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Developing Design Strategies to Support a Solution-First Design Process by Examining Experienced Engineers' Approaches

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Abstract

Engineering design processes often focus on beginning with a problem and considering multiple possible solutions, following problem-first design practices. Alternatively, design processes can start with a solution and diverge to identify potential problem applications it can solve before converging on one problem application to pursue, termed "solution mapping." Most design tools and strategies have been developed to support problem-first design practices. Tools and strategies to support solution mapping have been underexplored. We plan to expand on our prior work and build a tool to support solution mapping by examining engineering practitioners' approaches. Experienced engineers gain expertise as they spend more time scoping problems, gathering information, and considering alternative approaches compared to novice engineers who have limited experience in these areas.

We conducted think-aloud studies to analyze engineering practitioners' solution mapping behaviors. The think-aloud method asks participants to verbalize their thought processes during a task, allowing the research team to capture the details of their behaviors. Ten engineering practitioners were recruited and asked to generate possible applications for a technology. We examined the patterns in their solution-mapping practices to identify strategies used to identify problem applications.

This paper describes engineering practitioners' solution-mapping practices by capturing details about their thought processes. They demonstrated several key strategies such as replacing existing solutions to problems with new technology and adding to existing products to identify applications. By understanding specific strategies used in solution mapping, this study can lead to explicit instructional tools to support engineering students in developing solution mapping skills.

Introduction

In engineering, design is an important skill that involves devising a system, component or process to address needs [1]. A typical engineering design curriculum teaches design processes that begin by defining a problem and identifying potential solutions to address that problem [2]–[4]. Engineering textbooks focus on initial problem definition that often utilizes examining current needs through observation and interview as the primary stage in a design process [5].

However, defining the problem is not always the first step in design. When engineers engage in solution-first design processes, they often focus on developing a newly discovered technological solution without a clear problem to address [6]–[9]. A newly created technology may be a potential solution for a number of different problems. For example, carbon nanotubes, which have remarkable physical properties, have found applications in a number of areas, including energy and medical fields [10]. Within engineering, a specific solution-first design process would occur that begins with a technology and engineers diverge in search for possible applications before converging to select an application, called solution mapping [7]. Although solution mapping practices are demonstrated in several fields within engineering, engineering students have limited exposure and training in solution mapping as their curriculum mainly focuses on problem-first design processes. As a result, limited evidence-based design strategies and tools are available to support curriculum development and training for our students.

Using design strategies is important in supporting engineers to adopt evidence-based approaches to achieve design success [11]–[15]. In this study, we examined cognitive strategies used by engineering practitioners for solution mapping. Recent engineering studies have focused on developing best design practices to support both engineering instructors and students in design [16]–[22]. However, a gap exists in sharing solution mapping strategies to support engineers in solution-first design processes.

Background

Solution-first processes

Research on solution-first design processes has received far less attention compared to problem-first design processes [23]. The majority of design process models emphasize starting with a realized need and identifying possible solutions [2]. Researchers have also examined co-evolution of problem and solution, demonstrating that designers can jump between the problem and solution spaces through iterations [24]. Designers can modify the problem based on the understanding of possible solutions [25]. Both problem-first and co-evolution processes focus on starting with a problem statement.

Solution-first processes are a different approach to design as designers begin by developing novel technologies and applying them to problems. Some solution-first processes have been described in different contexts. Researchers have demonstrated technology-driven processes that focus on leveraging patented technologies or core components of novel technologies to address problems [26]. Studies in bio-inspired design documented designers leveraging existing biological solutions and identifying applications of their unique characteristics [27]. By examining key principles and functions from biological solutions, engineers identify problems they can address. Documented literature demonstrated that bio-inspired design has advanced technologies in tissue engineering and regenerative medicine [28]. For example, studying the surface of the gecko's foot to understand its adhesive capacity on the surface has led to biomimetic dry adhesive surfaces that have many applications in construction, and inspection [29]. Solution mapping is the process that emphasizes the divergent search for problems before converging on a problem to address using a technology.

Although solution-first approaches have been documented in several disciplines, entrepreneurship literature has often investigated solution-first processes in more detail [25]. Danneels and Frattini [30] described finding applications for technologies within four general steps: 1) characterize the technology, 2) identify potential applications, 3) select from the identified applications, and 4) choose the best entry mode. In the first step of characterizing the technology, entrepreneurs identify the functions of the technology to better understand its capabilities. Then, entrepreneurs can begin to explore new settings in which to leverage the technology. After the exploration, specific applications are selected and commercialization of the technology is pursued. However, how to identify problem applications for a new technology is not obvious [31] and a more deliberate approach to support solution mapping is needed.

Developing design strategies

Researchers have developed design strategies and tools to support different stages of design. One way to develop design tools is to examine design outcomes. For example, the do-it-yourself (DIY) prototyping principles were developed by studying key fabrication methods in prototypes within a database [32]. A set of design strategies for concept generation in microfluidics was created by extracting design patterns in patents [12]. TRIZ, a set of 40 strategies to support creative concept generation, was created from analyzing patterns in over 40,000 patents [11].

Researchers also developed design strategies and tools by studying designers' practices. For example, *Design Heuristics* were developed by examining designers' concept generation strategies as they engaged in addressing an ill-defined problem through a think-aloud protocol [14]. Prototyping strategies were developed by observing and interviewing engineering practitioners through ethnographic studies for an extended period of time [33]. In our previous work, we examined solution-mapping practices through semi-structured interviews of engineering practitioners who have successfully engaged in solution mapping by developing a novel technology, exploring applications, selecting an application, and creating a marketable product [7]. The results of this previous study were translated into the solution mapping tool and demonstrated that a 1-hour session with engineering students using the tool aided them in considering a large quantity of diverse applications of a technology [6]. However, our previous study had a limited number of strategies due to the nature of semi-structured interviews, which require participants to explain past events and may have incomplete information. In this study, we build on our previous work to examine engineering practitioners' solution-mapping practices through a think-aloud protocol, which allows participants to explain their thought processes more in-depth [34].

Methods:

The project was motivated by the following research question:

- How do engineering practitioners generate applications of technology?

Participants:

Participants included 10 engineers who received degrees in engineering with work experience in multiple disciplines including aerospace, automotive, biomedical, construction, and manufacturing as shown in Table 1. All participants were recruited on a rolling basis through targeted emails and snowball sampling. No incentives were provided for participation.

Table 1. Participant information

Pseudonym	Gender	Ethnicity	Level of Education	Industry	Years of Professional Experience
Abby	Female	Middle Eastern	B.S. in Mechanical Engineering	Biomedical	1
Brett	Male	Asian	B.S. in Mechanical Engineering	Biomedical	2
Chris	Male	Middle Eastern	B.S. in Mechanical Engineering	Biomedical	3
David	Male	Caucasian	B.S. in Mechanical Engineering	Automotive/ Construction	2
Ethan	Male	Hispanic	B.S. in Mechanical Engineering	Aerospace/Defense	3
Faith	Female	Middle Eastern	B.S. and M.S. in Mechanical Engineering	Defense/ Manufacturing	8
George	Male	Caucasian	B.S. in Mechanical Engineering	Aerospace/Defense	2
Hunter	Male	Asian	B.S. in Mechanical Engineering	Aerospace/Defense	3
Ian	Male	Caucasian	B.S. in Mechanical Engineering and M.S. in Systems Engineering	Aerospace/Defense	10
Jake	Male	Hispanic	B.S. in Mechanical Engineering	Aerospace/Defense	5

<u>Data Collection:</u>
The data collected involved a multi-step process as shown in Figure 1. Each step is described in further detail in the following section.

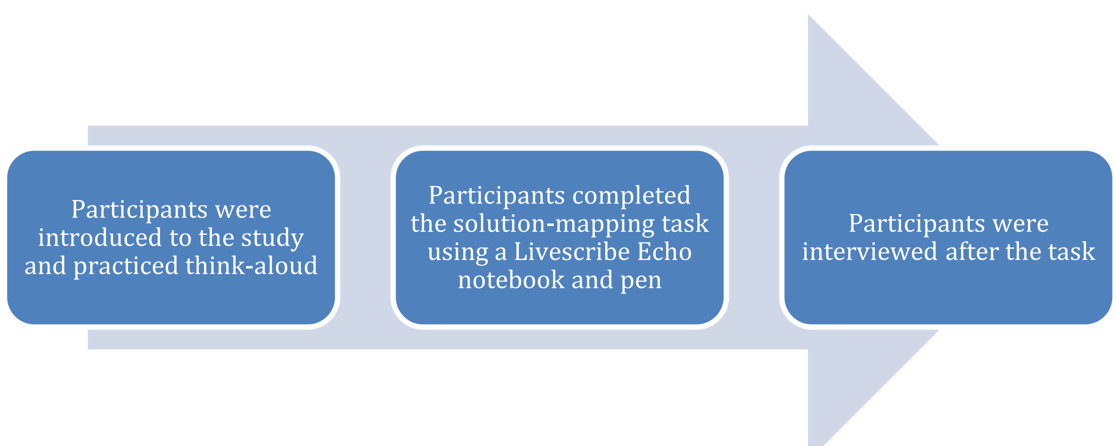

Figure 1: Procedure for Data Collection

The participants who volunteered in the research study were introduced to the task, signed a consent form, and had the opportunity to practice think-aloud prior to starting the task. Participants were asked to work independently on a solution mapping design task in a quiet room without access to outside resources for at least an hour and think-aloud data were collected using a Livescribe Echo notebook and pen. This allowed the participants to both speak and record their thoughts and applications through words and sketching. The prompt required participants to consider applications of shape memory alloys or aerogels. Half of the participants worked on the shape memory alloy task (Abby, Brett, Chris, David, and Ethan) while the other half worked on the aerogel task (Faith, George, Hunter, Ian, and Jake). The prompts are included in the Appendix.

After completing the task, the researcher interviewed participants following a semi-structured interview protocol, which lasted between 20-30 minutes. The purpose of the follow-up interview was to further explore the professionals' solution mapping practices and probe for clarity of the data. The interview protocol was developed through multiple iterations and two pilot studies were conducted prior to data collection. The interview protocol focused on open-ended questions to encourage storytelling and asked participants to describe their processes. For example, the researcher asked, *"From the beginning to the end, please describe how you came up with applications of the technology."* One researcher conducted all the data collection to ensure consistency. Across five participants, the researcher accumulated approximately 17 hours of recordings and data.

Data Analysis

The interview and think-aloud recordings were transcribed and checked by the researcher for accuracy. The data were examined both deductively and inductively to identify specific strategies used for solution mapping after multiple readings of raw data. For inductive coding, we examined if strategies aligned with one of the existing *Design Heuristics* and prior findings from semi-structured interviews with engineering professionals [6], and coded them as transferable strategies. Since solution mapping is a divergent thinking process like ideation, there may be overlapping strategies compared to other strategies that support divergent thinking, such as *Design Heuristics*. If the strategy was not previously identified, it was added as a potential new strategy. The data were coded in two cycles. The first cycle coding allowed themes to emerge and the second cycle coding was used to categorize codes identified in the first cycle based on conceptual similarity [35]. The first coder trained in qualitative analysis examined the transcript and generated the initial codes and a second coder coded a subset of the transcript. The two coders discussed the discrepancies until they reached an agreement to finalize the findings.

Findings:

Many solution mapping behaviors were identified in the participants' approaches as shown in Table 2.

Table 2. List of solution mapping behaviors

Behavior	**Number Observed (n =10)**	**Definition**
Substitute Way of Achieving Function*	10	Replace one or more components with other designs that can achieve the same function.
Change Geometry	10	Alter the physical or geometric form of the product while maintaining its intended function.
Identify and Relate to Specific Industry*	10	Relate a core technology to a specific industry before identifying applications.
Change Product Lifetime	10	Consider changing the life cycle usage of the product to extend the product's lifetime.
Cover or Wrap	7	Overlay a cover, form a shell, or wrap the surface of the product or its parts with another material. This can affect customizability, multifunctionality, durability, and safety.
Attach Product to User	4	Design the application around the user by attaching it to the user's body.
Add to Existing Product	1	Use an existing item as part of the product's function or create an add-on mechanism.

*****indicate strategies similar to our previous study using semi-structured interviews [7]

<u>Substitute Way of Achieving Function</u>
One of the main behaviors that the participants portrayed was that they substituted the way of achieving function by replacing other components with the technology. In many cases, the participants either applied this behavior to find applications within their fields of expertise or in their personal interests. For example, David thought of using the technology (shape memory alloy) to replace putty that is often used to repair patches when thinking about finding applications:

"*Something like a putty…Like grab this shape memory alloy [in] my hand and squeeze it. I can just alter it with my hand… like a putty where it could be used to patch [and] repair things. Yeah, there you go… not necessarily like a hole in the wall, but patching something.*"

As a second example, Abby considered using the technology (shape memory alloy) as a pump due to its ability to withstand temperature requirements needed:

"*Oh, OK. So the first thing that I thought of is using it for pumps…so it has to withstand a certain temperature… you have to make sure that it's not going to crack, so whatever fluid is running through it, it's not going to leak out.*"

Because of the temperature capabilities, she was able to apply this technology to consider developing a more efficient pump. In both of these cases, the participants considered replacing or substituting the existing solution with the technology (shape memory alloy).

Faith demonstrated that she considered using the technology (aerogels) as weapons after considering its key functions that emphasize its strength and low density:

"Weapons or swords, for example, since [it's] low density, it helps [people] swing it around without tiring themselves out. And if it's a high strength, that means you can strike objects without worrying about it breaking."

Although participants had different technologies, they demonstrated the same behavior *Substitute Way of Achieving Function* to identify applications.

<u>Change Geometry</u>

Participants also considered changing the geometry of the technology to consider applications. For example, Ethan thought about bending shape memory alloy to desirable shapes for glasses (Figure 2):

"I've take an impact to the head with my glasses [and] bent the frame… It would be nice if I just heat the metal and return [it] to what it was… just because I've tried [to bend it back] in the past. And I make it worse."

Figure 2: Ethan's application for fixing glasses

This application focused on changing the geometry and flexibility of the glasses based on his failed attempts at fixing his glasses in the past.

<u>Identify and relate to specific industry:</u>

Participants often narrowed to a specific industry sector to search for applications before considering a different industry sector to focus their attention. For example, Hunter focused his attention on aerospace applications before moving to other applications:

"First thing I want to say… it's most applicable to aerospace, right? Because then you have all the markings of good material. For aerospace, so you know, and typically in aerospace stuff… Strong, light, and rigid… Let's go [for] something fancier. Let's say… for F1 racing."

Chris focused on aerospace and automotive applications of shape memory alloys. He sketched potential application areas as shown in Figure 3:

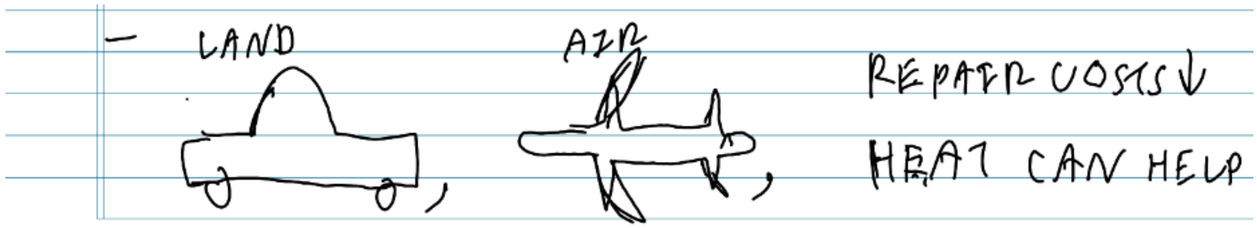

Figure 3. Sketches from Chris showing his focus on different industry sectors

Change Product Lifetime

Across multiple participants, they considered using the technology to change the product's lifetime and extend product use. For example, Brett generated an application to use the technology (shape memory alloy) as an automotive gasket that can be used again, extending the lifetime of a traditional gasket:

"Like I don't want to say fasteners. It might be possible to use them in, let's say, let's say we [use] them as gaskets, so we know that certain. I believe certain companies will use strong gaskets like possibly aluminum as part of their gasket structure in order to maximize on the longevity of the product. I think I think Tesla uses aluminum in their gaskets and the main problem with gaskets is. Generally, they're pressed against probably 2 pipes generally. And the problem is when the gasket no longer forms a very good fit and leakage occurs generally don't want that, so it's possible that gaskets are useful. Let's say they start to lose their ability to form a seal instead of recreating a new gasket, be probably easier to heat them up and ensure. It would heat them up so they would return to normal shape and would be able be available for use again."

Furthermore, participants considered utilizing shape memory alloys to create reusable materials to extend the product's lifetime. For example, a participant examined products that are currently thrown away such as plastic straws, and considered using shape memory alloys as a replacement material that can make the product reusable:

"The steel straws. You can't just bend the straws without it permanently altering them, right? Essentially replace straws, plastic straws with a reusable type of shape memory alloy so you can just use the straws normally like you would a plastic straw bend it all you want, and then instead of throwing it away, it gets sent back to the kitchen and you just flash heat it and it returns to its original shape. So I guess maybe something like that I don't know. Straws made of metal alloy that can actually bend then heated to return to their original shape… being reusable".

Cover or Wrap

Participants used the strategy "Cover or Wrap" to use the technology as an exterior shell of the product. For example, Chris considered using shape memory alloys to create an armor that serves as an exterior shell:

"And looking back to what I said about armor, I don't see it as the main protective, but as more like a shell to add protective material upon it. And this is assuming that we would make something that would be tougher than conventional steel in the future."

George was focusing on aerospace applications of the technology (aerogel) and considered using it as a shell to cover airplanes to minimize heat loss:

"*I thought it would be great for stuff that flies… so like airplanes, helicopters…satellites because you want to keep them…very strong but lightweight…You want to regulate the temperature inside of the plane, and when you're up and up further into the atmosphere, when it gets a lot colder, you don't want the inside of the plane to get freezing.*"

Attach Product to User

Participants also considered applications that related to attaching the product to their users in many of the medical-related applications. For example, Ethan considered using shape memory alloys to help patients realign and heal their broken bones:

"You bend the piece of metal a little bit upwards. Screw whatever bones you want to put back together and then with time let body temperature start heating it up… pulling the two joints together and then hopefully… with time they just heal."

In a similar approach, David also considered using a shape memory alloy to create wires for braces. The body temperature would allow the wire to go back to its original shape and help to realign their teeth as shown in Figure 3.

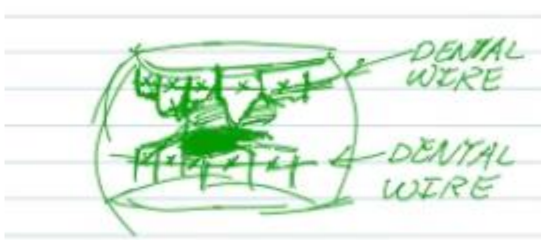

Figure 4: David's application describing using a shape memory alloy for braces

Faith was thinking about its ability to have low thermal conductivity and considered attaching the aerogel to the user's sole to minimize the effect on the user in hot or cold environments.

"Maybe the sole... So if say you're walking in an area that has a cold floor or hot floor… you wouldn't want your body heat to transfer out and go to the floor."

Add to existing Product:
This behavior was shown in one participant as he developed an application in which the memory shape alloy was an added component to drive the functionality of the machine. For example, David considered using the shape memory alloy to create a shutoff system for electronics when it overheats:

"To have a computer that shuts down the machine, it physically shuts itself down, depending on if it's heated to a certain point…A system overheats the shape of the system alters or the shape of a certain part in the system alters. And that certain part is the alloy. And because that alloy was heated, it changes shape, and it fails. The system fails, then it shuts down.

Discussion and Implications
Our exploratory study examined engineering practitioners' solution mapping practices through think-aloud interviews. The initial results demonstrated that engineering practitioners leverage many strategies similar to other divergent thinking practices such as previously identified *Design Heuristics*. For example, strategies such as *substitute way of achieving function* and *change product lifetime* were documented strategies from other divergent thinking practices [12], [14]. Prior research has documented the benefits of using design strategies and tools to support divergent thinking in different phases of design. However, most design strategies and tools were developed to support problem-first design processes, providing limited guidance to solution-first design processes. This initial study demonstrated that some of the divergent thinking design strategies may be transferable to support solution-first design processes as well.

In addition to documented practices from other divergent thinking processes, engineers working on solution mapping tasks demonstrated unique strategies. For example, they used the strategy *identify and relate to specific industry* and focused on industry sectors to search for applications of the technology before moving on to a different industry sector to search for additional applications. Oftentimes, this search for an industry sector was driven by their background. For example, Hunter who has several years of experience in the aerospace industry searched applications in the aerospace field before moving on to a different industry. Identifying specific industry sectors is similar to our previous findings examining solution mapping practices through semi-structured interviews [7]. Engineering practitioners intentionally constrained their search space to help them narrow their applications before expanding the search to other domains.

This study demonstrated that participants leveraged similar strategies regardless of the technology context. Although participants worked on identifying applications of two different technologies (shape memory alloys and aerogels), many of the same strategies were discussed. For example, participants used *substitute way of achieving function, change geometry, identify and relate to specific industry, change product lifetime*, and *cover or wrap* in both contexts. This might indicate that solution mapping strategies may be used to support divergent thinking for multiple, different technologies.

This current work builds on our previous work to expand the available solution mapping strategies for teaching our engineering students. A typical engineering education curriculum provides limited information about solution-first design processes and is limited to problem-first approaches. Because instruction on solution mapping is limited in existing engineering curricula, engineering students are underprepared to engage in a solution mapping practice. The prior work interviewed engineers who successfully engaged in solution mapping by developing novel technologies and bringing them out to market after identifying applications [7]. The interview results were translated into a small set of strategies and tested through a controlled experiment to demonstrate that a single, 1-hour session of instruction on solution mapping can support students in engaging in divergent thinking and developing solution mapping skills. The previous results showed that the solution mapping tool aided engineering students to generate a large quantity of diverse applications of a technology [6], aligning with recommended practices in divergent thinking [36]. However, our previous tool included a limited number of strategies as these strategies were discovered from interviews, which require participants to explain past events and may have incomplete information. Our previous tool focused on identifying key functions of the technology and identifying industry sectors prior to finding applications. In the current study, think-aloud was used as a direct method to gain insight into the participants' thought processes. Our current study discovered additional strategies that can be included in the previously developed solution mapping tool, expanding the list of available strategies for instructors to leverage.

The solution mapping strategies identified from this study can be incorporated into a single lesson in design courses to teach students about solution-first design processes. Similar to an idea generation lesson that introduces students to divergent thinking to consider a number of different solutions to a problem, the solution mapping strategies can be used to provide a lesson on how to engage in divergent thinking to identify applications of a technology. Building on our prior work [6], the lesson can introduce students to a novel technology, guide students in identifying key characteristics of the technology, and mapping the technology a number of different industry sectors. After the initial exploration, guided prompts such as *substitute way of achieving function* or *change product lifetime* can be presented to encourage students to consider additional possibilities. This single, 1-hour design lesson would allow engineering students to think through the steps in solution mapping using these strategies to gain experience with the solution mapping process.

As educators examine different ways to develop best practices in design education, instruction on solution-first design processes can expand students' approaches to design and address problems from more than one angle. Engineering students may learn and adopt effective ways to identify applications for new, emerging technologies that can lead to innovative product development.

Limitations and Future Research

This study examined a small sample of engineering professionals with mechanical engineering degrees. The purpose of the study was to gain an in-depth understanding of engineers' practices. Conducting in-depth studies with small sample sizes is common in design research [37]–[40]. Findings from a larger sample of engineering professionals with varying backgrounds may differ, and sample size will limit the generalizability of this study. Furthermore, our study did not explore differences among participants such as years of experience, and our study only included 2 females, which is not sufficient to represent the diverse demographics represented in engineering. Also, solution mapping strategies were examined from two technologies (shape memory alloys and aerogels). Examining solution mapping strategies with varying technologies may reveal additional strategies.

Engineering professionals in this exploratory study were asked to generate problem applications within a single session. In practice, engineers perform solution mapping over extended periods to identify problem applications for their technology. Additional studies can examine solution mapping strategies in long-term practices.

Conclusion

Engineers may engage in solution-first design processes that emphasize starting with a specific technology and diverging to consider multiple problems it can solve, called solution mapping. Although solution mapping has been demonstrated in multiple studies, there are limited strategies and tools to support solution mapping practices. We examined engineering practitioners' solution mapping practices to identify specific strategies that can be used to support solution mapping. These strategies can be developed into a single instructional lesson to educate engineering students and equip them with different approaches to addressing design challenges.

Appendix A1

Prompt 1

Shape Memory Alloy

A shape-memory alloy is an alloy that remembers its original shape. When it is deformed, it can return to its pre-deformed shape when heated. The transformation temperature can be adjusted to be between -100ºC to 200ºC through changing the alloy composition. The two main types of shape-memory alloys are copper-aluminum-nickel and nickel-titanium. These compositions can be manufactured to almost any shape and size. The yield strength of shape-memory alloys is lower than that of conventional steel, but some compositions have a higher yield strength than plastic or aluminum.

Identify potential applications of shape memory alloys.

Prompt 2

Aerogel

An aerogel is a synthetic porous ultralight material derived from a gel, in which the liquid component of the gel has been replaced with a gas. Aerogels have a porous solid network that contains air pockets, with the air pockets taking up the majority of space within the material. The result is a high-strength solid with extremely low density and low thermal conductivity. It is also translucent and can scatter light.

Identify potential applications of aerogels.

References

[1] J. D. Bronzino, *Management of Medical Technology: A Primer for Clinical Engineers*. Oxford, UK: Butterworth-Heinemann, 2014.

[2] N. Cross, *Engineering Design Methods: Strategies for Product Design*, 4th ed. West Sussex, England: Wiley, 2008.

[3] C. L. Dym and P. Little, *Engineering design: A project-based introduction*, Third. Hoboken, NJ: John Wiley & Sons, 2004.

[4] M. French, J. Gravdahl, and M. J. French, *Conceptual design for engineers*. London: Design Council, 1985.

[5] P. Yock *et al.*, *Biodesign: the process of innovating medical technologies*, 2nd ed. Cambridge University Press, 2015.

[6] J. W. Lee, S. R. Daly, A. Huang-Saad, G. Rodriguez, Q. DeVries, and C. M. Seifert, "A solution in search of problems: a cognitive tool for solution mapping to promote divergent thinking," *J. Eng. Des.*, vol. 32, no. 6, pp. 300–321, Jun. 2021, doi: 10.1080/09544828.2021.1887462.

[7] J. W. Lee, S. R. Daly, A. Huang-Saad, G. Rodriguez, and C. M. Seifert, "Cognitive strategies in solution mapping: How engineering designers identify problems for technological solutions," *Des. Stud.*, vol. 71, p. 100967, Nov. 2020, doi: 10.1016/j.destud.2020.100967.

[8] J. W. Lee, *Divergent Thinking in Front-End Design*. Ann Arbor, MI: University of Michigan, 2019. Accessed: Jul. 01, 2020. [Online]. Available: https://deepblue.lib.umich.edu/handle/2027.42/149892

[9] J. W. Lee, S. R. Daly, A. Huang-Saad, and C. M. Seifert, "Start With Problems or Solutions? Medical Device Design in Industry and Academia," *IEEE Access*, vol. 8, pp. 208623–208642, 2020, doi: 10.1109/ACCESS.2020.3035966.

[10] B. S. Harrison and A. Atala, "Carbon nanotube applications for tissue engineering," *Biomaterials*, vol. 28, no. 2, pp. 344–353, Jan. 2007, doi: 10.1016/j.biomaterials.2006.07.044.

[11] G. Altshuller, *40 principles: TRIZ keys to technical innovation*. Worcester, Mass.: Technical Innovation Center, Inc., 1997.

[12] J. W. Lee, S. R. Daly, A. Y. Huang-Saad, C. M. Seifert, and J. Lutz, "Using design strategies from microfluidic device patents to support idea generation," *Microfluid. Nanofluidics*, vol. 22, no. 7, p. 70, Jul. 2018, doi: 10.1007/s10404-018-2089-6.

[13] J. W. Lee, A. Ostrowski, S. R. Daly, A. Huang-Saad, and C. M. Seifert, "Idea generation in biomedical engineering courses using Design Heuristics," *Eur. J. Eng. Educ.*, vol. 0, no. 0, pp. 1–19, Sep. 2018, doi: 10.1080/03043797.2018.1514368.

[14] S. R. Daly, S. Yilmaz, J. L. Christian, C. M. Seifert, and R. Gonzalez, "Design heuristics in engineering concept generation," *J. Eng. Educ.*, vol. 101, no. 4, pp. 601–629, Oct. 2012.

[15] N. V. Hernandez, L. C. Schmidt, and G. E. Okudan, "Systematic Ideation Effectiveness Study of TRIZ," *J. Mech. Des.*, vol. 135, no. 10, pp. 101009-101009–10, Sep. 2013, doi: 10.1115/1.4024976.

[16] R. H. Allen, S. Acharya, C. Jancuk, and A. A. Shoukas, "Sharing best practices in teaching biomedical engineering design," *Ann. Biomed. Eng.*, vol. 41, no. 9, pp. 1869–1879, 2013.

[17] M. R. Goldberg and J. L. Pearlman, "Best practices for team-based assistive technology design courses," *Ann. Biomed. Eng.*, vol. 41, no. 9, pp. 1880–1888, 2013.

[18] P. King, “Design and biomedical engineering,” *Int. J. Eng. Educ.*, vol. 15, no. 4, pp. 282–287, 1999.
[19] A. L. Lerner, B. H. Kenknight, A. Rosenthal, and P. Yock, “Design in BME: challenges, issues, and opportunities,” *Ann. Biomed. Eng.*, vol. 34, no. 2, pp. 200–208, 2006.
[20] M. Oden, Y. Mirabel, M. Epstein, and R. Richards-Kortum, “Engaging undergraduates to solve global health challenges: a new approach based on bioengineering design,” *Ann. Biomed. Eng.*, vol. 38, no. 9, pp. 3031–3041, 2010.
[21] K. E. Reuther, M. J. Cennamo, and T. W. Guo, “Re-designing design: a technology-enhanced graduate-level biomedical design course,” presented at the ASEE Annual Conference, 2016.
[22] Y. Yazdi and S. Acharya, “A new model for graduate education and innovation in medical technology,” *Ann. Biomed. Eng.*, vol. 41, no. 9, pp. 1822–1833, 2013.
[23] H. Dubberly, *How do you design? A compendium of Models*. San Francisco, CA: Dubberly Design Office, 2004.
[24] K. Dorst and N. Cross, “Creativity in the design process: Co-evolution of problem–solution,” *Des. Stud.*, vol. 22, no. 5, pp. 425–437, Sep. 2001, doi: 10.1016/S0142-694X(01)00009-6.
[25] M. L. Maher and H. Tang, “Co-evolution as a computational and cognitive model of design,” *Res. Eng. Des.*, vol. 14, pp. 47–63, 2003.
[26] F. Dannemann and M. Jetzschmann, “Technology-Driven Design of a Scalable Small Satellite Platform,” in *Proceedings of 4S Symposium 2016*, Malta, 2016. Accessed: Apr. 13, 2023. [Online]. Available: http://www.congrexprojects.com/4S2016
[27] M. Helms, S. S. Vattam, and A. K. Goel, “Biologically inspired design: process and products,” *Des. Stud.*, vol. 30, no. 5, pp. 606–622, Sep. 2009, doi: 10.1016/j.destud.2009.04.003.
[28] A. Brennan and C. Kirschner, *Bio-inspired materials for biomedical engineering*. New York: Wiley, 2014.
[29] W. Wang, Y. Liu, and Z. Xie, “Gecko-Like Dry Adhesive Surfaces and Their Applications: A Review,” *J. Bionic Eng.*, vol. 18, no. 5, pp. 1011–1044, Sep. 2021, doi: 10.1007/s42235-021-00088-7.
[30] E. Danneels and F. Frattini, “Finding Applications for Technologies Beyond the Core Business,” *MIT Sloan Manag. Rev.*, vol. 59, no. 3, pp. 73–78, 2018.
[31] S. Shane, “Prior Knowledge and the Discovery of Entrepreneurial Opportunities,” *Organ. Sci.*, vol. 11, no. 4, pp. 448–469, Aug. 2000, doi: 10.1287/orsc.11.4.448.14602.
[32] B. A. Camburn *et al.*, “The Way Makers Prototype: Principles of DIY Design,” presented at the ASME 2015 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, American Society of Mechanical Engineers, Aug. 2015, p. V007T06A004-V007T06A004. doi: 10.1115/DETC2015-46295.
[33] C. A. Lauff, D. Kotys-Schwartz, and M. E. Rentschler, “What is a Prototype? What are the Roles of Prototypes in Companies?,” *J. Mech. Des.*, vol. 140, no. 6, pp. 061102-061102–12, Mar. 2018, doi: 10.1115/1.4039340.
[34] M. E. Fonteyn, B. Kuipers, and S. J. Grobe, “A description of think aloud method and protocol analysis,” *Qual. Health Res.*, vol. 3.4, pp. 430–441, 1993.
[35] J. Saldaña, *Fundamentals of Qualitative Research*. Oxford University Press, USA, 2011.
[36] J. Baer, *Creativity and Divergent Thinking: A Task-Specific Approach*. Psychology Press, 2014.

[37] K. Goucher-Lambert, J. Moss, and J. Cagan, “Using Neuroimaging to Understand Moral Product Preference Judgments Involving Sustainability,” presented at the ASME International Design Engineering Technical Conferences (IDETC), Charlotte, NC, Aug. 2016. doi: 10.1115/DETC2016-59406.
[38] G. Goldschmidt, “The designer as a team o f one,” *Des. Stud.*, vol. 16, no. 2, pp. 189–209, Apr. 1995, doi: 10.1016/0142-694X(94)00009-3.
[39] N. B. Damen and C. A. Toh, “Designing for Trust: Understanding the Role of Agent Gender and Location on User Perceptions of Trust in Home Automation,” p. V007T06A044, Aug. 2017, doi: 10.1115/DETC2017-68349.
[40] C. Cardoso, P. Badke-Schaub, and O. Eris, “Inflection moments in design discourse: How questions drive problem framing during idea generation,” *Des. Stud.*, vol. 46, pp. 59–78, Sep. 2016, doi: 10.1016/j.destud.2016.07.002.