 3D Mathematical Functions Application

MATLAB is an interactive, high-performance software projected for numerical calculation. In this software, an application was developed that, based on a three-dimensional mathematical function (X Y Z), a height Z is passed to the servo motors, generating a real X Y Z graph. With MATLAB it is possible to build 3D graphs (X,Y,Z) in a simple way with different color maps (legends) and analyze regions of these graphs interactively. We sought to develop an application with this program precisely because this tool can be used in a didactic way in teaching mathematics to students. When starting the application, you can choose between displaying predefined functions and writing a function  $x,y,z$ . By choosing the first option, it is possible to visualize 3 pre-defined functions. The functions are: peaks, membrane and sync. All functions are contained in MATLAB and already have the range of  $x$  and  $y$  also predefined. If the second option is chosen, the user can create any  $x,y,z$  function and display its graph. In this way, this application allows the study of mathematical functions in a three-dimensional space and ends up becoming much more interactive. The function is written as a function of the variables  $x$  and  $y$ . The variable  $z$  corresponds to the height of the graph. The MATLAB function used to generate the graph was the “surf” function. This function plots the surface of the 3D equation based on the selected colormap. Regarding the 2D graph, the function used was the “imagesc” function. This function plots the 2D graph of the three-dimensional equation at the best possible scale of values that display all the colors of the selected colormap. The “imagesc” function is very important in this application, because the image that this function generates is sent to the server, so that this application processes this image and, according to the colors, reproduces the correct height. In Figures 7 and 8, the 3D  $\cos(2x)$  graphs can be seen.

Figure 7.  $\cos(2x)$  function graphFigure 8. Surface formation of  $\cos(2x)$  function

### 3.2.4. Android Application

The last application to be described was made with the Android Studio program. Android Studio is an integrated development environment aimed at developing applications for smartphones, tablets and other electronic devices that run on the Android system. The programming language of this program is Java with some Android peculiarities. The application was developed for the Android system in order to make the use of the physical display even more interactive and dynamic. As the Android system is widespread and is an open source operating system, this system was chosen to create a differentiated application. In the developed application, it is possible to perform two functions. The first function is to select any image that is saved in the Android device's memory and send this image, via TCP protocol, to the server. The second function is to draw on the screen of the Android device and this device interacts dynamically, through the TCP protocol, with the server. As a drawing is made on the smartphone screen, this drawing is dynamically reproduced on the physical display, according to the colors applied in the drawing.

## 4. Results and Discussion

After building the display and carrying out tests involving developed applications, it was possible to analyze: the communication performance of the client applications and the server application, the behavior of the servo motors and their connecting rod-crank mechanism, the response time and the speed to change

the positioning of the rods. The physical display was developed using easily accessible and low cost materials, in addition to seeking the best efficiency. As it is a prototype used to prove the possibility of creating a display that presents physical 3D and its applicability, the cost and functionality of the materials were considered.

#### 4.1. Hardware group analysis

The servo motors that were used are the same used in satellite dishes and do not have much precision, but the cost is greatly reduced compared to other actuators or servo mechanisms. As for other attributes of servo motors, the rotation speed of the servos was relatively adequate for real-time applications, given a certain limit of the correct functioning of the servo motors themselves. Regarding the connecting rod-crank system, all parts of this system were made manually, some parts had a minimal difference, but they could cause a certain difference in the performance of the rods, with regard to the maximum and minimum heights that the sticks could reach. The SD84 controller boards that were used to control the servos are very efficient. Their response time is high and it is possible to control 84 servos at once. However, the control commands of this module are a bit complex, as they are serial commands in hexadecimal.

#### 4.2. Software group analysis

Regarding software, the purpose of creating the UDP server is to facilitate the addition of any application to the control of the physical display, so that there is a greater integration of research projects in different areas. Thus, it is not necessary to develop a control algorithm for SD84 modules in all applications, since certain programming languages can be more complex for this development. In this way, no matter which programming language is used, clients only have to send a string of integer values between 0 and 255. The maps application, despite having been developed with the system's own algorithms to optimize its operation, in terms of grayscale image processing, is still a time-consuming process since it converts the chosen image pixel by pixel. Thus, it takes a lot of time to process the images. To avoid processing delays, the only solution is to use computers with better processing resources, whether in RAM memory, video card or the processor itself. Regarding the two dynamic applications with Processing, they have a limit when it comes to the dynamic use of the physical display. The limitation concerns the operation of the servo motors, since the servos do not run at high speed. In dynamic applications with Processing, the refresh rate for applications with Kinect cannot be less than 250 ms. For updates with shorter times, closer to real time, the servo motors do not work correctly and their gears may misalign. In the application of visualization of three-dimensional mathematical graphics, it is necessary that the user has previous knowledge of the MATLAB

tool, to create 3D functions. This is due to the fact that when writing 3D functions, the matrices define the ranges of the functions, making operations with vector variables and not scalars. The way of writing the functions becomes different.

## 5. Conclusions

Scientific visualization evolves by the need for data interpretation. Therefore, with the creation of this display, we sought to represent the data in a different way than usual, as 3D is no longer representative on 2D screens and becomes closer to reality. Even with the development of this project, some limitations were found. Certain 3D representations that need a higher degree of freedom, with a vertical hole in the middle, for example, are not possible to represent. The project is limited to representing reliefs and surfaces. Despite certain limitations, it is concluded that in this project it was possible to achieve the purpose of presenting 3D information and data with greater realism, in a tangible way through augmented reality together with the physical presentation of data. In this way, information that was previously seen on a common 2D monitor is converted into information with one more dimension, which enriches the presentation and the way in which this information is understood. As future projects, there may be the study for the application of other types of smaller servo motors, as well as the application of more efficient systems for the transformation of the circular motion of the servos to linear motion, allowing the creation of more compact structures, with higher pixel-servo motor resolutions. In a complementary way, an application that is intended to be developed is the creation of Google Maps 3D, in which it is possible to visualize satellite images aligned with the height of their reliefs, with the user being able to zoom in on the map, change the location and servo motors automatically correspond to these variations on the map.

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