LAMPI - Live Ambient Physicalization Interface for Dynamic Data

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Abstract

Data physicalizations are becoming increasingly popular as a means of connecting people to abstract data. They may help integrate the flood of information collected by modern technology into our everyday lives. In this paper, we 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. We 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 and relies on paper for moving components. It is also capable of showcasing data for other use cases with minimal adaptations, further expanding the possibilities for data physicalization.

Keywords: Data Physicalization, Telemedicine, Remote Monitoring, Ambient Display

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 [11, 14].

However, not all physical objects representing data are physicalizations. An important distinction made by Dragicevic et al. [11] is that physicalizations convey abstract data of some kind.

Jansen et al. [14] define data physicalization as a "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 [11].

Many researchers in the field ([19, 11]) distinguish between static and dynamic physicalizations. Bae et al. [4] 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.

Two other topics closely related to Data Physicalization are ambient displays and shape-changing interfaces. 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 [2]. Ambient displays make use of the physical environment to represent digital data and changes in data through subtle changes in movement, sound, color, smell, temperature, or light [22].

The goal of this paper is to create an adaptable framework for physicalizing data and to design a display that continuously shows different types of data to help users monitor changes in dynamic data and blend into their environment. So that users do not need to remember or be reminded to check the data via their phone or another device to be aware of changes in the data they are monitoring. Data will be represented via a shape-changing interface that adapts its properties as the underlying data changes.

This paper's **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.

We use the data of a recorded dataset of human vital parameters [18] as input for a shape-changing display to simulate a fictional scenario of a remote user sharing their

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data with relatives or friends since remote monitoring is an aspect of medicine and care that has gained more popularity recently. The physicalization is constructed from a 3D-printed base supporting a moving paper tower structure, which is the main component of the physicalization.

2 Related Work

Increased availability of wearable sensors also led to growing interest in telemedicine 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 [6] . This often includes monitoring devices to collect health-related parameters and data concerning physical activities [1]. Such devices usually provide feedback, featuring numbers, traditional graphs, and charts, to patients and their relatives or caregivers [16, 1]. According to Ashlehhi et al. [3] users prefer simpler charts over more complex charts which can quickly become overwhelming when it comes to tracking health-related data, because they are able to understand them more easily.

This can make it difficult to effectively visualize and communicate more complex data which is quite common in the medical field. Physicalization can help users make sense of the flood of information and grasp the connection between different captured parameters. To enable users to interact and gain a better understanding of dynamic data, Houben et al. [13] proposed “Physikit”; a configurable ambient physicalization using movement, light, or airflow to communicate data. They also conducted a field study that showed that people developed a greater interest in and awareness of the data communicated through “Physikit” than using conventional means such as push notifications and traditional visualization through charts.

Recently, Daniel et al. [8] 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 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.

In their study, Davis-Owusu et al. [9] 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 the activity levels of the caregiver and patient for the respective counterpart. The concept presented in this thesis is unidirectional

Another example of a physicalization used in a remote monitoring scenario is Vital+Morph by Boehm and Iwata [7], 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 (Figure 1, 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 paper.

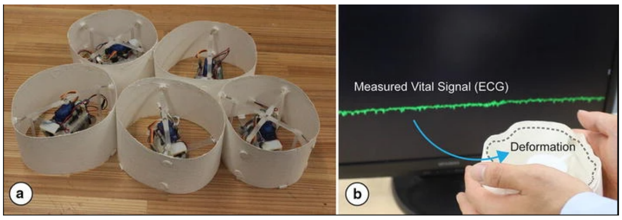


Figure 1: Vital+Morph: Haptic physicalization of vital parameters for a remote monitoring scenario [7]

Studies like those by Davis-Owusu et al. [9] and Boem and Iwata [7] have indicated that ambient displays that showcase activity levels and vital parameters can make relatives and caregivers feel more connected to the person whose data is displayed. Vice versa Davis-Owusu et al. [9] 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.

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 static physical objects instead, such as 3D-printed jewelry [21] based on physical activity, a singing bowl representing one year of blood pressure data [5].

Research Gap. While frameworks for modular and ambient data physicalization exist, applications in the biomedical area are sparse. Most solutions for physicalizing medical data are static and/or built for a highly specific use case. The framework we designed is flexible and can be used together with a cost-effective prototype.

3 Software Framework

3.1 Requirements

Biomedical data is very diverse so there are a lot of health-related use cases for ambient physicalization. We devise our requirements to make both the framework and the physicalization flexible so that they can be adapted and used for many potential use cases. We define 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

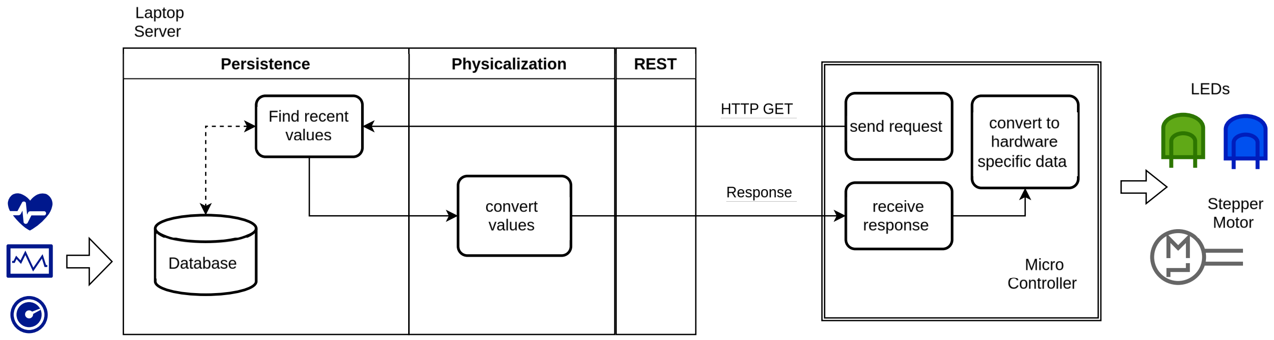


Figure 2: Flow diagram depicting the communication and data flow between the physicalization device and external server storing observed data.

most recent values for all parameters, even if they were collected at different times.

2. **Compatibility and adaptability:** The design should allow for easy adaptation of the framework for different use cases featuring different data, with little changes to the code. Transmission of values should occur in a uniform format so that it is compatible even if different hardware components are used for the physicalization.

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.

3.2 Design

Considering that in remote monitoring scenarios, data is often provided as a continuous stream of parameters, we 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 to 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**hysicalization **I**nterface

Many healthcare applications share 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.

We chose to use the same approach for the physicalization because this satisfies requirement 2 regarding adaptability and requirement 3 and **separates data storage and data rendering**.

The physicalization interface communicates with a remote server using a gateway device for example a micro-controller. The fact that it would be very easy to receive and persist live data from sensors via a similar gateway device satisfies requirement 3.

The values we chose to transmit data between the components 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.

3.2.1 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. For live data usage, the communication method can be changed to https with just a few adjustments to protect the sensitive information that is transmitted. A general overview of the system's communication and structure is depicted in Figure 2.

A small server created with spring boot and a simple layered architecture [20] is the basis for handling communication and persistence of data, opening the possibility to persist and use live data (Requirement 3). We 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 point number in the range between 0 and 1 using predefined min and max values, so changing to a different use case with other vital parameters and value ranges only requires changing min and max values in the code. Enumerated or boolean values are converted to integer numbers.

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. This makes it easy to adapt the whole system to different uses cases for example representing other vital parameters like for breathing rate or blood oxygen levels which fulfills 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.

4 Physicalization Prototype

After defining a framework for data processing, we now propose a versatile data physicalization concept to display continuously changing data.

4.1 Requirements

The requirements describing an ambient physicalization device for continuously updating medical data go hand in hand with the requirements we presented for our software framework in the previous section.

1. **Represent several different data types:** Biomedical data comes in a variety of data types [15]. Therefore fluctuating numerical values, constant numerical values and boolean or enumerated values, should be represented by the physical properties of the physicalization device.

2. **Dynamic:** The properties of the physicalization have to change when the corresponding data does [19]. Changes in the data embedded in the object should be easily recognized by users interacting with the physicalization.

3. **Easily adaptable:** Construction and design of the physicalization should allow for customization and easy adaptation to different use cases [10].

4.2 Design

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.[4], 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 that 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.

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

We 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. [9] 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 a 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. [8] 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**.

We chose paper as a material to construct the moving parts of the physicalization because it is flexible and reduces the number of electronics and 3D-printed parts compared to mechanisms made from non-flexible materials.

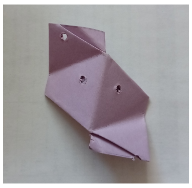
4.3 Physical Object

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.

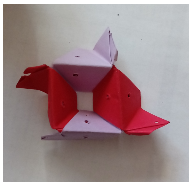
4.3.1 Paper Tower

For the main body, we chose the **origami twisted tower** structure first invented by Mihoko Tachibana, and used by Fei et al. [12] and Lee et al. [17]. As shown in Figure 3 many singular folded paper pieces make up flexible base segments that are layered to build a paper tower.

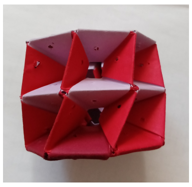
The unique structure allows for modifying tower height simply through the pulling of strings, without the need for springs or other components by making use of the inherent elasticity of the paper.



(a) Folded piece



(b) Basic segment



(c) Twisted tower

Figure 3: Twisted Tower(c) Assembly: Singular paper pieces are folded (a) and combined into basic segments which are then connected. Eight segments in a circle make up each individual layer of the tower(c).

4.3.2 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. 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**.

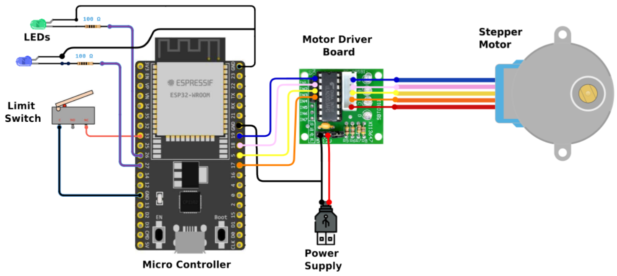
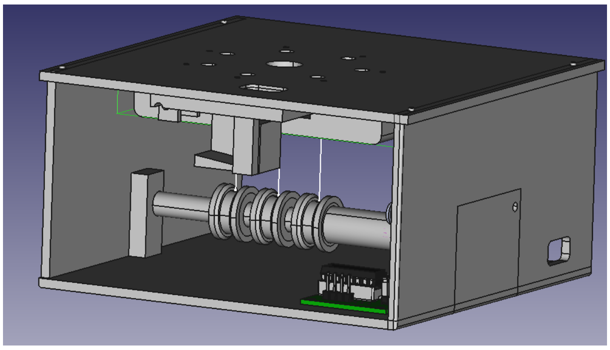
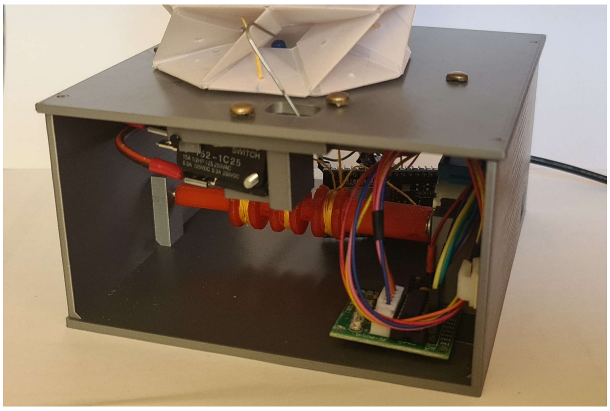


Figure 4: Most electrical components are directly connected to and powered by the micro-controller operating the physicalization, except the stepper motor which has it's own power supply.

To contain the electronics depicted in Figure 4 as well as a mechanism for winding up the string to move the twisted paper tower, we designed a **3D-printed cuboid base** (Figure 5) made of 5 different parts with fixtures for the components inside.



(a) 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.



(b) 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

Figure 5: Cuboid base

5 Case Study

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

5.1 Example Data and Encoding

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 [18] 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. 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, at intervals 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.

The **height** of the paper tower represents **blood pressure** and moves cyclically between two 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. We chose this encoding based on the design used by Davis-Owusu et al. [9], 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. This interval was chosen with respect to the smallest time interval in which data is collected in this case heart rate. If the server cannot be reached, the physicalization continues with the last values it received but is not illuminated. We 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 suddenly halting all movement could be perceived as the represented vital parameters stopping and a possible emergency situation. According to Boem and Iwata [7], this is a concern raised by several people after experiencing the physicalization of vital signs.

5.2 Physicalization of Patient Data

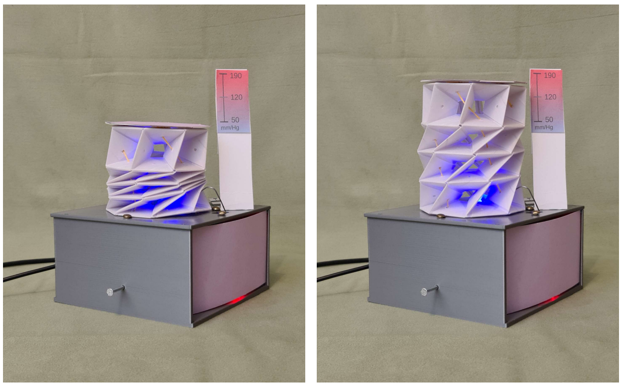
Three patients with different vital parameters were selected from the data set, and their values physicalized, as might be the case if they chose to share their data with some of their relatives with LAMPI.

The following pictures (Figure 6) show the vital parameters of example patients.

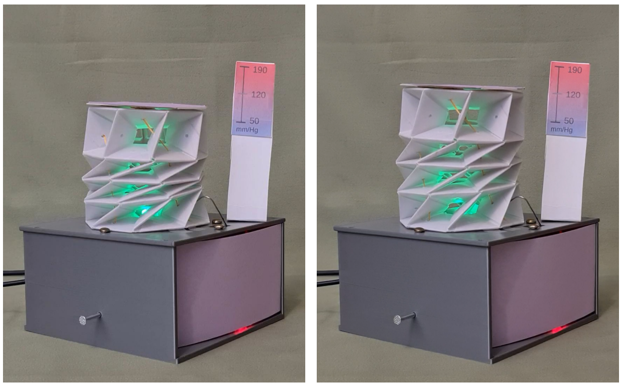
The first patient's values (Figure 6a) were captured at night. As illustrated by the blue light, he was asleep. To represent blood pressure, the tower moves between a lower position, indicating diastole and systole, scaled to the movement range the tower provides. A low diastole is embodied by a very low tower height as seen in Figure 6a, while the relatively high systole is likewise represented by a tower height value close to the maximum, depicted in Figure 6a

To show how changes in vital parameters are displayed, we captured the physicalization of values from a second patient on two different days (Figure 6b) to compare them. The picture on the left (Figure 6b) shows the patient's systole on the first day in the afternoon. She was more active the following day, possibly due to going for a walk, which raised her blood pressure and her heart rate as depicted in Figure 6b.

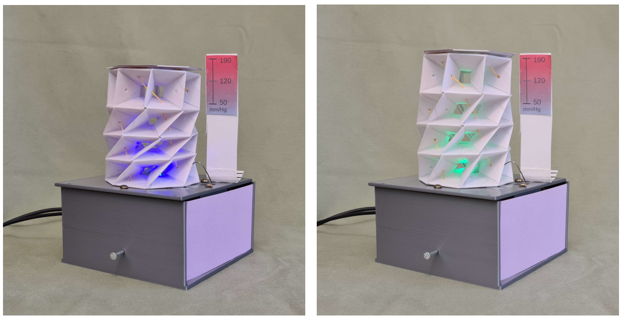
To demonstrate the range a person's, in this case, an elderly woman's, parameters can have throughout a normal day, we picked the time points to be at night and during the day for the fourth patient. On the left picture, her systole during sleep (Figure 6c), as indicated by the blue illumination, is displayed, while the right image (Figure 6c) shows her systole during the day. The change in heart rate was reflected by lower movement speed while displaying the first set of values.



(a) Patient 1: Tower height oscillates between systolic and diastolic pressure which was 161 and 72 mm/Hg, the rhythm represents the resting heart rate of 72 Beats/Min, the blue LED means that the patient is asleep.



(b) Patient 2: A systole of 113 mm/Hg was physicalized while the patient was awake (as indicated by the green light) and and resting, a higher systole of 126 mm/Hg after activity is reflected by a greater tower height.



(c) Patient 3: Tower height and light color vary as the patient's physical parameters change, during sleep heart rate and blood pressure are lower than during the day when the patient is awake.

Figure 6: Physicalization of patient data

6 Discussion

The physicalization has some limitations due to 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, we were 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 we 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.

Since the prototype presented in this paper was not evaluated, a user study would be a logical next step and could help further refine the encoding to be more effective. 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 paper, we 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.

Conclusion. LAMPI is an attempt to bridge the gap between data collection and ambient physicalization. The framework and prototype show the potential for ambient displays in telemedicine and remote monitoring and how they can help make data more accessible for users. Modular and flexible physicalizations like LAMPI can adapt to the many different use cases and kinds of data that the biomedical field has to offer and increase interest in and understanding of the data they represent.

References

[1] Salman Ahmed, Saad Irfan, Nasira Kiran, Nayyer Masood, Nadeem Anjum, and Naeem Ramzan. Remote Health Monitoring Systems for Elderly People: A Survey. *Sensors*, 23(16):7095, August 2023.

[2] Jason Alexander, Anne Roudaut, Jürgen Steimle, Kasper Hornbæk, Miguel Bruns Alonso, Sean Follmer, and Timothy Merritt. Grand Challenges in Shape-Changing Interface Research. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*, pages 1–14, Montreal QC Canada, April 2018. ACM.

[3] Yasmeen Anjeer Alshehhi, Mohamed Abdelrazek, Ben Joseph Philip, and Alessio Bonti. Understanding User Perspectives on Data Visualization in mHealth Apps: A Survey Study. *IEEE Access*, 11:84200–84213, 2023.

[4] S. Sandra Bae, Clement Zheng, Mary Etta West, Ellen Yi-Luen Do, Samuel Huron, and Danielle Albers Szafir. Making Data Tangible: A Cross-disciplinary Design Space for Data Physicalization, 2022. Version Number: 1.

[5] Stephen Barrass and Stephen Barrass@Canberra. ACOUSTIC SONIFICATION OF BLOOD PRESSURE IN THE FORM OF A SINGING BOWL. In *Proceedings of the Conference on Sonification in Health and Environmental Data*, pages 16–21, 2014.

[6] Stephanie Blackman, Claudine Matlo, Charisse Bobrovitskiy, Ashley Waldoch, Mei Lan Fang, Piper Jackson, Alex Mihailidis, Louise Nygård, Arlene Astell, and Andrew Sixsmith. Ambient Assisted Living Technologies for Aging Well: A Scoping Review. *Journal of Intelligent Systems*, 25(1):55–69, January 2016.

[7] Alberto Boem and Hiroo Iwata. "It's like holding a human heart": the design of Vital + Morph, a shape-changing interface for remote monitoring. *AI & SOCIETY*, 33(4):599–619, November 2018.

[8] Maxime Daniel, Guillaume Rivière, and Nadine Couture. CairnFORM: a Shape-Changing Ring Chart Notifying Renewable Energy Availability in Peripheral Locations. In *Proceedings of the Thirteenth International Conference on Tangible, Embedded, and Embodied Interaction*, pages 275–286, Tempe Arizona USA, March 2019. ACM.

[9] Kadian Davis-Owusu, Evans Owusu, Lucio Marcenaro, Carlo Regazzoni, Loe Feijs, and Jun Hu. Towards a Deeper Understanding of the Behavioural Implications of Bidirectional Activity-Based Ambient Displays in Ambient Assisted Living Environments. In Ivan Ganchev, Nuno M. Garcia,

Ciprian Dobre, Constandinos X. Mavromoustakis, and Rossitza Goleva, editors, *Enhanced Living Environments*, volume 11369, pages 108–151. Springer International Publishing, Cham, 2019. Series Title: Lecture Notes in Computer Science.

[10] H. Djavaherpour, F. Samavati, A. Mahdavi-Amiri, F. Yazdanbakhsh, S. Huron, R. Levy, Y. Jansen, and L. Oehlberg. Data to Physicalization: A Survey of the Physical Rendering Process. *Computer Graphics Forum*, 40(3):569–598, June 2021.

[11] Pierre Dragicevic, Yvonne Jansen, and Andrew Vande Moere. Data Physicalization. In Jean Vanderdonckt, Philippe Palanque, and Marco Winckler, editors, *Handbook of Human Computer Interaction*, pages 1–51. Springer International Publishing, Cham, 2021.

[12] Fei Fei, Ying Leng, Sifan Xian, Wende Dong, Kuiying Yin, and Guanglie Zhang. Design of an Origami Crawling Robot with Reconfigurable Sliding Feet. *Applied Sciences*, 12(5):2520, February 2022.

[13] Steven Houben, Connie Golsteijn, Sarah Gallacher, Rose Johnson, Saskia Bakker, Nicolai Marquardt, Licia Capra, and Yvonne Rogers. Physikit: Data Engagement Through Physical Ambient Visualizations in the Home. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*, pages 1608–1619, San Jose California USA, May 2016. ACM.

[14] Yvonne Jansen, Pierre Dragicevic, Petra Isenberg, Jason Alexander, Abhijit Karnik, Johan Kildal, Sriram Subramanian, and Kasper Hornbæk. Opportunities and Challenges for Data Physicalization. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*, pages 3227–3236, Seoul Republic of Korea, April 2015. ACM.

[15] Eugenijus Kaniusas. *Biomedical signals and sensors*. Biological and medical physics, biomedical engineering. Springer, Heidelberg, 2012.

[16] Sung-Hee Kim. A Systematic Review on Visualizations for Self-Generated Health Data for Daily Activities. *International Journal of Environmental Research and Public Health*, 19(18):11166, September 2022.

[17] Kiju Lee, Yanzhou Wang, and Chuanqi Zheng. TWISTER Hand: Underactuated Robotic Gripper Inspired by Origami Twisted Tower. *IEEE Transactions on Robotics*, 36(2):488–500, April 2020.

[18] Francesca Palermo, Yu Chen, Alexander Capstick, Nan Fletcher-Loyd, Chloe Walsh, Samaneh Kouchaki, Jessica True, Olga Balazikova, Eyal Soreq, Gregory Scott, Helen Rostill, Ramin Nilforooshan, and Payam Barnaghi. TIHM: An open dataset for remote healthcare monitoring in dementia, February 2023.

[19] Champika Ranasinghe and Auriol Degbelo. Encoding Variables, Evaluation Criteria, and Evaluation Methods for Data Physicalisations: A Review. *Multimodal Technologies and Interaction*, 7(7):73, July 2023.

[20] Mark Richards and Neal Ford. *Fundamentals of software architecture: an engineering approach*. O'Reilly Media, Inc., Sebastopol, CA, first edition edition, 2020. OCLC: 1138515057.

[21] Simon Stusak, Aurelien Tabard, Franziska Sauka, Rohit Ashok Khot, and Andreas Butz. Activity Sculptures: Exploring the Impact of Physical Visualizations on Running Activity. *IEEE Transactions on Visualization and Computer Graphics*, 20(12):2201–2210, December 2014.

[22] Craig Wisneski, Hiroshi Ishii, Andrew Dahley, Matt Gorbet, Scott Brave, Brygg Ullmer, and Paul Yarin. Ambient Displays: Turning Architectural Space into an Interface between People and Digital Information. In Gerhard Goos, Juris Hartmanis, Jan Van Leeuwen, Norbert A. Streitz, Shin'ichi Konomi, and Heinz-Jürgen Burkhardt, editors, *Cooperative Buildings: Integrating Information, Organization, and Architecture*, volume 1370, pages 22–32. Springer Berlin Heidelberg, Berlin, Heidelberg, 1998. Series Title: Lecture Notes in Computer Science.