A PNEUMATIC SYSTEM DESIGN TOOLKIT FOR LEARNING AND CREATIVE APPLICATIONS

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Abstract. Pneumatic systems are increasingly utilized in various fields. Applications of such systems include interactive installations, architectural skins, bionic designs, wearables, soft robotics, and more. This trend has heightened the need for professionals in design and art to integrate pneumatic systems into their work. However, most pneumatic simulation software emphasizes the expertise of devices; operating logic in different fields can become obstacles for designers. In this paper, we introduced a lightweight toolkit for interactive planning of pneumatic systems in design, built on the parametric modelling software Rhino Grasshopper. Our toolkit focuses on the comprehensive consideration of space, equipment, human sensory experience, and interactive scenarios. Users can map real equipment functions onto a virtual model within the 3D software, and these elements are organized in virtual space and linked in the visual programming interface to form the pneumatic system's initial framework. Three pneumatic design cases are used to test the toolkit, including one displayed at an art and technology exhibition. An integrated workflow is shown to produce preliminary pneumatic system diagrams and interactive scenario simulations. This proposed approach provides opportunities for integration and creative applications in the pneumatic and design fields based on modelling software familiar to designers.

Keywords. Pneumatic, Interactive Installation, Creative Applications, Workflow, Plug-in Tool

1. Introduction

Pneumatic systems achieve changes in form and structure through the control of airflow and pressure. Since the 20th century, there have been numerous practical use cases involving pneumatic systems (Chi & Pauletti, 2005). In recent years, driven by technological advancements, pneumatic structures have found extensive applications across diverse domains, from consumer products to mechatronics. In the creative fields, designers and artists use the movement and deformation of pneumatic structures to achieve adaptive and interactive design in a wide range of applications, e.g. kinetic

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building skins (Shahin, 2019; Zarzycki & Decker, 2019), interactive installations and interfaces (Yao et al., 2022), bionic designs, wearable devices, soft robots (Xavier et al., 2022), etc. Nowadays, pneumatic systems play an important role in soft and organic mechanisms and interfaces.

In the industry, engineers use pneumatic simulation software to assist with circuit design, simulation, and fluid calculations. However, the software cannot fully meet the requirements for creative applications in the design field. Designers may encounter challenges such as complex and non-intuitive interfaces that require specialized engineering knowledge to comprehend. Not to mention the difficulties for beginners to learn and implement their ideas. Moreover, when designing a pneumatic system, designers care more about the movement patterns, interactions, and sensorial experiences in space as the key design factors (Dickey, 2019). Therefore, a software toolkit designed to assist designers in planning pneumatic systems should focus on a low learning curve, contextual integrative considerations, and a rapid iterative planning environment. Based on these considerations, we propose such a software system to aid designers in the interaction design of pneumatic installations.

2. Research Background

The production process of physical interactive installations often requires the integration of structure, circuitry, and programming. As a result, platforms and tools have emerged specifically for non-engineering professionals to enable rapid development, application, and learning. For control boards, Arduino and Raspberry Pi are commonly used development boards in creative design projects because of their versatility and rich learning resources. For circuit simulation, Tinkercad and Fritzing are commonly used to simulate circuits using images of real electronic parts, and some even provide visual programming capabilities. However, most simulation platforms provide limited content and resources for pneumatic systems. To address issues and gaps in the design and implementation of pneumatic systems in creative fields, some tools have been developed specifically for the demands, as discussed in the following sections.

2.1. PNEUMATIC HARDWARE AND PLATFORM

Among the tools developed for pneumatic system needs, Pneuduino is a modular hardware platform that can connect multiple control boards for functions such as airflow control and pressure sensing (Ou et al., 2016). FlowIO is an integrated development platform equipped with pneumatic components, a wireless control function, and a control interface (Shtarbanov, 2021). These modular hardware tools are equipped with dedicated custom-designed modules integrating mini air pumps, solenoid valves, air pressure sensors, or specific pneumatic components. From the perspective of beginners, these tools ease the learning curve and speed up the prototyping. However, the user misses the chance to learn about the properties of pneumatics, the selection of the parts, and the flexibility of making custom experiments. This research is meant to focus more on the software tools and try to use the basic hardware toolkits, e.g. Arduino, and parts to compose the system.

2.2. INTERACTIVE PNEUMATIC SYSTEM

To enable an installation to adapt and react to the environment, the sensing capabilities are crucial elements for a pneumatic system. Park and Bechthold (2013) proposed the modular pneumatic system to verify the design process of the bionic smart building system. The pneumatic system of this module and dual feedback loop consists of an air pump, air valve, microcontroller, and air pressure sensor. Air Hug, a large-scale interactive device, uses a camera to sense the space, and then uses a Raspberry Pi to control relays to turn on and off the fans, thereby controlling the inflation and deflation of the pneumatic structure (Dickey, 2019).

From the above cases, we can tell the core parts and their relationships in the system for sensing and control. During the operation of the interactive pneumatic system, the microcontroller first receives environmental information or its own system status through sensors and then controls solenoid valves and air pumps. Moreover, the integration and arrangement of the entire system and equipment in the space is also important, so prior planning and preview also become significant.

2.3. PARAMETRIC DESIGN TOOL

Rhino and Grasshopper are commonly used software tools in the design field and have a wealth of plug-ins and use cases. This allows designers to integrate more design techniques and possibilities into their original workflow. There are also many examples of tool development related to the field of pneumatic technology. Sareen et al. (2017) developed a Grasshopper extension as a design and simulation platform for inflatables. By developing and using different plug-in tools, some design needs and processes can be integrated and met.

3. Pneumatic System Design Toolkit

The proposed toolkit for pneumatic system design and planning was built on Rhino and Grasshopper to allow creative workflow and applications of pneumatic systems. We divide the design process of interactive pneumatic design into four steps:

- Scenario: Including integrated creative ideas such as design concepts, interactive scenes, and technologies.
- Workflow: The process in which users use software to integrate pneumatic systems, interactive scenes, and designs.
- Diagram: The generated diagrams are used to assist users in adjustment, implementation, and testing.
- Physical: Assist in the implementation and design of pneumatic devices based on diagrams.

The toolkit helps designers organize design scenarios and pneumatic system diagrams in familiar software and workflows, which can be used for testing and planning before the implementation phase (Figure 1).

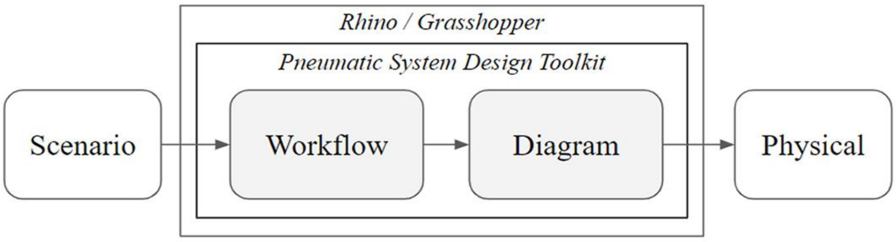

Figure 1. The relationship between the toolkit and design process

3.1. FROM SCENARIO TO WORKFLOW

The toolkit enables the integration of pneumatic systems into standard design workflows, which includes parametric models for common electronic and pneumatic components. Instead of creating an extensive database, this toolkit utilizes the operational specs of these components to generate corresponding parametric models. Based on literature in 2.1 to 2.3 and our prior experience, vital components for interactive pneumatic systems include power supplies, sensors, air pumps, solenoid valves, relays, motor drivers, and microcontrollers. Electronic components in the toolkit require inputs for rated voltage, rated current, and input voltage, while pneumatic components additionally require output airflow data. Furthermore, each component can be associated with a customizable 3D model, enhancing its representation in the pneumatic system. Upon connection, components assess their operation based on the preceding component's data (Figure 2).

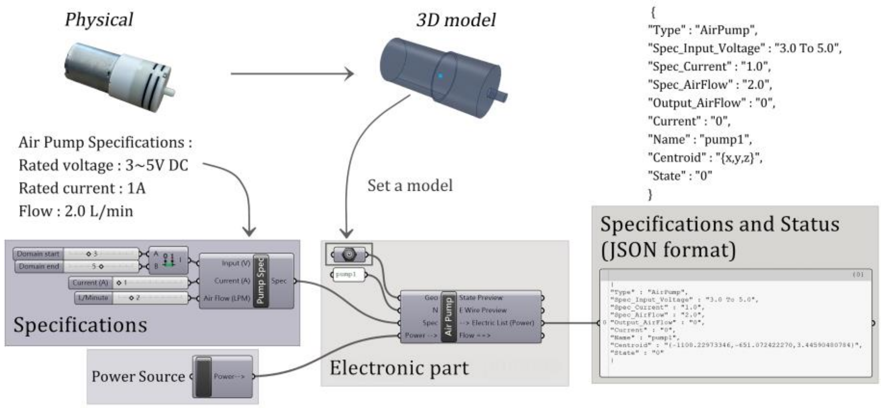

Figure 2. The design and operation of components in the toolkit

In the toolkit, the data communicated between components is in JSON format, which helps users read and understand the data. Through the connection between components, each component analyses the JSON data from the previous component to update its own operating status. Finally, a list is formed according to the connection order of the components (Figure 3).

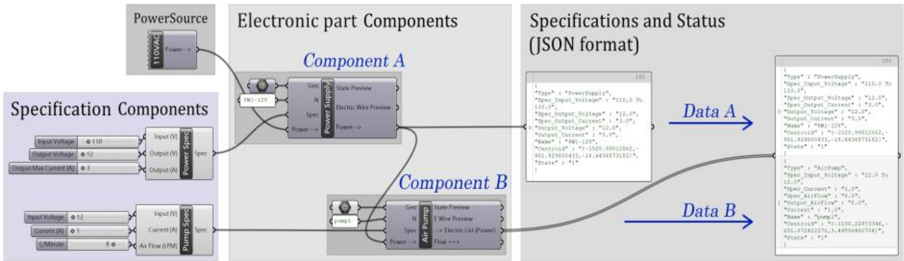

Figure 3. Connection relationships and data transmission between components

3.2. FROM WORKFLOW TO DIAGRAM

When connecting the components in Grasshopper, the 3D preview models of the components will be connected through lines in the preview port in the Rhino interface to represent the connection diagram. When a component is connected to a preview component, the corresponding model and connection lines change colour based on whether the component meets operating specifications. This enables users to swiftly review, plan, examine, and adjust their designs. The default colour for 3D preview models is grey when the device is not running and blue when the device is running (Figure 4). If the input data of the component exceeds the specification, it will display red to alert the user. Designers can also customize the operational colour of models and relationship lines to match the desired visual style of the design.

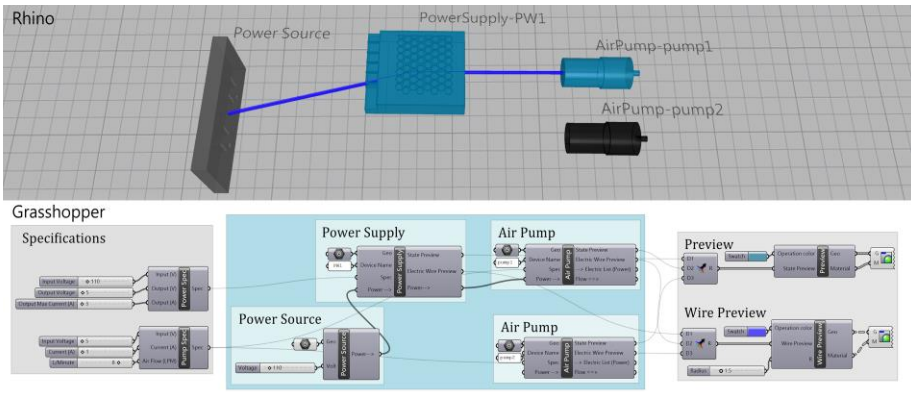

Figure 4. Diagram of the pneumatic system generated by the toolkit in Rhino and Grasshopper

3.3. FROM DIAGRAM TO PHYSICAL

The interactive scenario of the first case in our pneumatic interactive design case is an airbag that will respond by inflating and deflating based on the distance between the target object and the sensor. Therefore, the pneumatic system switches the valves based on the distance of the target. To implement this scenario, we used parts including a power supply, an ultrasonic distance sensor, a microcontroller, an air pump, relays, and solenoid air valves. The design toolkit is used for pneumatic system planning, functional simulation, and interactive scenario previewing. Then, we verified the feasibility of this tool to assist interactive pneumatic system design through functional testing of sensing, inflation, and deflation. Moreover, the diagram of the pneumatic system generated in this toolkit is compared with the actual installation status of the physical pneumatic equipment (Figure 5). In addition, the toolkit can be used with other functions or plug-in tools, such as expansion simulation, fluid calculation, etc., providing more creative applications, possibilities, and completeness for design.

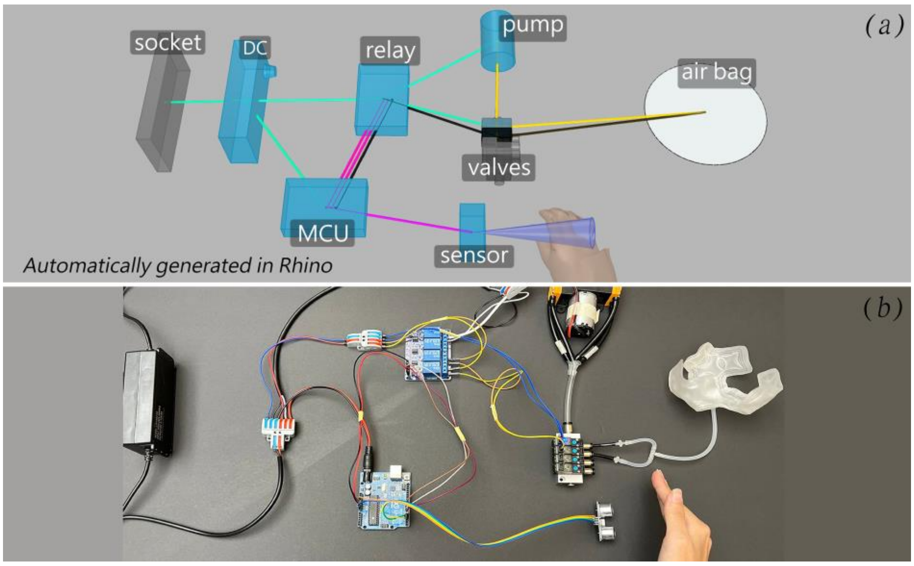

Figure 5. (a) Diagram of the connection relationship of the pneumatic system in Rhino. (b) Implementation and test result of the interactive pneumatic system in case 1

3.4. INTEGRATED WORKFLOW

In the general workflow of integrating design and pneumatic systems, dispersed software tools, work logic, and workflows in different fields make it difficult to quickly iterate, integrate, or output design results. The toolkit proposed in this paper brings an integrated design workflow. During the modelling process, designers can design the pneumatic system through the connection relationships of parts and generate interactive pneumatic system diagrams (Figure 6). Designers can think holistically, adjust, and influence the outcome of work projects within the same design environment. Not only does it reduce the need for designers to learn complex tools from other fields, but it also helps integrate pneumatic technology into design applications. Overall, this design workflow provides designers with a more comprehensive approach to integrating, designing, and testing pneumatic systems during the planning phase.

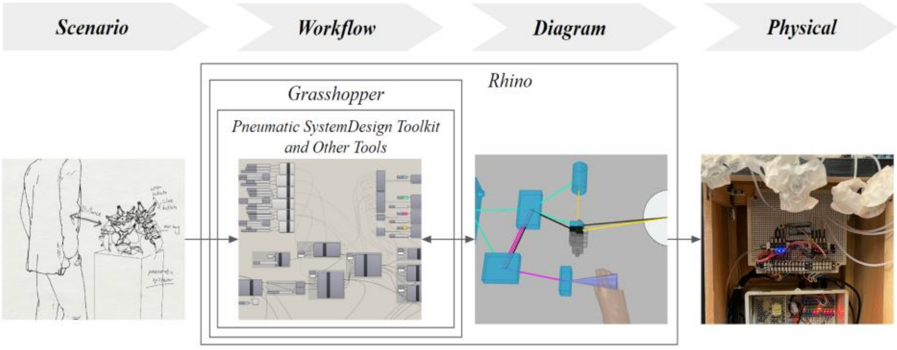

Figure 6. Diagram of the integrated design workflow of this toolkit

4. Implementation and Application

We present three implementation cases of pneumatic interactive design assisted by this toolkit, including the first case mentioned in 3.3 and the two cases in this section. The second case is an interactive design that integrates conductive ink sensing, inflation, and lighting functions. To allow beginners to quickly learn and implement interactive pneumatic devices, we held a workshop to allow participants to assemble and connect circuits by themselves. The toolkit assisted us in preparing equipment, planning, and integrating structures and pneumatic systems. Users could instantly move and adjust 3D preview models to correspond to the positions of physical parts and structures, making it easier to understand, explain, and demonstrate the relationships of components within the structure (Figure 7).

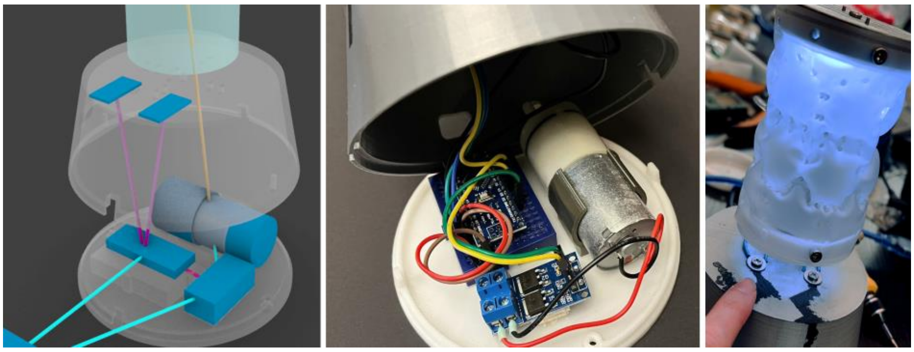

Figure 7. Pneumatic system planning and implementation results in case 2

The third case shown in is a pneumatic interactive installation exhibited in an art and technology exhibition for three months. In the design and implementation stage, we used this toolkit to plan a more complex pneumatic system to achieve the purpose of controlling the actions of more airbags. This interactive pneumatic installation enabled the soft airbag structure to achieve biomimicking opening and closing movements by controlling the airflow (Figure 8).

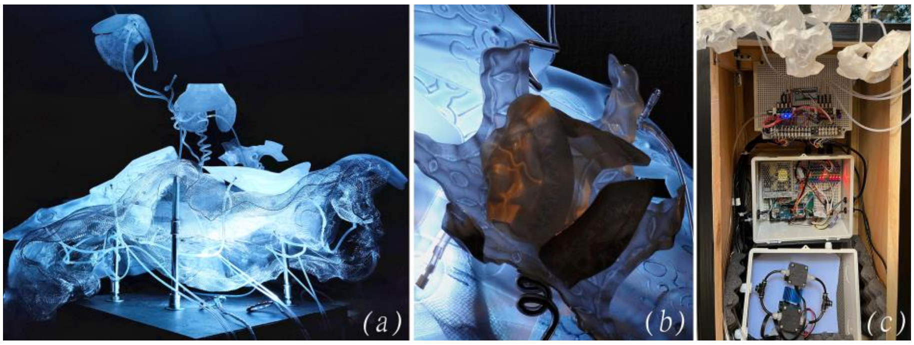

Figure 8. (a) Case 3 of interactive pneumatic design. (b) Close-up photo of airbag inflating. (c) Pneumatic system implementation of Case 3

In this case, we built a 3D preview model of the exhibition space in Rhino and placed models of the audience, installation structure, and pneumatic system into it for configuration and simple simulation (Figure 9). This approach enables designers to simultaneously explore design and integration methods for structures, interactive scenarios, pneumatic system relationships, implementation, and exhibition planning.

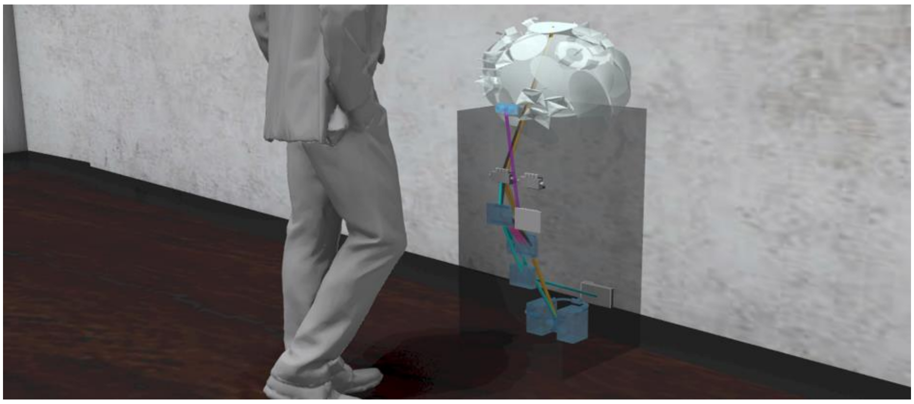

Figure 9. The interactive scene with the integrated pneumatic system in Rhino

5. Conclusions and Future Work

In the ongoing trend of integration and innovation, the fields of design, architecture, art, and technology are at the intersection. This paper reveals the challenges designers, architects, and artists face in learning and applying pneumatic systems in this booming environment. Among them, technology integration tools in the design field have relatively little support for pneumatic technology in terms of resources and have different aspects from pneumatic systems in the industrial fields. To cross the boundaries of technology and expertise in different fields, innovative ways need to be found to respond to changing needs.

In this paper, we propose a pneumatic system design toolkit based on the Rhino and Grasshopper, aiming to promote the integration of pneumatic system design into creative design application and learning. This toolkit converts pneumatic system parts into parametric components by focusing on the spatial context, structure, pneumatic system, human sensory experience, and interactive scenarios. Furthermore, the integrated workflow simplified the design process by eliminating the need for designers to use multiple software tools for planning. We demonstrated the possibilities of this toolkit by implementing three cases, including an interactive installation that was displayed at the exhibition for a month.

The toolkit concept presented in this paper starts from pneumatic systems and may also be developed into a more general tool suitable for other parts. At this stage, we have yet to include features such as fluid calculations or expansion simulations. Users can add different plug-in tools based on the parametric design software to make the pneumatic system design more complete. Several possible directions for future work include expanding parametric components and more interactive scenarios to promote more learning, integration, innovation, and exploration of pneumatic systems in creative applications.

Acknowledgements

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