Towards a Framework for Dynamic Data Physicalisation

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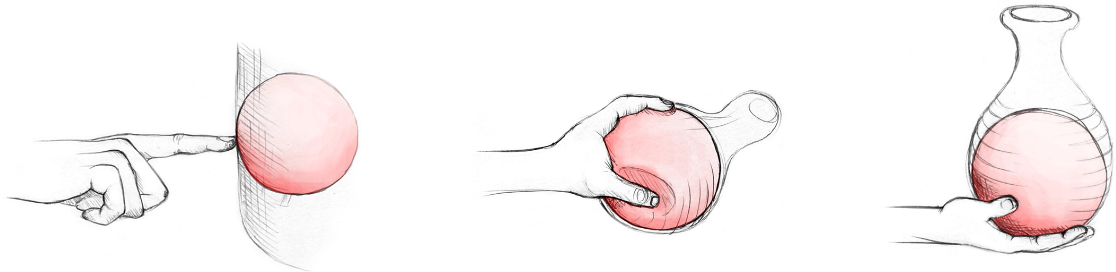

Fig. 1. Various types of interactions with dynamic data physicalisations (pointing on the left, squeezing in the middle and weighting on the right) as they might in the future be supported by different end effectors of the tangible hologram (TangHo) [17] platform or other dynamic data physicalisation solutions

Abstract—Advanced data visualisation techniques enable the exploration and analysis of large datasets. Recently, there is the emerging field of *data physicalisation*, where data is represented in physical space (e.g. via physical models) and can no longer only be explored visually, but also by making use of other senses such as touch. Most existing data physicalisation solutions are static and cannot be dynamically updated based on a user's interaction. Our goal is to develop a framework for new forms of *dynamic data physicalisation* in order to support an interactive exploration and analysis of datasets. Based on a study of the design space for dynamic data physicalisation, we are therefore working on a grammar for representing the fundamental physical operations and interactions that can be applied to the underlying data. Our envisioned *extensible data physicalisation framework* will enable the rapid prototyping of dynamic data physicalisations and thereby support researchers who want to experiment with new combinations of physical variables or output devices for dynamic data physicalisation as well as designers and application developers who are interested in the development of innovative dynamic data physicalisation solutions.

Index Terms—Data physicalisation, conceptual framework, software framework, interactive data exploration, data analysis

1 Introduction

Advanced data visualisation techniques are often used to deal with information overload when exploring and analysing large datasets. These visualisations help us in finding hidden patterns and connections but might also be used for designing the information space and interactions in order to tell a story and enable the audience to explore the (data) landscape with their eyes, as nicely illustrated in a TED Talk by David McCandless about *The Beauty of Data Visualisation*[1]. Hans Rosling, who introduced new interactive visualisation tools for working with data, further stated that by using the right tools for visual data exploration and analysis we might *"let the dataset change your mindset"*[2].

Whilst data visualisation only makes use of a single modality (vision) for exploring and analysing a dataset, *data physicalisation* (DP) is a recently emerging research field that aims to go beyond a visual data representation by encoding data in physical space and, for example, enabling haptic interactions with a dataset. A survey on different designs for haptic data visualisations and how these are useful for blind people to feel line graphs has been presented by Paneels and Roberts [13]. They showed that not only blind people can profit from haptic data encoding, but the haptic modality can also be used alongside other modalities to increase the number of variables that can be "visualised".

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[1]https://www.youtube.com/watch?v=5Zg-C8AAIGg
[2]https://www.ted.com/talks/hans_rosling_at_state

The term *data physicalisation* has recently been proposed by Jansen et al. [9] as *"A data physicalization (or simply physicalization) is a physical artifact whose geometry or material properties encode data"*. This definition has further been extended by Willett et al. [22] by suggesting that data physicalisation should be considered in both, embedded as well as situated context. While situated data representations display data in proximity to data referents, embedded data representations display data so that it spatially coincides with data referents. Hogan and Hornecker [6] use the term *multisensory data representation* as an alternative for data physicalisation and carried out some work towards a design space for multisensory data representation. The same idea of multisensory information visualisation has been discussed by Roberts and Walker [14] in their proposal for a united theory of visualisation that would unify multiple senses and allow users to integrate different modalities. They motivate further research on the identification of different perceptual variables and design strategies for representing information across different modalities. Multisensory data representation—including for example touch or sound—can help in enhancing the perception of complex data relationships. However, these new forms of data representation approaches require a better understanding of the semiotics of multisensory data design [16]. Note that the emerging interest in data physicalisation is also reflected by recent workshops about the challenges and future directions for making data physical [1] as well as some dedicated data physicalisation websites, including a Wiki on data physicalisation[3].

Physical visualisations are not new and the earliest forms of physical visualisations date back to the use of Mesopotamian clay tokens in 8000 BC [15]. While many different forms of physical visualisations have been used in the past, these are normally *static physicalisations* which cannot easily be updated when the underlying data changes, or be

[3]http://dataphys.org/wiki/Data_Physicalization

dynamically changed based on some user interaction with the physical data representation. A major advantage of using data physicalisation for the exploration and analysis of datasets is the fact that physical visualisations can be more efficient as shown in a study by Jansen et al. [8] where the interaction with 3D bar chart visualisations on a screen has been compared to the interaction with a physical version of the bar charts. Vande Moere [11] questions the current use of information displays to simulate real world metaphors which are then used to represent abstract data, and proposed different forms of data physicalisation via ambient displays and pixel sculptures to go beyond *"the tyranny of the pixel"*. Instead of using classical screen-based data visualisation techniques, abstract data can be physically embodied in data sculptures as illustrated in a qualitative study by Vande Moere [12].

Many sophisticated data visualisations are based on heuristic approaches [3] rather than any structure or grammar. However, in *The Grammar of Graphics* [21], Wilkinson follows a more formal and fundamental approach for data-driven visualisation. An early implementation of automatic data visualisation was Mackinlay's [10] automatic design of graphical presentations of relational information stored in databases which later resulted in the VizQL language to query, analyse and visualise data, and inspired solutions such as the well-known Tableau[4] data visualisation tool. While there is currently no formal and fundamental data-driven approach for data physicalisation, this might be the key for automatically dealing with complex data physicalisations in the future.

The process of creating static data physicalisations via MakerVis has been studied in three case studies by Swaminathan et al. [18] and the limitations of current physicalisation fabrication workflows have been illustrated. While existing data physicalisation solutions currently offer limited support for dynamic updates, there is a need for *dynamic data physicalisation* [9] to support interactive data exploration and analysis tasks where the physicalisation is updated based on a user's interaction. Dynamic data physicalisation in the form of bar charts on a shape-changing display has, for example, been investigated by Taher et al. [19]. In the long term, the vision-driven design research on radical atoms and programmable matter by Ishii et al. [7] might lead to more flexible materials with programmable physical properties which could be applied in data physicalisation. While Ishii's research group is currently developing shape-changing physical interfaces to simulate interactions with programmable mater that might be available in the future, our lab is working on tangible holograms and the tangible hologram (TangHo) platform [17] that can also be used for different forms of dynamic data physicalisation.

The emerging field of data physicalisation is promising for the representation of multidimensional datasets and the exploration and analysis of data via multiple modalities, but there are many *open research problems*—as for example stated by Jansen et al. [9]—that have to be addressed in order to better understand and develop better data physicalisation experiences. In the following, we list the research problems related to our work on a framework for dynamic data physicalisation:

- Most existing data physicalisation applications are static and cannot be easily updated. In order to support an interactive exploration and analysis of datasets as seen in on-screen visualisation solutions (human-in-the-loop data exploration), there is a need for new forms of *dynamic data visualisation*.

- Many existing data physicalisation solutions follow a heuristic approach. In order to build more flexible and data-driven physicalisations, there is a need for a formal and fundamental definition in the form of a *grammar of data physicalisation*.

- While there is some initial research on the data physicalisation design space, there is a need to better understand the *design space for dynamic data physicalisation*, including the physical encoding of data and the perceptual effectiveness of this encoding via different modalities.

[4]https://www.tableau.com

- For a more systematic approach in the design and development of data physicalisations, there is a need for a *conceptual data physicalisation framework* as, for example, seen for the domain of tangible interaction [20].

- Rather than implementing data physicalisations from scratch, there is a need for *data physicalisation software frameworks* to support designers and developers in the rapid prototyping of design alternatives and the evaluation of their performance.

- The combination of physical interactions and synthetic interactions is a challenging task and there is a lack of data physicalisation *interaction design guidelines* on how to best combine physical with synthetic interactions. Also new forms of flexible multi-user interactions that are supported by data physicalisation—and go beyond the traditional WIMP interaction—need to be further investigated.

2 Dynamic Data Physicalisation Framework

While many existing data physicalisation solutions are built from scratch, our objective is to develop a conceptual as well as software framework that can be used for the rapid prototyping and experimentation with dynamic data physicalisation solutions. For a more systematic approach in the design and development of data physicalisations, there is a need for a *conceptual data physicalisation framework* as, for example, seen for the domain of tangible interaction [20], which can then also serve the development of a *software framework for dynamic data physicalistion*. The core of our dynamic data physicalisation framework will be informed by an investigation of the dynamic data physicalisation design space as well as a dynamic data physicalisation grammar. The software framework for dynamic data physicalisation that we are currently developing is going to be extensible via specific software drivers in order to ensure that it can deal with future data physicalisation technologies and smart materials. An overview of our conceptual framework for dynamic data physicalisation is given in Figure 2.

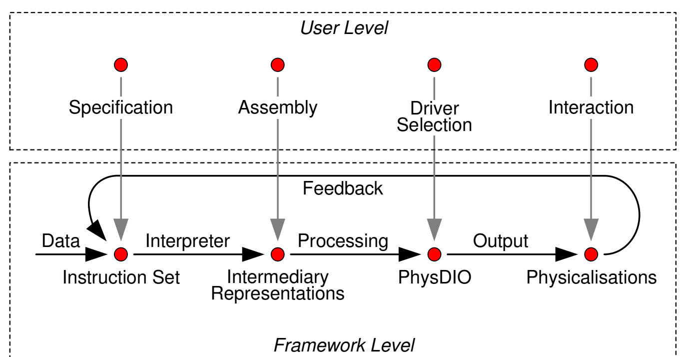

Fig. 2. Conceptual framework for dynamic data physicalisation

Data is going to be interpreted based on a number of specifications provided by the user (e.g. the set of data dimensions to be physicalised) in combination with the instruction set defined by the data physicalisation grammar. The resulting intermediary representation is then shown to the user together with possible physical variables in order that they can assemble the desired physical device-independent output (PhysDIO) consisting of a selection of these physical variables based on their preferences (e.g. a user might prefer haptic over thermal physicalisation). In a final phase, the user has the chance to select between different available drivers/devices which will then be used for transforming the PhysDIO into a concrete dynamic data physicalisation. Note that in contrast to existing static data physicalisations, at this stage any interaction by one or multiple users with the physical data representation might change the underlying specification and result in a dynamic update of the corresponding data physicalisation.

Our goal is to design a software framework for dynamic data physicalisation by envisioning future technological advancements similar to

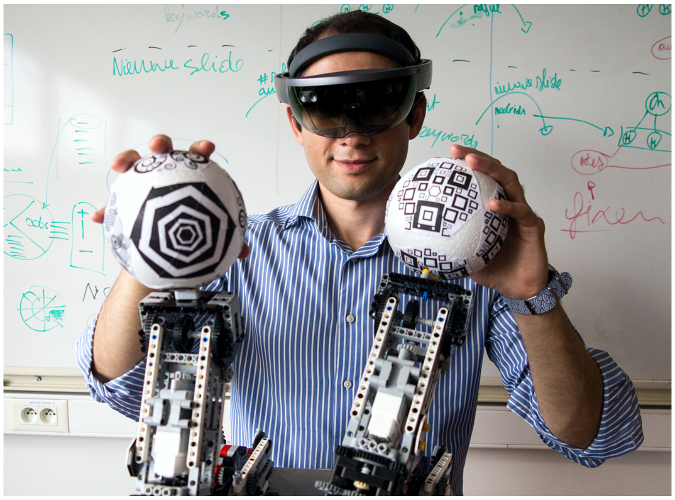

Fig. 3. User interacting with an early prototype of the TangHo platform consisting of a Microsoft HoloLens and two wearable Lego Mindstorms-based robot arms with their changeable end effectors for the physical augmentation of digital holograms

the *vision-driven design research* approach proposed by Ishii et al. [7] for programmable matter. While we focus on the fundamental operators and interactions for dynamic data physicalisation, not all of the features offered by the core of our framework might already be supported by existing data physicalisation technologies. However, our framework for dynamic data physicalisation can be extended via specific software drivers transforming the physical device-independent output into some concrete data physicalisations. For example, such a driver might transform the PhysDIO produced during the processing phase into commands for the tangible hologram (TangHo) [17] platform which is currently developed in our research lab and enables the experimentation with different physical variables for new forms of dynamic data physicalisation. Figure 3 shows a user interacting with an early prototype of the TangHo platform.

Our data physicalisation framework is going to make use of existing approaches for importing data (e.g. reading data from a file, connecting to a relational database management system (RDBMS) or connecting to a cluster). We see our dynamic data physicalisation approach as an alternative to pure data visualisation and will therefore not focus on other issues of data analysis (e.g. data warehousing, machine learning or clustering) but rather assume that users understand that some pre-processing might be necessary depending on the type of data.

Further, our goal is to make the software framework available to the research community in order that other researchers working on data physicalisation can profit from its rapid prototyping and extensibility features. The resulting framework can be used for building various forms of data physicalisation applications, ranging from physical interfaces for the playful exploration and analysis of datasets (e.g. in a museum as seen in ArtVis [5]) to the professional use by a data scientist in an exploratory data analysis task.

2.1 Dynamic Data Physicalisation Design Space

In order to build a dynamic data physicalisation framework, we first have to investigate the design space for dynamic data physicalisation and evaluate recent technological developments for dynamic data physicalisation. Thereby, we have to define a set of physical variables for dynamic data physicalisation and verify their effectiveness in the multisensory representation of multidimensional datasets. This can be achieved by taking existing work on multisensory data representation [6] into account and by analysing recent technological developments for dynamic data physicalisation. These technological developments range from low-level actuators for implementing physical variables such as smoothness, hardness or sponginess to the simulation of programmable matter [7] or the use of tangible holograms [17] for dynamic data physicalisation. As stated earlier, we take existing technologies into account, but in our vison-driven design research we also consider dynamic physicalisations which might currently not yet be technically feasible.

A detailed investigation of the dynamic data physicalisation design space helps in coming up with different forms of physical *data encodings* and a mapping of physical variables to the variables of a data physicalisation grammar. Thereby, we have to take into account that the features of a physical variable will dictate the type of digital information that it can represent (e.g. depending on how many different values a user will be able to distinguish). It is therefore necessary to evaluate the *perceptual effectiveness* of individual physical variables as well as the potential combinations of physical variables in order to know how effective they are in encoding and communicating data. This can happen through the study of existing literature as well as via specific experiments which help us to better understand for what kind of data a physicalisation makes sense and will ultimately result in an improved perceptual effectiveness.

2.2 Data Physicalisation Grammar

We are less interested in designing specific data physicalisations based on a heuristic approach but our objective is rather to define a formal grammar for dynamic data physicalisation. This formal specification can then be used in the *automatic and data-driven data physicalisation approach* shown earlier in Figure 2, which will be able do deal with complex physicalisations and interactions. To the best of our knowledge, there is currently no such grammar and data-driven approach for dynamic data physicalisation.

We are currently investigating a way to formally represent physicalisations and defining a set of rules and models to produce them. The definition of a grammar for data physicalisation is thereby informed by existing work in the domains of Information Visualisation (InfoVis) and Scientific Visualisation (SciVis) as well as recent developments in Human-Computer Interaction (HCI) and Tangible, Embedded and Embodied Interaction (TEI). Note that we are adopting a more general meaning of grammar—that goes beyond a grammar for programming languages—similar to the work of Wilkinson [21]. The data physicalisation grammar is going to support different types of *variables*. We plan to distinguish between *atomic variables* which are supported by the data physicalisation grammar out of the box and *complex variables* which are produced from atomic variables via the grammar's *algebra*.

The data physicalisation algebra dictates the possible sets, rules and operators over physicalisations and defines the set of possible operators between physicalisations. It is an open research question whether it is possible to apply all existing operators (e.g. unary and binary) to physicalisations or whether we have to define a subset of these operators. An advantage of dynamic data physicalisation is that new direct forms of interactions for the exploration and analysis of the underlying data are supported. Similar to Ishii's interactions for programmable matter [7], we therefore plan to define a set of possible *interactions* (e.g. squeezing or weighting) over physicalisations. These interactions can be atomic but the data physicalisation grammar's algebra should also enable the production of more complex interactions out of the atomic ones. Note that the data physicalisation grammar forms the foundation for our data-driven approach for data physicalisation and the corresponding software framework.

2.3 Design Guidelines

Similar to Bertin's [2] work for information visualisation, we are developing a systematic catalogue to help designers in choosing the right physical variables and combination of modalities when designing interactions for their data physicalisations. Our general guidelines for the new field of dynamic data physicalisation will include some formal *design guidelines* in terms of which physical variables and data physicalisations can be used for what type of data. In addition to these data physicalisation design guidelines, one also has to investigate guidelines for the *interaction* with data physicalisations and how to best combine different physical and digital variables for input as well as output in order to provide an effective human-information interaction. The definition of these design and interaction guidelines is tightly coupled to our framework's data physicalisation grammar and the guidelines are systematically evaluated for their perceptual effectiveness via a growing set of dynamic data physicalisation use cases that are implemented based the proposed dynamic data physicalisation software framework.

3 Discussion and Conclusion

The proposed framework for dynamic data physicalisation is going to serve different user groups. First of all, the grammar for dynamic data physicalisation represents a formalisation of the supported physical variables and instructions as well as their potential combinations and might foster the discussion within and across different research communities—including data physicalisation, human-computer interaction (HCI) or tangible, embedded and embodied interaction—about fundamental forms of data physicalisation interactions. Note that the grammar is expected to evolve over time based on new insights by the research community about possible physical variables and their potential combinations to form new dynamic data physicalisations.

Researchers and developers of new output devices for dynamic data physicalisations can also profit from the presented dynamic data physicalisation framework since they get immediate access to different existing datasets as well as the entire processing and generation of physical device-independent output by only having to implement a software driver for their new data physicalisation output devices. Of course also data scientists and knowledge workers could profit by having access to innovative interfaces for the exploration and interaction with high-dimensional datasets which might help to improve their efficiency and insights while exploring and analysing rich multi-dimensional datasets. Our data-driven approach with a grammar specifying the mappings of data to physical variables and their possible combinations to form more complex data physicalisations might further guide data scientists when creating dynamic data physicalisations and thereby foster the gain of knowledge through systematic study [4]. Existing interactive clustering approaches in the data science research field might profit from new interfaces making use of dynamic data physicalisation in order to not only make the decision making more accurate, but also more user-friendly and enjoyable for data workers. Note that different forms of data physicalisation are often also used in art installations for transporting messages about potentially complex datasets and facts to a larger audience or to enable post-WIMP interactions with these physical installations. The proposed framework for dynamic data physicalisation might support artists in building new forms of tangible multi-user interfaces (e.g. as seen in the ArtVis [5] project for digital output only) and provide them access to the latest findings on how to combine various physical variables, the best forms of multimodal interactions as well as recent developments regarding output devices for dynamic data physicalisation.

It is important to stress that we are interested in a conceptual as well as software framework for dynamic data physicalisation that enables the experimentation and definition of fundamental guidelines for data physicalisation. In our vision-driven research approach we thereby ignore the fact that the necessary technology for some of the proposed physicalisations might not yet be available, and already want to investigate new forms of interactions that might be supported by new forms of data physicalisation output devices in the near future. We strongly believe that, similar to the field of information visualisation and the work of Bertin [2], there is a need for fundamental research on dynamic data physicalisation design guidelines for the representation of higher-dimensional datasets and that the presented dynamic data physicalisation framework can serve as a common ground and communication platform (e.g. via the formalised data physicalisation grammar for data-driven physicalisations) for researchers and developers working on these design and interaction guidelines. By presenting and discussing our proposal and current work on a framework for dynamic data physicalisation with the scientific community, we hope to establish a working group who might be interested in contributing to the idea of a formal data physicalisation grammar and a dynamic data physicalisation software framework that can serve as a research platform for the experimentation and evaluation of emerging forms of dynamic data physicalisation.

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