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Live Ambient Physicalization Interface for dynamic Data - LAMPI

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Iliari Schultes
Matrikelnummer 12025959

an der Fakultät für Informatik

der Technischen Universität Wien

Betreuung: Dipl.-Ing. BSc Daniel Pahr
Mitwirkung: Dr. Renata Raidou

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Iliari Schultes

Daniel Pahr

TU WIEN Informatics

Live Ambient Physicalization Interface for Dynamic Data - LAMPI

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Iliari Schultes
Registration Number 12025959

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Advisor: Dipl.-Ing. BSc Daniel Pahr
Assistance: Dr. Renata Raidou

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Iliari Schultes | Daniel Pahr

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Iliari Schultes

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Iliari Schultes

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Kurzfassung

Datenphysikalisierungen erfreuen sich zunehmender Beliebtheit als Mittel Menschen abstrakte Daten näher zu bringen und könnten helfen die durch moderne Technologien gesammelte Informationsflut in unser Leben zu integrieren. In dieser Arbeit beschreibe ich den Designprozess für ein Software-Framework, das die Physikalisierung von Live-Daten ermöglicht, sowie für den Prototyp eines dynamischen Physikalisierungsobjekts, das Form und Farbe verändert. Durch die Verwendung eines aufgezeichneten Datensatzes, habe ich ältere Patienten simuliert die ihre Daten mit Bezugspersonen teilen, um dadurch die Fähigkeiten des Software-Frameworks und der Physikalisierung zu zeigen. Das vorgeschlagene Konzept bietet eine neue Methode zur Datenkommunikation in Remote-Monitoring-Szenarien, die aus zugänglichen Materialien erstellt werden kann. Es ist auch möglich, Daten anderer Anwendungsfälle mit minimalen Anpassungen darzustellen, wodurch die Möglichkeiten zur Datenphysikalisierung erweitert werden.

Abstract

Data physicalizations are becoming increasingly popular as a means of connecting people to abstract data and may help integrate the flood of information collected by modern technology into our everyday lives. In this thesis, I describe the design process for a software framework facilitating the physicalization of a stream of live data as well as the prototype of a dynamic shape and color-changing data physicalization for said data. I simulated elderly patients sharing their data using a recorded dataset to show the capabilities of the software framework and physicalization. The proposed concept provides a new method for communicating data in remote monitoring scenarios that can be built from accessible materials. It is also capable of showcasing data for other use cases with minimal adaptations, further expanding the possibilities for data physicalization.

Contents

CHAPTER 1

Introduction

Throughout history, humanity has invented countless ways to facilitate the communication and understanding of data, many of them visual, especially in recent years due to the rise of computer screens. Another method for representing data that has existed for quite some time involves three-dimensional representations. Aside from physical models like terrain models, physical objects can also be used to convey abstract information. These objects represent data through their geometric or material properties, which provides new ways to access and interact with data possible [DJVM21, JDI+15].

While static representations and models have been in use for many years, dynamic shape-changing displays have emerged as new form of representing changes in continuous data flows using physical properties to make abstract data perceptible to humans [JDI+15]. Due to the spreading usage of embedded sensor networks and mobile systems, more and more data is collected and made accessible to people in their everyday lives. The collected data is then displayed, often in abstract format. At the same time, data physicalization is being researched as a new way of connecting people with data [JDI+15].

Increased availability of wearable sensors also led to growing interest in telemedicine since to make monitoring more accessible for people such as the elderly, who mostly live alone or in care facilities. Often, these systems are built for recognizing emergencies and then alerting help [AIK+23]. However, remote monitoring systems can also help caregivers and family maintain a connection with people and help keep peace of mind despite not always being present, for example, when living a long distance away. Such devices often provide standardized feedback, featuring numbers and graphs displayed on a screen [Kim22, AIK+23].

The goal of this thesis is to create an adaptable framework for physicalizing data and to design a display that continuously shows different types of data. Data will be represented in an intuitive way so that information can be easily understood, even by laypersons, via a shape-changing interface. Additionally, the materials used in the construction of the shape-changing interface should be affordable and easily accessible.

This thesis' **contribution** is a software framework to process data of numerical and other types into a uniform format so that physicalization is independent of data processing and the design of a physicalization device that can dynamically embody said data types through its physical properties. As a result, physicalizing data from different use cases only requires minimal adaptations to the data processing software on the laptop server and no changes to the hardware and the code controlling it.

I use the data of a recorded dataset of human vital parameters [PCC+23] as input for the shape-changing display to simulate a fictional scenario of a remote user sharing their data with relatives or friends since remote monitoring is an aspect of medicine and care that has gained more popularity recently. The dataset is processed by a server using a software framework and then sent to the physicalization device at appropriate intervals via a WiFi connection. The physicalization is constructed from a 3D-printed base supporting a moving paper tower structure, which is the main component of the physicalization.

CHAPTER 2

Related Work

In the following chapter, I will introduce some previous work that has that is relevant to the topic of this thesis and describe how it relates to this work.

2.1 Data Physicalization

Physical data representations have existed for a long time and have been used to teach and to help scientists understand and solve problems [DJVM21]. However, not all physical objects representing data are physicalizations. An important distinction made by Dragicevic et al. [DJVM21] is that physicalizations convey abstract data of some kind. This excludes certain 3D-representations, like for example terrain or architectural models.

Jansen et al. [JDI+15] define data physicalization “physical artifact whose geometry or material properties encode data”. Physicalizations were used as tools to convey information for specific topics in the past, but only recently has research focused on the methods of physical data representation itself. Since visualizing such structures via computer screens can cause issues like perceptual distortion and occlusion, scientists regularly rely on solid physical models for complicated structures [DJVM21].

3D printing, in particular, is popular for producing physical data representation due to its versatility. One drawback to 3D printed physicalizations is their static nature, which makes it hard to show changes in data [DJVM21].

Aside from their geometry, physicalizations can embody data in a variety of different ways [BZW+22]. From sound (sonification) to taste and all other senses, physicalizations are multi-sensory experiences. According to Ranasinghe and Degbelo [RD23] artifacts used to represent data have different so-called information channels to convey information. Information channels refer to the perceptual aspects that can carry information like color or shape. In the context of Data Physicalization, variables are the ways through which information channels can be manipulated. Variables for visual information channels can include color hue, shape, visual location, and visual orientation. Another example of variables are temporal frequency and duration which are both dynamic variables.

Many researchers in the field ([RD23, DJVM21]) distinguish between static and dynamic physicalizations. Bae et al. [BZW+22] take this even further and classify physicalizations into three different categories depending on data duration and control the user can exercise over it: Permanent, for physicalizations that have data permanently embedded into their properties, persistent for physicalizations that allow the user to decide how long information is displayed and ephemeral for physicalizations that render data in real-time without the option to recall it.

Ranasinghe and Degbelo [RD23] conducted a systematic review and defined a seven-stage model to describe the process of designing and evaluating a physicalization. Summing up, after deciding on a purpose and selecting a fitting data set, the representational material is chosen, which strongly determines the encoding variables and vice versa. Finally, the interaction is designed and the artifact is evaluated. While this often describes the way from idea to physicalization, this field of research is still new and can change quickly. It's also closely related to the more artistically inclined disciplines like installation art and data sculpture, so defining a uniform approach can be difficult [DJVM21].

An important aspect of the design process of a physicalization is the intended purpose and target audience. Data representations designed for experts in the field may differ from those made to be displayed in public spaces or for personal use [DSM+21].

2.2 Shape-Changing Interfaces and Ambient Displays

Two other topics closely related to Data Physicalization are ambient displays and shape-changing interfaces. Both terms will be explained in the following chapter, together with an overview of some works concerning these topics that are relevant to this thesis.

shape-changing interfaces are defined by the fact that they change their shape and other properties to represent different contexts, this makes them dynamic physicalizations simply by nature of their definition. These interfaces are used for both user input and to present output. In the context of this thesis, only the presentation of output to users is relevant [ARS+18].

Ambient displays make use of the physical environment to represent digital data and integrate themselves into the space instead of focusing the user's attention onto a small rectangular screen. Changes in data are represented through subtle changes in movement, sound, color, smell, temperature, or light. This makes ambient displays well-suited to keep users up to date with their peers or the general state of more complex systems [WID+98].

Some interesting examples include ActuAir by Margariti et al. [MVDK24] a shape-changing display of air quality featuring inflatable pouches with embedded coloured LED strips and CoralMorph a shape-changing textile installation that adapts to the emotions of people interacting with it, by Huang et al. [HR24].

Recently, Daniel et al. [DRC18] have designed and built CairnForm, a dynamic cylindrical physicalization. CairnForm represents forecasts in renewable energy in the form of a ring chart that can be read from all angles. The stacked circular structure was chosen to improve the issues of occlusion effects encountered when using a vertical physical bar chart to display information as an ambient display. The variables used to encode data are light intensity and the diameter of individual segments.

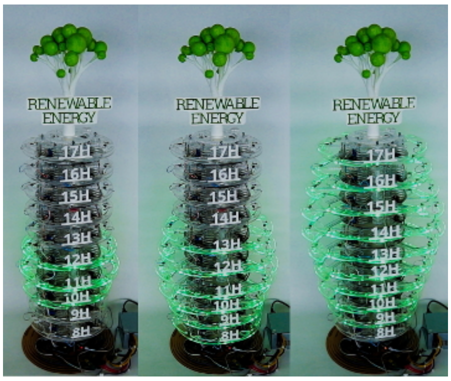


Figure 2.1: CairnForm: Illuminated expandable ring chart [DRC18]

The physicalization framework presented in this thesis is an ephemeral shape-changing display of a continuous data flow. Little research currently exists to bridge the concepts of data physicalizations and ambient displays [DSM+21].

2.3 Remote Monitoring and Ambient Assisted Living

Ambient Assisted Living generally refers to the usage of information technology and smart home devices to help a person remain independent and improve their daily life.[BMB+16] This often includes monitoring devices to collect health-related parameters and data concerning physical activities [AIK+23].

Studies like those by Davis-Owusu et al. [DOOM+19] and boem and Iwata [BI18] have indicated that ambient displays which showcase activity levels and vital parameters can make relatives and caregivers feel more connected to the person who's data is displayed. Vice versa Davis-Owusu et al. [DOOM+19] also found that knowing that someone is seeing their activity levels made some people feel secure and connected because they know someone is looking out for them.

In their study, Davis-Owusu et al. [DOOM+19] researched the behavioral implications of a bidirectional ambient display in an ambient assisted living setting. They used several different ambient displays such as a smart cane and a smart wallet to represent activity levels of caregiver and patient for the respective counterpart. The concept presented in this thesis is unidirectional.

Another example for a physicalization used in an remote monitoring scenario is Vital+Morph by Boehm and Iwata [BI18], which physicalizes the vital parameters of a fictional intensive care patient for their relatives. Individual vital parameters like ECG and respiration are represented by shape-changing cylindrical structures with the movement controlled by a servo motor and springs, which are perceived as haptic sensations by the person holding the physicalization. Real recorded patient data from a public data set was used to create the fictional scenario for Vital+Morph. The same approach was also used for the prototype presented in this thesis.

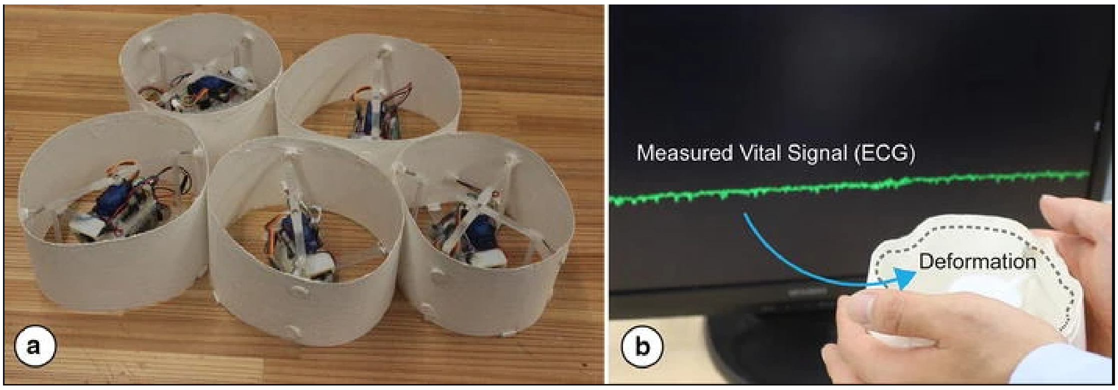


Figure 2.2: Vital+Morph: Haptic physicalization of vital parameters for a remote monitoring scenario [BI18]

While there has been an increase in remote monitoring applications regarding health data, the majority of user interfaces to represent collected data are screen-based. There are some new methods to represent personal health or fitness-related data for oneself or others that rely on physical objects instead, such as 3D-printed jewelry [STS+14] based on physical activity, a singing bowl representing one year of blood pressure data [BBA14] or other permanent static physical objects.

There is very little when it comes to dynamic, not permanent physicalizations such as shape-changing interfaces especially when it comes to Telemedicine. I chose a remote monitoring scenario as an example for the physicalization framework presented in this thesis to explore the potential of Data Physicalization for Telemedicine.

CHAPTER 3

Data and Software Framework

The following chapter describes the dataset used in his work and outlines the requirements, design concept and implementation for a software framework that can be used to support a dynamic physicalization like the one described later in this thesis.

3.1 Data

The data set used to create a fictional example scenario was collected during a feasibility study for a newly developed digital platform for patient monitoring [PCC+23] funded by the Surrey and Borders Partnership National Health Service Foundation Trust. Physiological data and daily activities of several people living with dementia were gathered through various smart sensors such as a sleeping mat and a pulse oximeter. Blood pressure, heart rate, and data concerning sleep state were collected during the study. Measurements of these values were conducted at different times and with different frequencies. A blood pressure measurement was taken a few times a day while sleep state values were collected only when the patient was in bed, but in an interval of one minute. The heart rate was measured every few hours during the day additionally, every sleep state entry contains a heart rate value as well.

3.2 Requirements

My design process closely resembled the design part of the seven-stage model by Ranasinghe and Degbelo [RD23]. I had an initial idea for physicalization in a remote monitoring scenario and selected a data set that provides appropriate data to simulate such a scenario. Considering this scenario of an elderly person sharing their health-related data with relatives and friends, making it an ambient display seemed fitting. Keeping the selected data set and the scenario in mind, I came up with some requirements. Biomedical data is very diverse and while choosing the data set mentioned in the previous section [PCC+23], I realized that there may be a lot of other health-related and non-health-related use cases for a physicalization like this. So I adapted my requirements to make both the framework and the physicalization more flexible so that they could adapted and be used for more than just this singular use case. In the end, I defined the following requirements:

1. **Handling of asynchronous data:**
   Different types of parameters may be collected in different time intervals. The framework should be able to provide the most recent values for all parameters, even if they were collected at different times.
2. **Compatibility and adaptability:**
   The design of the framework should allow for easy adaptation of the framework for different use cases, with little changes to the code. An example for a different use case could be displaying different health parameters such as breathing rate or blood oxygen. Transmission of values should occur in a uniform format so that it is compatible even if different hardware components are used for the physicalization, or the physicalization is slightly modified to be more fitting for a particular use case.
3. **Possibility for live data usage and continuous data flow:**
   Since this is a prototype, a recorded data set will be used, but the system architecture should allow for saving and using live data from different sources without major changes to the code.
4. **Possibility for remote use:**
   The system structure should make it possible for the external server to be located remotely from the physicalization device.

3.3 Design

In the following section I explain the design concept, its implementation and how the final design satisfies the requirements defined in the previous section.

3.3.1 Design Concept

Considering the example scenario simulated using a data set, which provides a continuous stream of vital parameters, I decided that the physicalization should continuously render data collected close to the current date and time.

Due to representing changing values, the physicalization is dynamic. Since the physicalization is meant to be displayed in the living space of friends and relatives and help maintain a sense of connection to the patient, it can also be classified as an ambient display.

LAMPI, the name for the physicalization Framework derives from some of the characteristics mentioned above: **L**ive (data) **Am**bient **P**hyicalization **I**nterface

Many health care applications share a a 3-tier architecture separating data collection via sensors from data persistence and the actual system extracting information and presenting it to users through a graphical interface. A "gateway device" communicates between a server located remotely and sensors capturing data using the world wide web. Aside from generating alerts in cases of emergency, other main purposes of the remote server include, recording data for each patient in a database and providing an interface for real time monitoring [MIA19]. I chose to use the same approach for the physicalization because this satisfies requirement 2 regarding adaptability and Requirement 3.

Due to the nature of the interface being physical I applied this architecture principle to **separate data storage and data rendering**. Electrical components of the physicalization interface communicate with a remote server using a gateway device for example a micro controller. To simulate patients the remote server loads a prerecorded data set which contains vital parameters of several patients. The fact that it would be very easy to receive and persist live data from sensors via a similar gateway device satisfies requirement 3.

To make **transmitted data independent of the specific pieces of hardware** used to operate the shape changing interface I decided to transmit floating point values which represent the relative percentage of a range and are not hardware specific. The values, sent by the remote server, are received and converted to hardware specific values by the gateway device, which operates independently. This makes changing the physicalization device possible without modifying the remote server in any way.

The values I chose to transmit data, are **linearly scaled** floating point values between 0 and 1 and simple mapping using integers. Additionally the specific numerical intervals used to scale the value for each physicalization variable can be easily accessed and changed due to the remote servers internal architecture.

3.3.2 Technical Implementation

The software needed to provide the physicalization with the required data runs on a laptop and communicates with a micro controller in the physicalization over a **Wi-Fi connection** and HTTP requests, to ensure compatibility and a possibility for remote use like stated in Requirement 2 and 4 previously. A general overview over the system's communication and structure is depicted in Figure 3.1.

A small server created with spring boot and a simple layered architecture [RF20] is the basis for handling communication and persistence of data, opening the possibility to persist and use live data instead of a prerecorded data set (Requirement 3). I chose to use layers to **separate data acquisition** from **persistence** and **data processing**. Data can either be read from a file or originate from a continuous, live source.

Processing of persisted values is handled by its own layer, referred to as the Service Layer ensuring that data processing is independent and unaffected by changes in data acquisition and vice versa. The Service Layer linearly scales numerical values to a floating

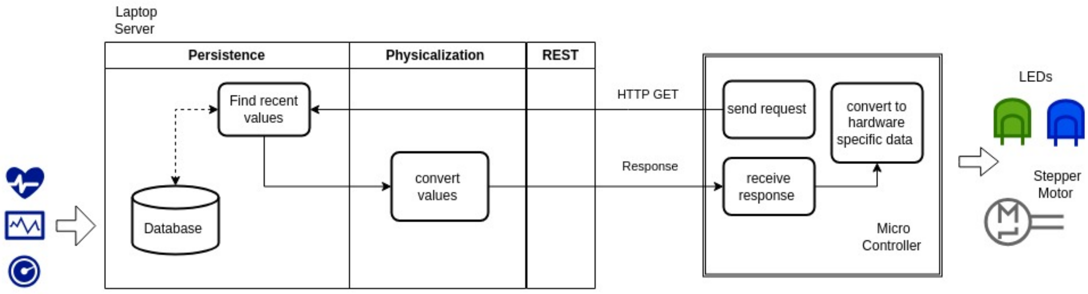


Figure 3.1: Flow diagram depicting the communication and data flow between the physicalization device and external server storing observed data.

point number in the range between 0 and 1 using predefined min and max values, so changing to a different use case with other value ranges only requires changing min and max values in the code. Enumerated or boolean values are converted to integer numbers.

After receiving a GET request with a timestamp from the physicalization micro controller, the persistence layer retrieves the parameters collected closest before the given time. The physicalization service linearly scales the parameters encoded to tower height and rotation speed using their predefined min and max values. Values outside the min to the max range are converted to 0 or 1, respectively. Each physicalization variable has its own converter, handling the min and max values or map for the conversion as depicted on Figure 3.2. Since the scaling operation is the same for tower height and rotation speed, this operation is done by a scaler used by both converters.

The processed values consisting of scaled floats and integers are sent to the physicalization in response to the GET request. All of these processed values are then **converted** to **hardware-specific values** so that adjustments to the scale of the physicalization, can be easily accommodated and hardware components changed fulfilling requirement 3. Values between 0 and 1 represent relative tower heights and relative speed, respectively, while integers refer to LEDs. For example when using height as a variable, a scaled value of 0.6 is converted to a hardware specific value that moves the physicalization to 60 percent of the overall possible maximum height. Likewise, 0.3 for movement speed is converted to 30 percent of the overall maximum speed possible for the physicalization. A mapped integer of 1 could indicate one of several different colors.

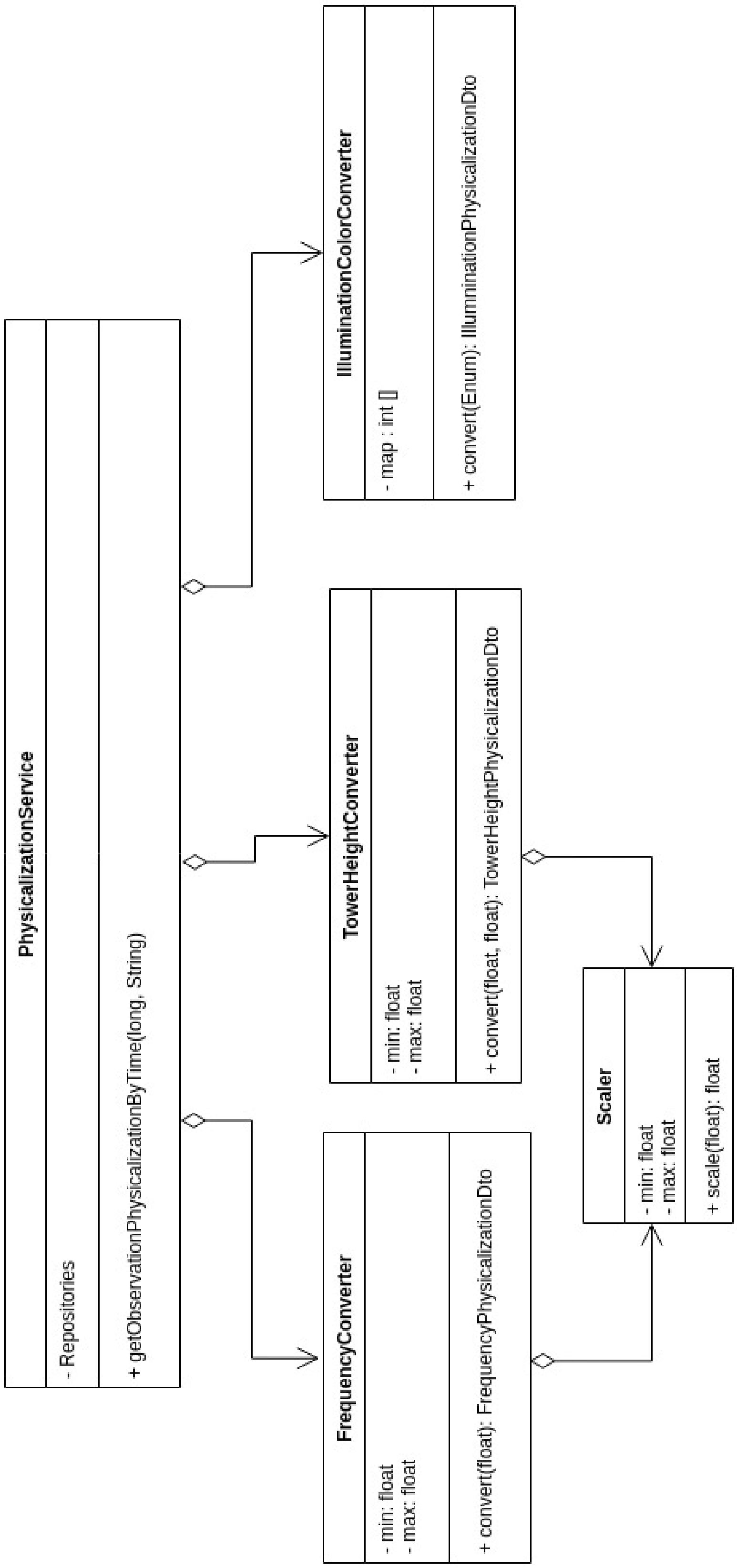


Figure 3.2: Class diagram of service layer which handles the conversion from raw data values into scaled uniform values used for transmission. Dedicated converters store fixed min and max values for the respective health parameter they convert.

CHAPTER 4

Physicalization

I designed an ambient physicalization to represent data for the physicalization framework presented in the previous chapter. The following sections describe the requirements, design and final implementation.

4.1 Requirements

After coming up with the requirements for the software framework did the same for the actual physical object, many of the requirements listed below go hand in hand with the requirements defined in the previous chapter and have the same reasoning behind them:

1. **Represent several different data types:**
   Biomedical data comes in a variety of data types, since it includes everything from inspection results by medical professional to signals recorded from the body using sensors [Kan12]. Therefore complex and simple data types, such as a fluctuating numerical values, constant numerical values and boolean or enumerated values, should be represented by the physical properties of the physicalization device.

2. **Dynamic and intuitive:**
   Since the data represented by the physicalization are not fixed, the properties of the physicalization have to change when the corresponding data does [RD23]. Because facilitating easy access to information is at the core of Data Physicalization, changes in the data embedded in the object should be easily recognized and understood by users interacting with the physicalization [SGE+18].

3. **Accessible materials:**
   The materials used to construct the physicalization device should be budget-friendly and easily accessible, including 3D-printed parts or paper and commonly available electronic components [BZW+22].

4. **Easily adaptable:**
   Construction and design of the physicalization should allow for customization and easy adaptation to different use cases [DSM+21].

4.2 Design

In the following section, I describe the design concept and the construction of the resulting physicalization in detail.

4.2.1 Design Concept

As mentioned before the physicalization is an ambient display, but the fact that it displays live data means that it can be classified as ephemeral physicalization, as defined by Bae et al.[BZW+22], since data is physicalized in (simulated) real-time and the user has no control over how long a set of collected values is displayed. This implies the physicalization is dynamic and that the variables representing data are always changing. Since multiple different values have to be represented at the same time it was challenging to come up with a device that has multiple modifiable properties that can serve as variables.

The design I came up with allows for the simultaneous physicalization of three values: A boolean/enumeration Value, a fluctuating numerical value. Through representing these different data types the physicalization satisfies requirement 1 mentioned in the previous section.

I settled on the origami twisted tower structure designed by Japanese artist Mihoko Tachibana and used by Fei et al. [FLX+22] because it is modular, capable of expanding and contracting and has a surface texture that can represent the current state of expansion to an observer even if they see the structure for the first time, at least to some degree. This makes the display intuitive which is part of requirement 2. Additionally, the twisted tower is a prismatic structure based on a symmetric octagon, which closely resembles a cylindrical structure. Cylinders have some advantages when it comes to ambient displays, since they are easily observable from all sides [DRC19].

While paper has been used in Physicalization before, previous paper-based physicalizations are static and often involve assembly as a user interaction to communicate data, [DSM+21] neither is the case here. I chose paper as a material to construct the moving parts of the physicalization because it is flexible and reduces the amount of electronics and 3D-printed parts compared to mechanisms made from non-flexible materials, making it easily accessible as laid out in requirement 3

After much deliberation and research, I decided on the following **visual variables**:

The **color of the light** illuminating the tower represents **boolean/enumerated values**. Similar to how the ambient displays used by Davis et al. [DOOM+19] use colored light to encode activity levels, LAMPI uses colored light to represent the patient's sleep state.

My prototype features blue and green but adding more colors would only take additional LEDs and some minor code adjustments.

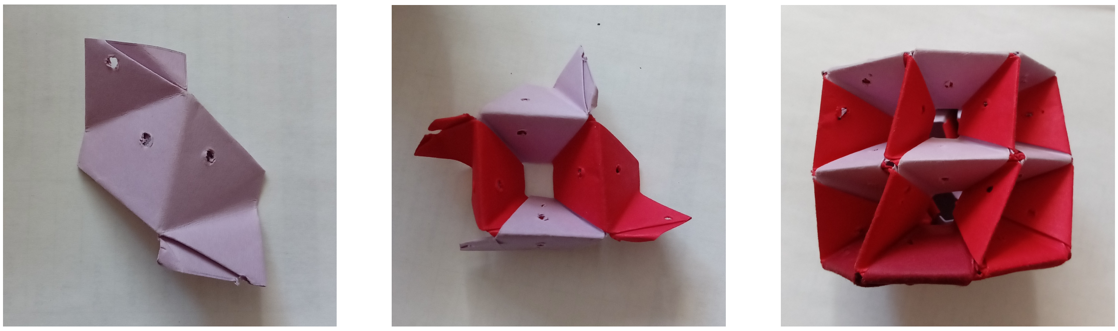
Periodic fluctuating **numerical values** are encoded using the **height of the tower**, which moves from a temporary minimum height to a temporary maximum height continuously. The concept of encoding data into the visual shape of an ambient physicalization was already evaluated and found to be an effective way of communicating data by Daniel et al. [DRC19] using CairnForm. Their design encodes data into the diameter of stacked rings, while the height of CairnForm remains unchanged. The **tower movement speed**, which can be classified as a dynamic variable, embodies one additional **numerical value**.

4.2.2 Physical Object

LAMPI has two main components: the main physicalization device, made of paper, and a 3D printed base containing the electronic components necessary to operate it.

Paper Tower

For the main body, I chose the **origami twisted tower** structure first invented by Mihoko Tachibana, and used by Fei et al. [FLX+22] and Lee et al. [LWZ20]. As shown in Figure 4.1 many singular folded paper pieces make up flexible base segments that are layered to build a paper tower.



(a) Single folded piece (b) Basic segment (c) Twisted tower

Figure 4.1: Assembly of the Origami Twisted Tower structure (c): Singular paper pieces are folded (a) and then assembled into basic segments which are then connected to each other. Eight segments in a circle make up each individual layer of the tower(c).

The unique structure allows for modifying tower height simply through the pulling of strings, without the need for springs or other components by making use of the inherent elasticity of the paper. This multi-layer structure also allows for easy modification in height since the number of layers can be adjusted by simply taking the tower apart and adding an additional layer of paper segments and this also fulfills requirement 4 as it allows for adaptation to different use cases.

Due to it's ability to **extend**, **contract** and bend this structure has gained the interest researchers in the field of robotics recently. Some new robotic designs rely on the twisted tower structure for horizontal movement [FLX+22] or grasping objects of different shapes [LWZ20].

Base Structure and Electronics

An ESP32 Wroom-DA development board functions as a communication and control device for LAMPI, but could easily be replaced by a SOC device like a RasberriPi or something similar with Wifi capabilities. Additionally, a 28-byj48 **stepper motor** and the corresponding driver board are needed, as well as two colored **LEDs**, two 100 Ω resistors, and a **limit switch**. Nonelectronic components include: some string, cut and filed nail which serves as axis, some screws, nuts, several paper split pins, and a paperclip. To satisfy requirement 3 (Easily Acessible Materials) I took care that all the components mentioned above are commonly available items or can be easily reproduced.

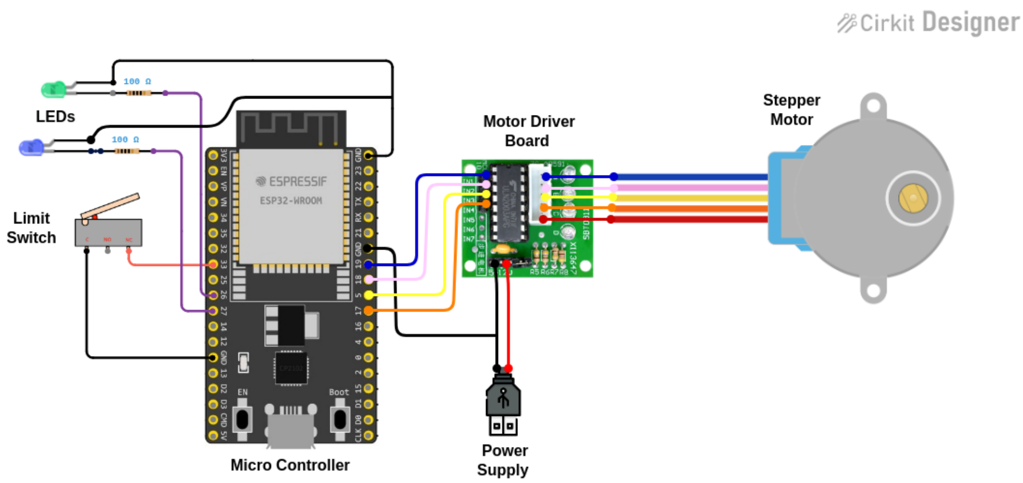


Figure 4.2: Wiring diagram: The physicalization is operated by a micro controller. LEDs and limit switch are directly connected to and powered by the micro controller, but the stepper motor is operated through a driver board and has it's own power supply.

To contain the electronics depicted in Figure 4.2 as well as a mechanism for winding up the string to move the twisted paper tower, I designed a **3D-printed cuboid base** (Figure 4.3, Figure 4.4) made of 5 different parts: a sideless base with fixtures for the stepper motor, and the axis, a spool, a string guide, a fixture for the limit switch and a top. The top part has holes for the three strings which contract the tower to pass through, for affixing the paper tower, for affixing and operating the limit switch. Finally there is also hole where the center of the paper tower is, for the LEDs to illuminate the whole structure. In contrast, CairnForm [DRC18], a similar physicalization employing expandable ring mechanisms made from 3D printed and laser cut parts requires multiple stepper motors, limit switches as well as both a RasberriPi and an Arduino Mega.

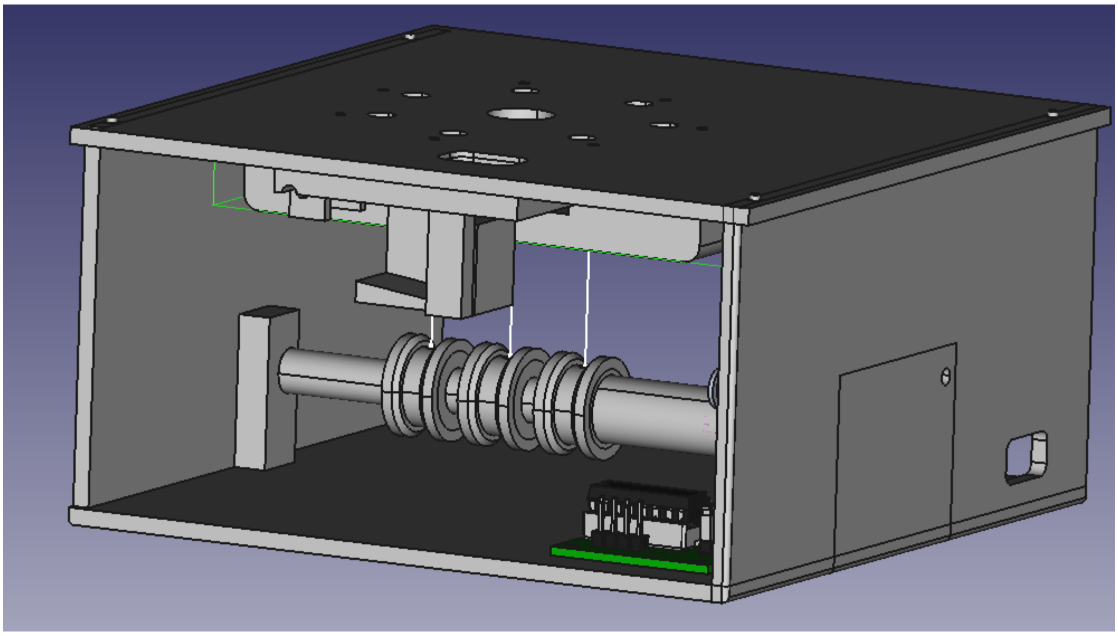


Figure 4.3: Cuboid base design consisting of a side-less bottom, a spool for the strings regulating physicalization height, a string guide and a fixture for the limit switch.

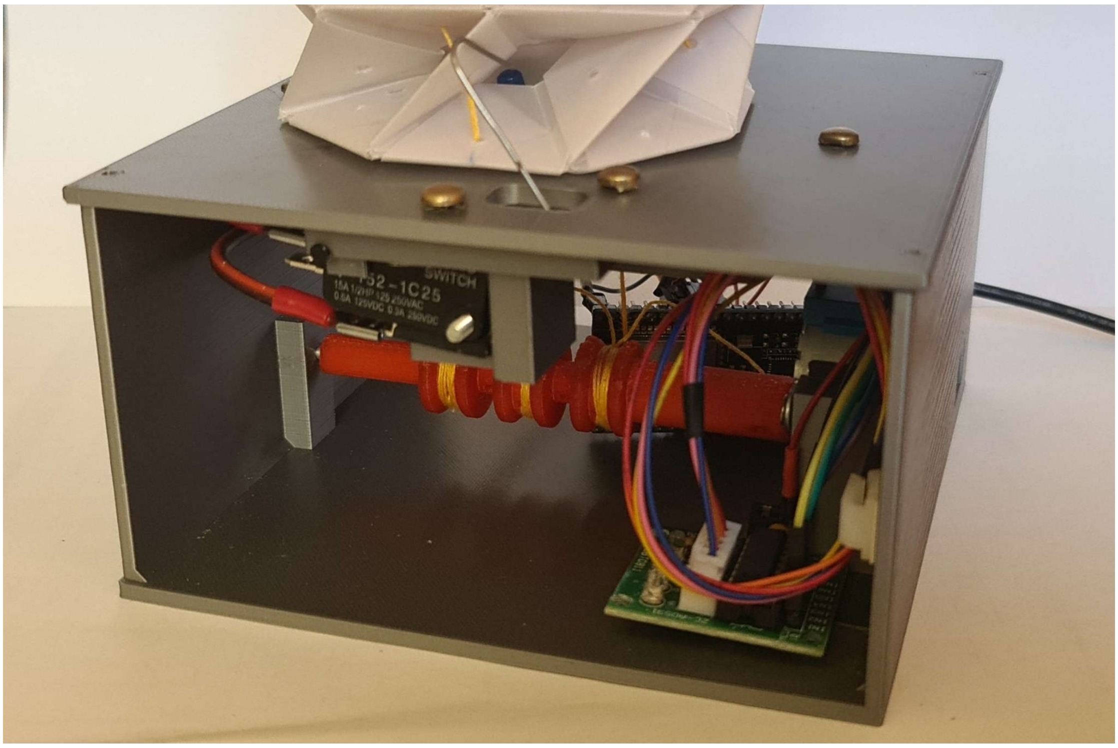


Figure 4.4: 3D-printed cuboid base containing electronics, connecting wires and paper tower on top with string traded trough holes in the paper and ready for operation

CHAPTER 5

Results

I simulated an example scenario to showcase LAMPI's capabilities. The following chapter contains information about the example scenario and physicalized values of two different patients, selected from the recorded data set.

5.1 Example Scenario

To show the capabilities of the physicalization framework described, in this thesis, I used a prerecorded data set that contains heart rate, blood pressure, and sleep state data of 56 People living with dementia over the course of several weeks.

The **height** of the paper tower represents **blood pressure** and moves cyclically between two states states representing systole and diastole, just like blood pressure. Collected values in the range from 50 to 190 mm/Hg are scaled to relative tower height values.

The **speed** at which the physicalization moves between systolic and diastolic height represents the patient's **heart rate**, so the correlation between movement speed and tower height matches the correlation between the change in blood pressure caused by heartbeats. Values between 50 and 110 beats/Min are converted to relative motor speed.

Sleep data is down-sampled from several sleep stages (REM, LIGHT, DEEP, AWAKE) to simply awake indicated by the green **LED**, and asleep indicated by the blue LED. I chose this encoding based on the design used by Davis-Owusu et al. [DOOM+19], who likewise used warmer colors for more active states and cooler colors for states of rest.

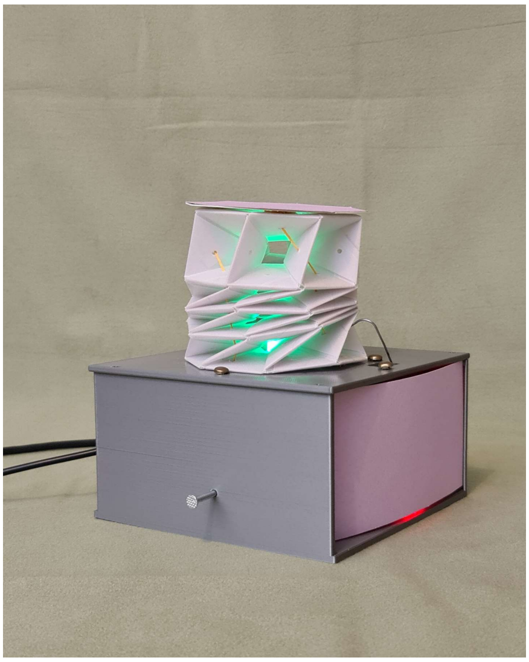
The physicalization sends a request for values to the server every 30 seconds. If the server cannot be reached, the physicalization continues with the last values it received but is not illuminated. I chose this way of notifying the user that the connection was lost, instead of halting all movements to prevent emotional distress for the user, since the movement representing the heart rate suddenly stopping could be interpreted as an emergency of a loved one. According to Boem and Iwata [BI18], this is a concern raised by several people after experiencing the physicalization of vital signs.

5.2 Physicalization of Patient Data

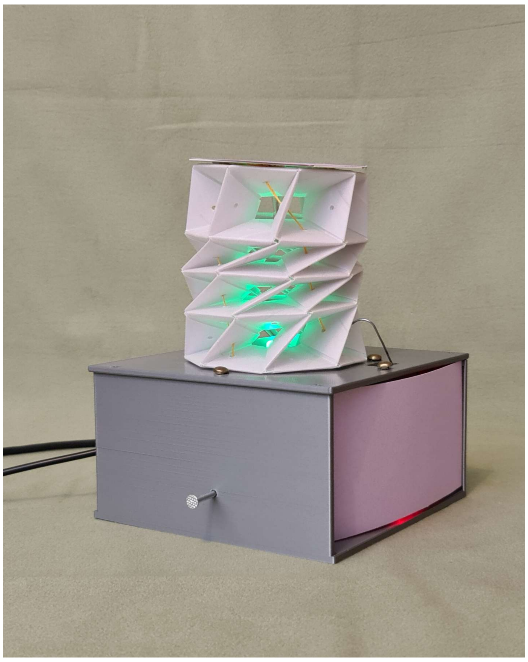
Two patients with different vital parameters were selected from the data set, and their values physicalized, as might be the case if they chose to share their data with some of their relatives with LAMPI.

Patient 1

The first example patient is an 80 to 90-year-old male. His data was physicalized in the following pictures (Figure 5.1). The values were collected on April 4th, 2019, before 12:30: He was awake, his heart rate was 83 Beats/Min, and his blood pressure was 138/89 mm/Hg. The paper tower moves between a lower position representing diastole as seen in Figure 5.1a and a higher position representing systole as depicted in Figure 5.1b with moderately high speed, which indicates his heart rate relative to the scaling interval. Green light illuminates the tower, suggesting that the patient is awake.



(a) Diastole

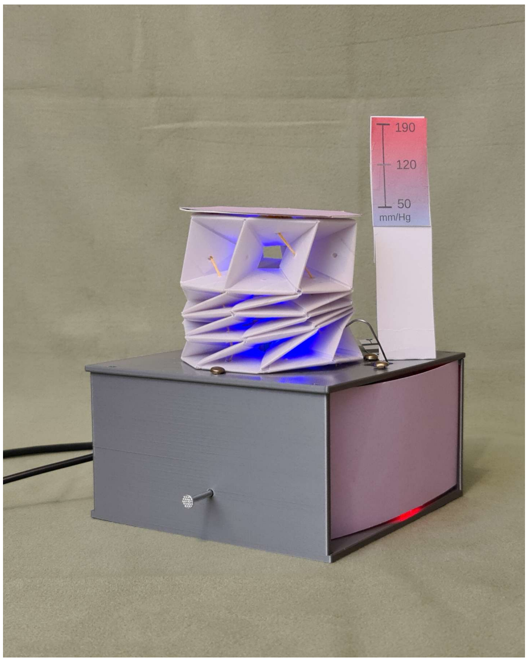


(b) Systole

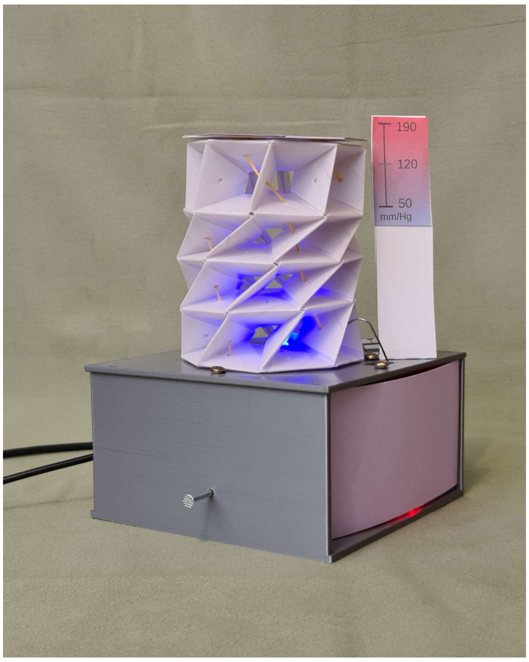
Figure 5.1: Diastole and systole of patient 1

Patient 2

The following pictures (Figure 5.2) show the vital parameters of the second example patient, an 80-to-90-year-old male, on April 15th, 2019, before 22:20: As illustrated by the blue light, he was asleep, his heart rate was 72 Beats/Min, and his blood pressure was 161/72 mm/Hg. To represent blood pressure, the tower moves between a lower position, indicating diastole and systole, scaled to the movement range the tower provides. A diastole of 72 mm/Hg is embodied by a very low tower height as seen on Figure 5.2a, while the relatively high systole of 161 mm/Hg is likewise represented by a tower height value close to the maximum, depicted in Figure 5.2b



(a) Diastole



(b) Systole

Figure 5.2: Diastole and systole of patient 2 with scale

Patient 3

Patient 3 is an 80-to-90-year-old woman. Her physical parameters collected on the 17th and 18th of May 2019 are displayed in the following pictures (Figure 5.3). To show how vital parameters can change over time and how those changes are displayed, I captured the physicalization of values on two different days to compare them. The picture on the left (Figure 5.3 a) shows the patient's systole on the 17th in the afternoon. Her heart rate was 70 beats/Min, her blood pressure was 113/61 mm/Hg, and she was awake. She was more active the following day, possibly due to going for a walk, which raised her blood pressure to 126/72 mm/Hg and her heart rate to 75 beats/min, as depicted in the picture on the right.

(a) Systole after resting (b) Systole after activity

Figure 5.3: Systole of patient 3 after resting and being active

Patient 4

The fourth patient's physical parameters were collected on the 10th and 11th of June 2019. To demonstrate the range a person's, in this case, a woman aged 80 to 90, parameters can have throughout a normal day, I picked the time points to be at night and during the day. On the left picture, her systole during sleep at 176 mm/Hg (Figure 5.4a), as indicated by the blue illumination, is displayed, while the right image (Figure 5.4b) shows her systole during the day which was 189 mm/Hg. Her heart rate was 74 beats/min during sleep and a bit higher at 84 beats/min during the day. This was also reflected by a lower movement speed while displaying the first set of values.

(a) Systole during sleep

(b) Systole while awake

Figure 5.4: Systole of patient 4 while sleeping and being awake

5.3 Fulfillment of Requirements

I laid out requirements for the physicalization and the supporting software framework at the beginning of chapters 3 and 4. This section describes how the example scenario described in the previous section showcases the fulfillment of those requirements.

5.3.1 Software Framework

The health parameter values for the examples depicted in the previous section (Figure 5.1, Figure 5.2, Figure 5.3, Figure 5.4) were often collected at different times and at different intervals. In the case of patient 1 (Figure 5.1) the most recent values collected before 12:30 include sleep state data from the morning of that day since it's only collected while the patient is in bed and blood pressure measurements from two hours prior. All of these values are retrieved correctly and displayed together satisfying requirement 1 for the software framework defined in chapter 3.

During the physicalization of the examples for the previous section (Figure 5.1, Figure 5.2, Figure 5.3, Figure 5.4), the physicalization device and the external server were connected only via the WiFi network. While both devices were in the same network and the same room at the time, maintaining the connection from a different location would not require big changes and requirement 4 is also fulfilled.

5.3.2 Physicalization

Since the physicalization represents blood pressure (a fluctuating numerical value), Heart Rate, and Sleep state at once requirement 1 is fulfilled. When comparing the physicalizations in the previous section, differences in health parameters such as blood pressure (Figure 5.3) and sleep state (Figure 5.4) are recognizable. This satisfies part of requirement 2, namely being intuitive. The physicalization is also dynamic since new values are periodically requested and displayed, which fulfills the second part of requirement 2.

The top part of the physicalization is made out of paper, while the supporting structure is 3D-printed and contains commonly available electronics. All of these are very accessible materials that satisfy requirement 3. The paper tower can also be extended or modified by adding layers on top or different colored LEDs, fulfilling requirement 4 concerning adaptability.

CHAPTER 6

Conclusion

In this thesis, I describe the design process for a physicalization framework, including a shape-changing physicalization device that can serve as an **ambient display**. The physicalization framework and physicalization prototype I created are capable of physicalizing the vital parameters of patients in a meaningful way. It is possible to **adapt the framework to other use cases** in a few steps. This opens up new possibilities, LAMPI could, for example, be used to display breathing rate and blood oxygen or data unrelated to medicine that can be described as a periodic wave. Additionally due to being made from **easily accessible materials**, this prototype may contribute to making data physicalization more readily available for a broad audience.

Limitations and Future Work

The physicalization has some limitations due the nature of its construction, such as a **limited range of motion** due to friction. While there is no optimal solution, using different strings may help. Another drawback, which might pose an issue when using it as an ambient display, is the **noise** that LAMPI makes when moving. The stepper motor, while relatively quiet, still makes a low noise when running, as does the limit switch when pressed. Unfortunately, I was not able to find a transparent paper that is quiet when folded and moved, so there is also some crinkling. The use of different paper and a light or ultrasound sensor instead of the limit switch may help to reduce noise. On the other hand the low noise can also communicate some information to the user when they are not looking at the display. It was also quite difficult to get the top of the tower to be even one of the strings was always too loose or too tight, which resulted in a slightly tilted tower top. To remedy this the strings could be controlled by individual motors.

LAMPI has the potential to be expanded, for example, by **replacing the recorded dataset with actual live data** or by encoding additional parameters and adjusting the physicalization. Live data usage may require the implementation of encrypted communication, however, since sensitive patient data is being transmitted. Expanding the physicalization itself may be as easy as adding more colored LEDs and encoding an enumerated value or encoding a new property into the light intensity. In that regard, it might also be interesting to explore controlling the strings with individual motors as I mentioned before, making it possible to not only keep the tower perfectly straight but also, tilt and bend the tower in a controlled manner. This permits **encoding** some other **parameter** into the **tower's lopsidedness** for example relative change between currently displayed value and previous value.

Another interesting direction for future work may be exploring the conversion from raw measured parameters to uniform values in more detail. The method used to derive uniform values from measured properties for tower height is linear scaling, but other methods of scaling could be employed, making it easier to show values in large intervals. Different scaling methods could be compared to each other, perhaps through a user survey. With the framework presented in this thesis, I hope to show that data physicalization has great potential. Future work may be needed to explore further how data physicalization can improve data communication in health care and telemedicine.

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