INTERNATIONAL DESIGN CONFERENCE – DESIGN 2022
https://doi.org/10.1017/pds.2022.43

Pro2Booth: Towards an Improved Tool for Capturing Prototypes and the Prototyping Process

L. Giunta ✉, J. Gopsill, L. Kent, M. Goudswaard, C. Snider and B. Hicks
University of Bristol, United Kingdom
✉ l.giunta@bristol.ac.uk

Abstract
The act of prototyping is a key element of the design process. However, capturing information on how prototypes evolve and influence one another is a complex problem. This paper presents an iterative evolution to a prototyping capture platform, termed Pro2Booth, designed to address the shortcomings encountered in previous systems. The Pro2Booth hardware and online software described in this paper provide a new baseline for future innovation and exploration of the prototype capture process.

Keywords: prototyping, data collection, product development, design analysis, design process

1. Introduction

Proposed in 2017, Protobooth was a platform aimed at easily capturing the output of the prototyping processes (Sjoman et al., 2017). Output defined here as both the knowledge generated and the resulting prototype. The driving motivation for the platform was the complexity of capturing and visualizing information in the design process. One example of the complexities encountered is found in the "fuzzy front end" of design. The "fuzzy front end" plays a large role in the success or failure of design projects (Herstatt and Verworn, 2004). However, due to its inherently unstructured nature, this process is difficult to study and capture effectively. Different organizations or design teams may choose to tackle the initial stages of the design process in different ways.

Prototypes are a valuable tool to process and share knowledge, both between design team members and stakeholders (Erichsen et al., 2016). As discussed by Subrahmanian et al. (2003), prototypes act as boundary objects between participants in the design process. However, to adequately fulfil this function, prototypes must be constantly updated to match the realities of the design process lest they lose their ability to effectively support the communication between the participants and generate a common ground. By focusing on the prototypes generated it is possible to measure the tangible outputs of a design process and analyse the design process. The generation of prototypes will also continue throughout the design development process, allowing for a roadmap to be generated, including any and all tangents that the designers chose to explore.

While a number of tools have been developed and tested by the research community to capture the output of the prototyping process, challenges remain in their successful application and adoption within the design process. Trials of these tools highlight the challenge of capturing relevant data and the practicalities of designers inputting information as part of their day-to-day activities.

The paper begins by discussing related work in capturing prototype knowledge and output (Section 2). Subsequently, any shortcomings in existing methodologies and research tools are identified and highlighted. The paper continues by discussing Pro2Booth - a tool that has been developed by building on the existing research and addresses the shortcomings identified (Section 3). Validation of the tool has been achieved through a pilot study run to assess Pro2Booth's efficacy in capturing prototyping knowledge and output data (Sections 4 & 5). Finally, a discussion of the results is provided and future work necessary for the improvement of the Pro2Booth platform is highlighted (Section 6). The paper then concludes with the key findings from the study (Section 7).

2. Related Work

Section 2 discusses pre-existing work as well as laying the groundwork for the definitions used in the remainder of the paper. Firstly, the terms prototype and prototyping are described. Thereafter, the section continues by discussing two preceding iterations of platforms that have sought to capture the output of the prototyping process: Protobooth and ARCHIE. Lastly, this section concludes by discussing the opportunities for further development as well as shortcomings in the existing platforms.

2.1. Prototypes

Despite featuring prominently in the literature, neither the word “prototype” nor “prototyping” have definitions that are widely accepted/adopted by the research community (Jensen et al., 2016). Mathias et al. (2018) discuss the existing literature surrounding prototypes providing insight into the existing schools of thought. Their comparison highlights that several attempts have been made at categorizing prototypes. Citing Ullman (2003) Mathias et al. (2018) provide four different uses for prototypes:

- **Proof-of-Concept:** Explores how to tackle the initial stages of product development.
- **Proof-of-Product:** Analyses the viability of manufacture as well as the product embodiment.
- **Proof-of-Process:** Used to understand whether the product as designed is compatible with the chosen manufacturing requirements.
- **Proof-of-Production:** Validates the production process's ability to meet the desired outcomes.

However, Mathias et al. (2018) contrasts this view of prototypes, as simple outputs, to that of Camere and Bordegoni (2016) who describe prototyping not just by the output generated but at the "activity of engaging with the product-to-be, instantiating the design process." (Camere and Bordegoni, 2016). Ultimately, Mathias et al. (2018) provide some form of definition for a prototype by amalgamating the six characteristics (material, interactivity, visual detail, purpose, surroundings, and technology) described by Jensen et al. (2015) with the additional dimension of technique. Technique is discussed as either the method of prototype creation or the tools involved as discussed by Blomkvist and Holmlid (2011) and Hallgrimsson (2012).

In summary: a prototype can be characterised in many ways and there is no universally accepted definition. However, it is possible, by focusing on certain characteristics of prototypes, to catalogue and categorize them. It is important to note that prototypes need not be physical or 3D. A cardboard model, a sketch on paper, or a CAD model are all equally valid forms of prototypes (Mathias et al., 2018).

As a result, the prototyping process lacks a universally accepted methodology, with different approaches adopted. Often information about the prototype and product development process is sparse, or known only to the team or individuals working on the project, as there is little to no expectation that it will be communicated to others (McAlpine et al., 2006). However, the information relating to the process of product development, rather than the information pertaining to the individual prototypes can yield interesting insights and learnings to improve future development activities (Barhoush et al., 2019; Bracewell et al., 2009; Siddharth et al., 2020). Soomro et al. (2021) analysed six technologies aimed at supporting the capture of prototyping activities, categorising them into three groups: software, hardware and hybrid approaches. Their analysis highlights the importance of accessibility, flexibility, and ease of use to the adoption and use of a prototyping process recording tool.

2.2. Protobooth

Protobooth was first discussed as a concept by Sjoman et al. (2017) as a tool to easily capture information about prototypes in development. The tool was envisioned as a device capable of quickly and effortlessly capturing prototypes and storing these into a repository. By capturing prototypes over time, the intention was to shed light into the prototype development process as well as the design evolution. Ease of use was emphasised by allowing the process to function automatically. On

https://doi.org/10.1017/pds.2022.43 Published online by Cambridge University Press

presenting an RFID card to a reader mounted on Protobooth, the cameras would automatically snap two photos, one for each camera mounted on the booth.

Erichsen et al. (2021) further improved the booth design by increasing the number of cameras used to capture prototypes to seven. Figure 1 shows the updated version of Protobooth developed by Erichsen et al. (2021). In addition, metadata, such as timestamps, is automatically stored when the capture process is initiated. The user interface continues to be through an RFID reader that users must scan a card with. All this data is automatically uploaded to an online database. Here users can log in to review their prototypes and add additional information to the database. Prototypes can be linked to one-another to show how design progression or organized into separate projects.

While some data can be automatically processed, such as the number of prototypes generated vs the timestamps, other data needs to be manually inputted by researchers following a coding scheme. Information such as prototype material and tools are assessed post capture.

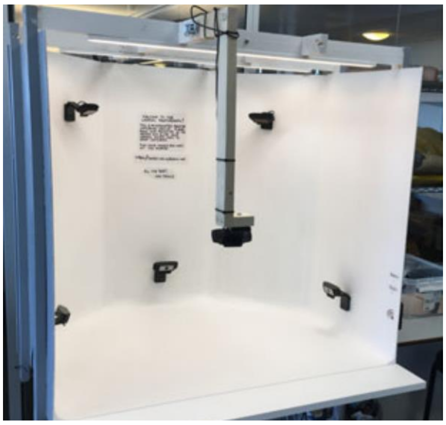


Figure 1. Updated version of Protobooth showing the seven camera positions (one camera at top dead centre of the booth) (Erichsen et al., 2021)

Figure 2 shows the data captured for a single project consisting of 82 prototypes. The graphic shows how the various prototypes have influenced one another going from the very first (leftmost side) to the final prototype (rightmost side) of the graphic. It should, however, be noted that this graphic was generated entirely by hand by a researcher analysing the data from the project, this adds considerable time to the process of analysing and preparing the data. Furthermore, as noted by the authors, participants have not embraced the adding of metadata post capture, resulting in less data for analysis[1]. Out of 1209 prototypes only 13.8% were given names, 15.4% had text in the free text box, and only 7.9% had both inputs completed. This leaves a sparse dataset which generates uncertainty should the data be used in the future. Lastly, the authors note that there are still unanswered questions with regards to the type of data captured and that important context may be missing from the captured data, potentially requiring the use of additional interviews (Erichsen et al., 2021).

Figure 2. Prototype evolution with influence links (Erichsen et al., 2021)

[1] Thank you to NTNU for providing an open access version of the dataset for the review.

https://doi.org/10.1017/pds.2022.43 Published online by Cambridge University Press

2.3. ARCHIE

ARCHIE (Archiving Results and Capturing Human Innovation in Engineering) is a tool developed to tackle four key objectives. These were (Nelson et al., 2019):

1. The design must collect data throughout a project, particularly in the later stages of design.
2. The device needs to collect data without researcher intervention.
3. The device needs to link physical prototyping efforts to designer knowledge at specific points in time.
4. The device needs to incentivize designers to use the device by providing high-quality documentation of prototyping efforts.

These four objectives were derived in part by Nelson et al's (2019) perceived shortcomings of Protobooth. As shown in Figure 3 (left), ARCHIE makes use of a single camera mounted at the top of the enclosure. To capture all angles of a prototype a turntable rotates in synchrony with the camera. Figure 3 (right) explains the process for using ARCHIE. Unlike Protobooth, ARCHIE attempts to incentivise users to complete the survey with additional prototype information by presenting them with it prior to taking any pictures. The user is first prompted for an ID, they then place the prototype on the turntable and, as part of the login process, completes the survey. Once this is complete the photographs of the prototype, and survey results, are taken and stored in a file storage system. Subsequently, they are then sent both to the participant and the researcher. Table 1 shows the survey questions asked to participants prior to capturing the prototype. It should be noted that in the case of "select multiple" and "select one" types the selection occurs from a pre-set pool of options.

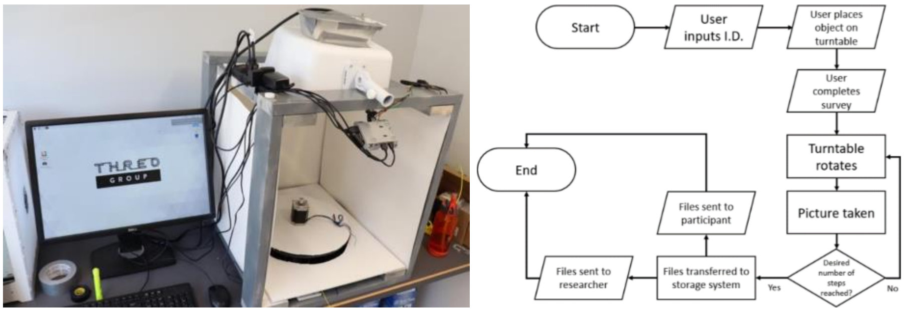


Figure 3. ARCHIE setup showing single camera and stepper motor (left) flow diagram showing intended usage process for ARCHIE (right)(Nelson et al., 2019)

Table 1. Survey questions and admissible response types (Nelson et al., 2019)

No.	Item	Type
1	List the requirements of your prototype	Free response
2	Select all of the applicable goals of your prototype	Select multiple
3	What did you learn from this prototype	Select multiple
4	What tools did you use in the creation of your prototype	Select multiple
5	Estimate the total time spent on the prototype	Select one
6	Estimate the cost of the prototype	Select one
7	Rate the value of your prototype with respect to (a) the project success, (b) learning about fabrication, (c) learning about the design problem, (d) refining project requirements	Five-point Likert Scale
8	Rate your confidence in (a) your ability to successfully complete the design task, (b) the completeness of requirements, (c) understanding of the design problem, (d) the feasibility of your solution, (e) your ability to test your solutions	Seven-point Likert Scale

While the ARCHIE platform improves on Protobooth by addressing the difficulties encountered with metadata collection forcing all input boxes to be fully filled in prior to prototype capture, several shortcomings were identified. The data collection methodology provided for the survey, while thorough, appears to be somewhat narrow. The use of set answers for questions such as prototype

https://doi.org/10.1017/pds.2022.43 Published online by Cambridge University Press

goals and learnings limit the variety and nuance of data that can be captured. While this is undoubtedly beneficial for the quantification of the design process, it may prevent the capture of data that shows emergent behaviour in the prototyping process. The authors acknowledge this shortcoming, reflecting that some of the items asked for in the survey may not be present in all designs.
Furthermore, the experiment that was presented as a test of ARCHIE's capabilities was limited to seven users and documented only nine designs. This limited number did not allow for an analysis of the influence prototypes had on one another, as was done with Protobooth (Figure 2). Like with Protobooth, the link between prototypes would need to be manually evaluated, as would any data generated by the survey. Lastly, ARCHIE's diminutive envelope size resulted in some of the pictures taken not managing to fully capture the prototype.

2.4. Identified Challenges

Both Protobooth and ARCHIE highlight important areas of attention for researchers wishing to capture the output of the prototyping process. The major challenges identified through an analysis of the work performed for both platforms were:

1. **Automation of the process for data capture and post-processing**
   The data capture and post-processing should tend towards automation and simplicity for the participants and the researchers leading the study. The data collection should flow naturally during the design process in order to avoid recollection bias. Post-processing should be simple to allow for the processing of larger dataset, permitting larger studies to be run without hindrance. This was highlighted by Protobooth's difficulty in collecting data from surveys and in collating the collected data into graphs (Erichsen et al., 2021).
2. **Ease of use**
   The act of using the platform should flow naturally with the participants' design process lest they resent the use of the platform and prevent effective data collection and should not distract them from the design challenge they are face with. This challenge was identified by Erichsen et al. (2021) who saw engagement difficulties with the survey.
3. **Envelope size**
   The size of the photo envelope, the area that the cameras can capture, should be large enough to allow for a wide array of prototypes to be photographed. Cameras should allow for the capture of prototypes of different shapes and sizes. This issues was identified by Nelson et al. (2019) when their platform failed to fully capture some prototypes due to their size.
4. **Data presentation**
   The data should be processed in such a format as to allow for the clear and effective presentation of data. Graphs showing the evolution of prototypes with influences, designers, and other relevant factors linked. This allows for emergent behaviour, that may not be immediately quantifiable, to be examined and explored.
5. **Capture of relevant data**
   The data captured must be both meaningful, allowing the researchers to understand how the prototype development and the design process develop, and avoid loaded questions that may force participants to misreport their work and experiences during the design process. This issue became apparent during a review of Nelson et al. (2019). The data captured did not necessarily allow for a full understanding of how the prototype evolution progressed. Equally designers should only need to impart information that cannot be captured through automated means in order to reduce their data input burden.

3. Pro2Booth Infrastructure

Pro2Booth is an evolution of the Protobooth (Erichsen et al., 2021) design process capture tool that seeks to address the previously identified challenges. This section describes both the hardware and online software components (independent of the hardware, and can be run without it, so long as images, videos, or other files can be uploaded to it) of Pro2Booth, and how they address the

https://doi.org/10.1017/pds.2022.43 Published online by Cambridge University Press

challenges. The use of a hybridised software/hardware system provides benefits by supporting a wide variety of user background and skill levels (Soomro et al., 2021).

3.1. Online Software

The online software is a web-based interface and data collection tool hosted on a Virtual Private Server (VPS). By hosting the software on a VPS, it becomes accessible to any individual with an internet connection. As the software is run entirely from a browser, any device, be it phone, tablet, or PC can interface with the software and make use of it. To interface with the online system, a participant needs to simply login, either from the web or Pro2Booth hardware client. Once logged in, the participant can create projects, add users, and upload prototypes to existing projects. When uploading a prototype, the system prompts the user for 7 fields. These are Name, Project, Prototypes that have influenced the work (optional), creator, description, rationale, insights, and the file to be uploaded. The project, influences, and creator boxes auto populate with the relevant names of projects, prototypes and users. In this way the uploader only has to select from a drop-down menu. The remaining fields are free form and allow any input, including none. The upload option allows for the upload of any file, allowing participants to upload not just pictures but also videos, CAD files, sketches, etc.

Figure 4 shows the underlying logic of the online system. Each box represents a node containing fields which are tracked by the online software. Some, such as username, email, and images are manually inputted by the user. Other fields, such as dates, ID, and status are automatically generated by the system. Figure 4 can be understood as follows: a query to the database generated by the online software can call for information on a Project, a User, or a Prototype. These calls will provide information on the respective nodes. Each node is influenced by other node, for example, the Prototype node gains information from the Project node.

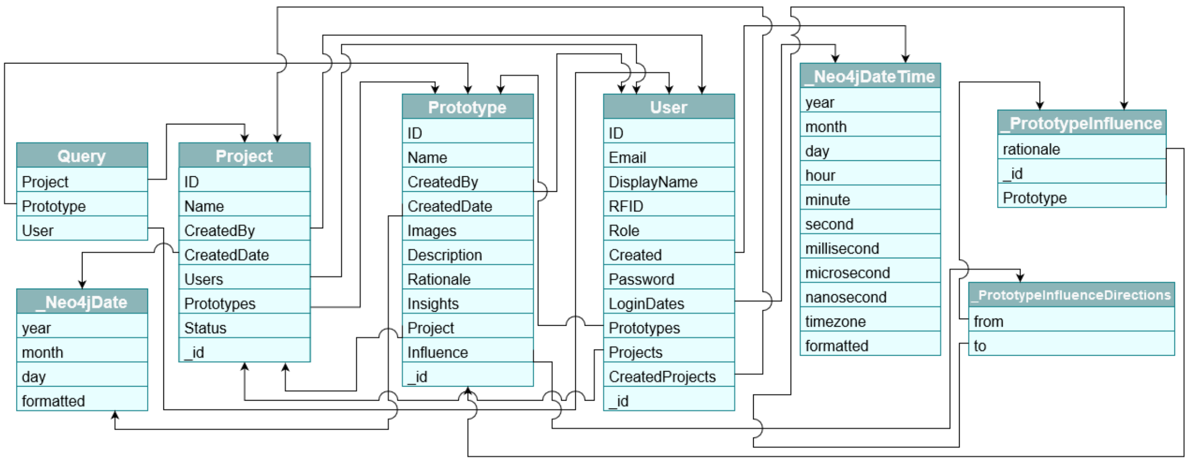
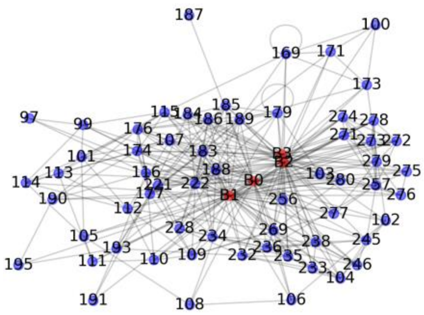


Figure 4. Graph showing the data collected or autogenerated by Pro2Booth's online component

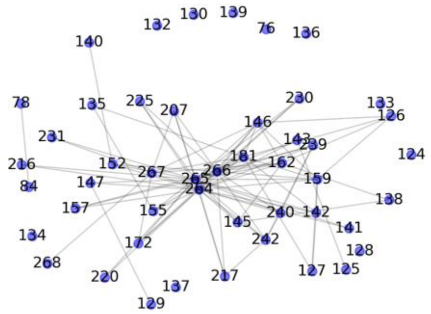
This linking of information allows for a dynamic database that can be easily queried and adjusted to show specific information. This allows a researcher to easily query information regarding a specific project, a user, or other node and see how other nodes have been influenced. As the system updates dynamically as uploads are made to Pro2Booth it can be used for live tracking of the design process.

This is illustrated in Figure 5. Figure 5a shows how the prototypes have influenced one another and the users who have generated the prototypes. Figure 5b shows only the links between the prototypes. By changing the parameters of the query, it is possible to visualize different variables. In both graphs the users and prototypes are identified by their ID; however, it is possible to see the timestamps of prototype creation, or to see the rationales and insights to see how linked prototypes influenced one another. Additionally, Pro2Booth allows for the visualization of data both in 2D, as displayed here, and in 3D allowing for more complex graphs to be explored. Furthermore, as the nodes presented here are dynamic, allowing the user to set their position, allowing the creation of timelines.

https://doi.org/10.1017/pds.2022.43 Published online by Cambridge University Press



(a) Prototype network including prototypes and designers



(b) Prototype network (only prototypes)

Figure 5. Graph data model enabling real-time graph analytics and prototyping process insights to be generated. Each number refers to a prototype captured

The online software presented in this section attempts to address challenges 1, 2, 4, and 5. In addition to these four challenges, one unforeseen benefit of the online software was its flexibility. As it did not rely on a physical booth to run but could be accessed from any internet device, the online software allowed for data capture during the COVID19 pandemic lockdowns. This is achieved by:

1. The online software allows for automation of data capture, by providing Pro2Booth users with auto-populating lists for projects, users and prototypes. Furthermore, data processing is automated through the generation of network graphs. These graphs are automatically generated based on simple queries of the database that is populated as Pro2Booth is used.
2. The act of inputting data into Pro2Booth is simplified as the uploads can be done from any internet connected device without needing to transfer files. The entry fields allow for the filling of a wider array of data, auto-populating where necessary, and the prototype capture process supports multiple types of files and formats, allowing for CAD files to be uploaded as well as videos, photos, etc.
4. The data can be easily manipulated and placed into graphs linking each prototype, user, project, etc. based on simple queries. The graphs are dynamic, allowing researchers to arrange the data as needed to create timelines or 3D representations to visualize additional variables.
5. Pro2Booth captures the data required to create connections between the prototypes generated, as well as additional information regarding the influences and learnings. The open-ended fields are left completely up to the participants to fill as they deem fit, with no restrictions on what type of information they include.

3.2. Hardware

Table 2 describes the hardware used to build Pro2Booth. The system consists of a LattePanda Single Board Computer (SBC) connected to a powered USB hub. The USB hub connects to 3 cameras placed at 120° from each other. Each camera is mounted on a sliding bracket that allows the camera to be translated vertically, as well as pivoted along two joints. The system is able to support up to 8 webcams. The SBC plugs into a monitor and can be interfaced with by means of a keyboard and mouse interface. The frame of Pro2Booth consists of aluminium extrusions with matte white acrylic panels to provide a neutral background for photography. The frame is octagonal in shape and measures 1.25m between faces, with each face measuring 0.5m in both length and height. Pro2Booth's large size is designed to allow the cameras to fully capture a 300mm cube from all angles with no occlusions.

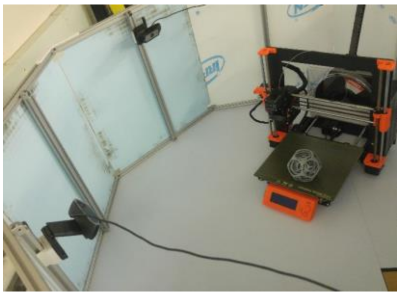
Table 2. List of Pro2Booth hardware

Electronics	LattePanda (RAM: 2GB, Memory: 32GB eMMC and 32 GB SD card), Powered USB hub, Acer 19" monitor, 1x Keyboard 1x Mouse, Power and HDMI cables
Cameras	2x 1080p Logitech webcam 1x 1080p Razer ring right webcam
Frame	Aluminium extrusions, acrylic panelling, 3D printed brackets, and LattePanda Case
Camera Brackets	3D printed adjustable slider brackets

https://doi.org/10.1017/pds.2022.43 Published online by Cambridge University Press

Figure 6 illustrates Pro2Booth's hardware. As can be seen from the figure, the platform's large size (Figure 6(a)) allows it to easily envelop even large objects such as the 3D printer shown in Figure 6(b). Figure 6(c) shows the movable cameras which allow for multiple angles of photography to best capture a prototype. Included in Pro2Booth is a small script to view all the camera feeds simultaneously and allow for an individual snapshot or film to be taken from each. This simplistic interface allows the participant clear oversight over the positioning of the prototype with respect to the cameras.


(a) Aerial view


(b) Volume demonstration

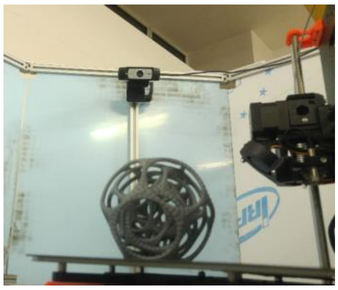

(c) Camera positioning

Figure 6. Pro2Booth

The hardware presented in this section attempts to address challenges 1, 2, and 3. This is achieved by:

1. Providing an easier overview of the photos being taken and making adjustments to camera position possible.
2. Allowing simple 1 click photography from multiple angles, all saved to a single pre-selected directory
3. Enlarging the photography envelope to allow for large objects to be photographed. Allowing for modularity in camera position and number.

4. Pro2Booth Pilot Study

In order to validate the utility of the Pro2Booth setup, a pilot experiment was run as a stress test for Pro2Booth. This consisted of a hackathon, the "IDEA Challenge". Inspired by the events of the COVID19 pandemic, the goal of the hackathon was to develop a carry case for vaccine distribution in Colombia. Requirements for the case were resistance to drops, number of doses carried, and thermal insulation. This section briefly discusses the setup of the hackathon and the major learnings gained through this study.

4.1. Study Setup

The participant demographics were: 14 participants (4 female 10 male), divided in 4 teams. Each participating team represented a different university, and all participants were PhD students. The IDEA Challenge hackathon lasted four days, with a kick-off on Monday and closing ceremony on Thursday in total 204 prototypes were created across all teams. Participants were first briefed about the challenge on Monday morning and informed about Pro2Booth, its operation and the role it would play in the challenge. Participants were informed that their final scores in the hackathon would be calculated using Pro2Booth but were not provided any specifics on how the calculation would occur. Participants were informed of the three requirements their designs had to optimize for (resistance to drops, number of doses carried, and thermal insulation). Due to the COVID19 pandemic and the difficulties of international travel, participants all worked from their own university labs, video conferencing when necessary. As such, it was not possible for them to make use of the Pro2Booth hardware; only the online software was tested.

5. Results

The major learnings from the stress test of Pro2Booth during the hackathon were as follows:

- Participants filled out all the fields when registering their prototypes.

https://doi.org/10.1017/pds.2022.43 Published online by Cambridge University Press

- Participants made good use of the ability to upload more than just photos. Uploads included CAD models, videos, technical drawings and photo renders of their prototypes.
- Based on informal feedback collected after the completion of the hackathon, participant reported a moderately positive opinion of the Pro2Booth, noting however that there was still a fair amount of development necessary, in particular for usability.
- Participant engagement with Pro2Booth was incentivised by the nature of the IDEA Challenge, as this was the tool they would be evaluated with. It is unclear whether engagement with Pro2Booth would have been comparable had the study framework been different.
- A range of devices were used demonstrating the need for multiple clients that can be deployed/accessed on multiple platforms to support engagement.
- The linking of prototypes to visualise influences and prototype evolution is a feature that allows for more in depth understanding of the design process. The ability to integrate data analytics automatically and make use of network analysis improves the utility of Pro2Booth as a tool.

6. Discussion and Future Work

This paper set out to iterate on the original Protobooth (Erichsen et al., 2021) by analysing and addressing some of the shortcomings in current prototype capture platforms. This paper analysed two prototype capture platforms: Protobooth (Erichsen et al., 2021) and ARCHIE (Nelson et al., 2019). In doing so, it highlighted five challenges that needed to be tackled to improve upon existing platforms. To tackle these challenges, Pro2Booth was developed as a platform. The Pro2Booth hardware was aimed at tackling the challenges of automation, platform ease of use, and photography envelope size. The Pro2Booth online software also tackled the challenges of automation and ease of use but additionally tackled the challenges of data presentation and capture.

A pilot study was conducted using the Pro2Booth online software to support and assess a hackathon, the IDEA Challenge. The results of this pilot study highlighted that Pro2Booth made some improvements where data capture and visualization were concerned. Additionally, the overall feedback from participants on the use of the platform was positive. However, the pilot study highlighted some issues with the Pro2Booth setup, in particular with regards to usability. Furthermore, while participation and engagement with the platform was high during the hackathon, this may have been the result of the hackathon conditions.

6.1. Future Work

Future work should focus on the improvement of usability and the user interface. The ability to access the online software from any device has greatly expanded the utility of Pro2Booth in comparison to its predecessors. Potentially improving its adoption and integration in the design process. However, the ability to access the software from any device complicates the creation and maintenance of a stable user interface that can be used on any screen, regardless of size, resolution, or mode of interaction (touch, keyboard and mouse, etc.).

In addition, the exploration of use cases for prototype capture platforms should be explored to a greater extent. The high engagement with the platform may well have been a direct result of how the design task was structured as a hackathon. Additional analysis should aim to investigate whether other forms of design tasks can be structured in such a way as to incentivise the use of the prototype capture platform. This would reduce the pressure on perfecting the platform prior to adoption while simultaneously allowing the platform to be used for academic research.

As discussed by Kohtala et al. (2018), there are advantages to the digitalisation of physical prototypes. Having captured the data that only a designer can provide, additional data from automatic capture means, such as materials and components using photogrammetry, machine learning and connections to workshop inventory systems can be made. This would serve the triple purpose of reducing the workload of the user when inputting information, capturing additional data, and serving as an incentive to use the prototype capture platform by automatically generating a CAD file (photogrammetry) or a bill of materials (machine learning detection of materials).

https://doi.org/10.1017/pds.2022.43 Published online by Cambridge University Press

7. Conclusion

This paper provided an improved tool for the capture of prototyping process data. The proposed tool, Pro2Booth, is an evolution of the ProtoBooth concept and builds on the shortcomings identified with both ProtoBooth and ARCHIE, particularly where data capture and process automation are concerned. Thus, Pro2Booth is more easily integrated within the design process thereby incentivising its use, improving the captured data quality, and facilitating the achievement of meaningful results.

References

Barhoush, Y.A.M., Erichsen, J.F., Sjöman, H., Georgiev, G. V. and Steinert, M. (2019), "Capturing Prototype Progress in Digital Fabrication Education", Proceedings of the Design Society: International Conference on Engineering Design, Vol. 1, pp. 469–478.

Blomkvist, J. and Holmlid, S. (2011), "Existing Prototyping Perspectives: Considerations for Service Design", Nordic Design Research Conference, pp. 1–10.

Bracewell, R., Wallace, K., Moss, M. and Knott, D. (2009), "Capturing design rationale", CAD Computer Aided Design, Elsevier Ltd, Vol. 41 No. 3, pp. 173–186.

Camere, S. and Bordegoni, M. (2016), "A lens on future products: An expanded notion of prototyping practice", in Dorian, M., Mario, S., Neven, P., Nenad, B. and Stanko, S. (Eds.), Proceedings of the DESIGN 2016 14th International Design Conference, pp. 155–164.

Erichsen, J.A.B., Pedersen, A.L., Steinert, M. and Welo, T. (2016), "Using prototypes to leverage knowledge in product development: Examples from the automotive industry", 2016 Annual IEEE Systems Conference (SysCon), IEEE, pp. 1–6.

Erichsen, J.F., Sjöman, H., Steinert, M. and Welo, T. (2021), "Protobooth: gathering and analyzing data on prototyping in early-stage engineering design projects by digitally capturing physical prototypes", Artificial Intelligence for Engineering Design, Analysis and Manufacturing, Vol. 35 No. 1, pp. 65–80.

Hallgrimsson, B. (2012), Prototyping and Modelmaking for Product Design, Laurence King Publishin, London.

Herstatt, C. and Verworn, B. (2004), Bringing Technology and Innovation into the Boardroom, Bringing Technology and Innovation into the Boardroom: Strategy, Innovation and Competences for Business Value, Palgrave Macmillan UK, London, available at:https://doi.org/10.1057/9780230512771.

Jensen, L.S., Özkil, A.G. and Mortensen, N.H. (2016), "Prototypes in engineering design: Definitions and strategies", in Dorian, M., Mario, S., Neven, P., Nenad, B. and Stanko, S. (Eds.), Proceedings of the DESIGN 2016 14th International Design Conference, pp. 821–830.

Jensen, M.B., Balters, S. and Steinert, M. (2015), "Measuring prototypes-a standardized quantitative description of prototypes and their outcome for data collection and analysis", Proceedings of the International Conference on Engineering Design, ICED, Vol. 2, pp. 1–14.

Kohtala, S.M.I., Erichsen, J.A.B., Sjöman, H. and Steinert, M. (2018), "Augmenting physical prototype activities in early-stage product development", Proceedings of NordDesign: Design in the Era of Digitalization, NordDesign 2018.

Mathias, D., Hicks, B., Snider, C. and Ranscombe, C. (2018), "Characterising the affordances and limitations of common prototyping techniques to support the early stages of product development", Proceedings of International Design Conference, DESIGN, Vol. 3, pp. 1257–1268.

McAlpine, H., Hicks, B.J., Huet, G. and Culley, S.J. (2006), "An investigation into the use and content of the engineer's logbook", Design Studies, Vol. 27 No. 4, pp. 481–504.

Nelson, J., Berlin, A. and Menold, J. (2019), "ARCHIE: An Automated Data Collection Method for Physical Prototyping Efforts in Authentic Design Situations", Volume 7: 31st International Conference on Design Theory and Methodology, Vol. 7, American Society of Mechanical Engineers, pp. 1–11.

Siddharth, L., Chakrabarti, A. and Ranganath, R. (2020), "Modeling and structuring design rationale to enable knowledge reuse", Systems Engineering, Vol. 23 No. 3, pp. 294–311.

Sjoman, H., Erichsen, J.A.B., Welo, T. and Steinert, M. (2017), "Effortless capture of design output a prerequisite for building a design repository with quantified design output", 2017 International Conference on Engineering, Technology and Innovation (ICE/ITMC), IEEE, pp. 564–570.

Soomro, S.A., Barhoush, Y.A.M., Gong, Z., Kostakos, P. and Georgiev, G. V. (2021), "Tools for Recording Prototyping Activities and Quantifying Corresponding Documentation in the Early Stages of Product Development", Proceedings of the Design Society, Vol. 1, pp. 3159–3168.

Subrahmanian, E., Monarch, I., Konda, S., Granger, H., Milliken, R., Westerberg, A. and Then-dim group. (2003), "Boundary Objects and Prototypes at the Interfaces of Engineering Design", Computer Supported Cooperative Work (CSCW), Vol. 12 No. 2, pp. 185–203.

Ullman, D.G. (2003), The Mechanical Design Process, 3rd ed., McGraw-Hill, New York.