A PRODUCT-SERVICE SYSTEM APPROACH FOR DESIGNING MOBILE ROBOTS

AN APPLICATION TO INDUSTRIAL DESIGN STUDIO PROJECTS

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As robots become more prevalent in homes and public spaces, there is a growing need for their development in industry and inclusion in industrial design curricula. However, teaching robot design poses challenges due to their unique nature of autonomous and dynamic behavior, service aspects, and connectivity to a larger system. Such complex nature of robots asks for new design approaches and methods by expanding the focus of users to include non-human agents like robots in the design process. This paper proposes to design mobile robots from a product-service system approach and examines the design process and methods for mobile robots. Visual mapping tools are introduced for the initial system analysis and design. Concurrent design of product and interface, integration of the two, and visual storytelling are shown as methods for designing a product-service system holistically. Using three years of studio projects in a university's industrial design program as case studies, the proposed approach, process, methods, and outcomes are examined with reflections on their effectiveness and limitations.

Keywords: Mobile Robot, Industrial Design, Product-Service System, Systems Thinking, Robotics

1. INTRODUCTION

The presence of robots in human life has been increasing as they become smarter and more physically capable due to technological advancements in sensors, actuators, and artificial intelligence (AI) (Simon, 2020). They are no longer confined to factories or labs, as their applications have expanded to homes and various areas of the service industry. Recent breakthroughs in AI will further accelerate the adoption of robots in various areas of human life and work, expanding the roles of robots from simple and repetitive tasks to even highly interactive services that require higher intelligence (Huang & Rust, 2018). Consequently, there is a growing need for tech companies and the service industry to develop new robots, particularly those designed to operate in complex real-world environments with close interactions with humans. Such aspects ask for an increased involvement of industrial designers in developing robots, leading to a need for robots to be covered in the industrial design curriculum. However, teaching robot design in studio courses is challenging for design educators because robots have a unique nature compared to conventional non-robotic products. Robots show autonomous and dynamic behaviors (Lee, Kim, & Kim, 2007). They understand the surroundings, make decisions, move around, and conduct tasks on their own, that also requires operation in and connection to a larger system. Robots' autonomy also makes people perceive them differently from other products, often anthropomorphizing them (Bartneck et al., 2020) and expecting social aspects in the interaction (Lee et al., 2009; Bartneck et al., 2020). Such complex nature of robots requires new design approaches and methods to deal with multiple, interrelated factors surrounding robots. This paper proposes to view a robot as a product-service system based on systems thinking and examines the methods for designing mobile robots through studio projects in an industrial design program. This study particularly focuses on mobile robots because they exhibit more complex and autonomous behaviors and have been more widely deployed in homes and for service. Accordingly, the paper begins by analyzing the characteristics of mobile robots and presents a conceptual framework aimed at aiding designers in comprehending the agency of robots and their interactions with humans, environments, and other system elements. Building upon this framework, the paper introduces visual mapping tools for the analysis and design of a robotic system, along with delineating the five phases of the design process and the corresponding methods and tools employed in each phase. The proposed approach and methodology have been implemented in an industrial design studio course at the University of Cincinnati over the past three years. This paper delves into an examination of the process and outcomes derived from the studio, followed by discussions concerning the effectiveness and limitations of the approach.

2. MOBILE ROBOT AS A PRODUCT-SERVICE SYSTEM

2.1 CHARACTERISTICS OF MOBILE ROBOTS

The International Organization for Standardization [ISO] (2021) defines a robot as a "programmed actuated mechanism with a degree of autonomy to perform locomotion, manipulation or positioning" with autonomy referring to the "ability to perform the intended function without human intervention". Autonomy and actuation (mechanical action) are the core qualities of robots that differentiate them from traditional products. With non-robotic products, human users make decisions and exert power through their body parts to control and operate the products. For example, a handheld vacuum cleaner relies on the user to recognize dirty areas and maneuver it, whereas a robot vacuum cleaner can sense its surroundings, make decisions, and perform cleaning tasks with minimal or no human intervention. Mobility and autonomy are essential characteristics of mobile robots, which, as represented by robot vacuum cleaners, exhibit dynamic behavior (Scholtz, 2003; Lee, Kim, & Kim, 2007). Moreover, the majority of robots encountered in homes and public spaces serve to assist humans in tasks traditionally performed by people, indicating their service-oriented nature. For example, the replacement of human service providers with service robots is already happening and is expected to continue (Harris, Kimson, & Schwedel, 2018; Mende et al., 2019).

2.2 PRODUCT-SERVICE SYSTEM AND SYSTEMS THINKING

The characteristics of mobile robots mentioned above imply that they require different approaches to designing robots. First, their autonomous and dynamic behaviors make the current human-centered design approach fall short of acknowledging a robot's agency. Humans are not the sole agents, but robots take active roles, interacting with the surrounding environment, co-present people, and the other system elements. Cruickshank and Trivedi (2017) argue that the issue of the agency of autonomous objects, like robots, questions the validity of placing humans at the center of focus in the design process. They propose to “accommodate non-human agents” in the design process. Lee, Kim, and Kim (2007) even argue for robot-oriented design for mobile robots, as “the interactions with both human users and environments are vital”. This viewpoint can be summarized as Figure 1, which also serves as a basic conceptual framework for this paper’s approach to designing mobile robots.

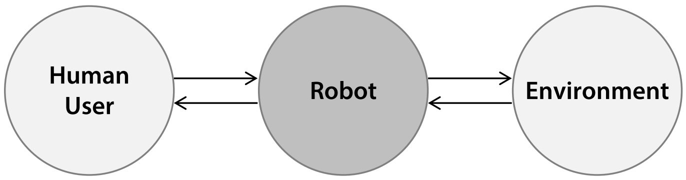


Figure 1. Conceptual Framework for Designing Mobile Robots.

Combined with the service aspect of robots, this leads to the second implication: understanding and designing robots from a holistic viewpoint as a product-service system. Lee et al. (2009) approached the design of a robot for snack delivery from the perspective of a product-service system, proposing to consider the social and physical context of the use environment, form, and social interaction concurrently. Indeed, the scope of designing robots is large, requiring holistic consideration of various aspects such as form, function, autonomy, interaction modalities, users, and context (Bartneck et al., 2020). This viewpoint aligns with systems thinking, which looks at things in the context of relationships rather than in isolation, enabling people to see the whole with the interconnecting and interacting parts together (Mononen, 2017). Systems thinking also regards a product as a set of cohesive and integrated experiences that involve process and service aspects, for which the entire experience should be considered through thoughtful analysis (Norman, 2009). In addition to robots’ general service nature, their recent integration into larger connected systems, where their physicality blends with digital services, makes the systems thinking approach highly relevant to designing robots.

3. STUDIO APPLICATION

The design approach mentioned in the previous sections has been applied to a fourth-year industrial design studio at the University of Cincinnati for the past three years. The studio ran for 15 weeks in the fall semester as team-based projects, and the topic was designing mobile robots for public spaces such as airports, supermarkets, hospitals, etc. Students worked in cross-disciplinary teams consisting of industrial design and communication design students, with each team typically having two ID students and one communication design student. For teams without a communication design student, one ID student was required to work on interface design. Figure 2 shows the overall design process, including the duration of time, design methods, and tools for each phase. This process and the subsequent project schedule were delivered to students on the first day of the studio, and students were continuously reminded of the process throughout the semester, with weekly assignments given out to them according to the design process.

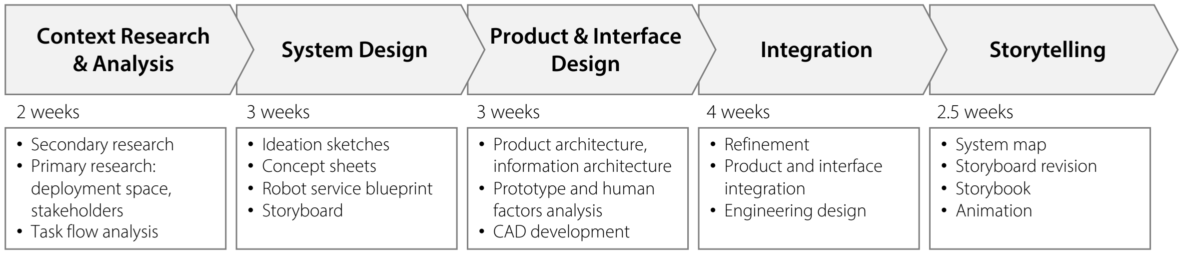


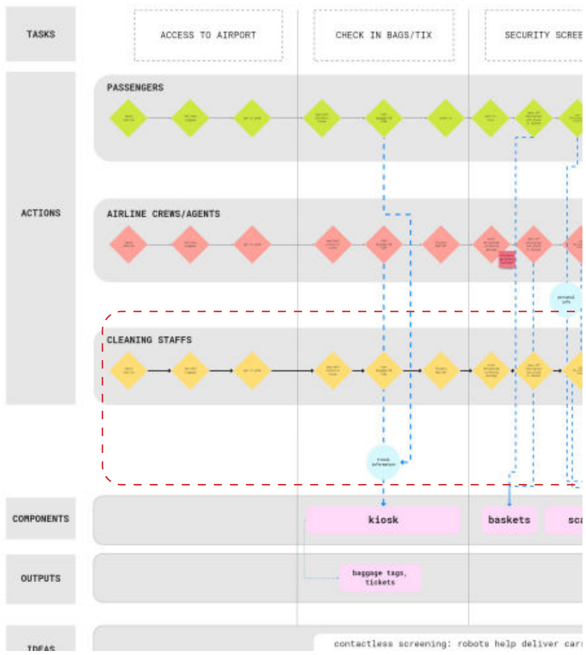
Figure 2. Studio Design Process.

3.1. CONTEXT RESEARCH AND ANALYSIS

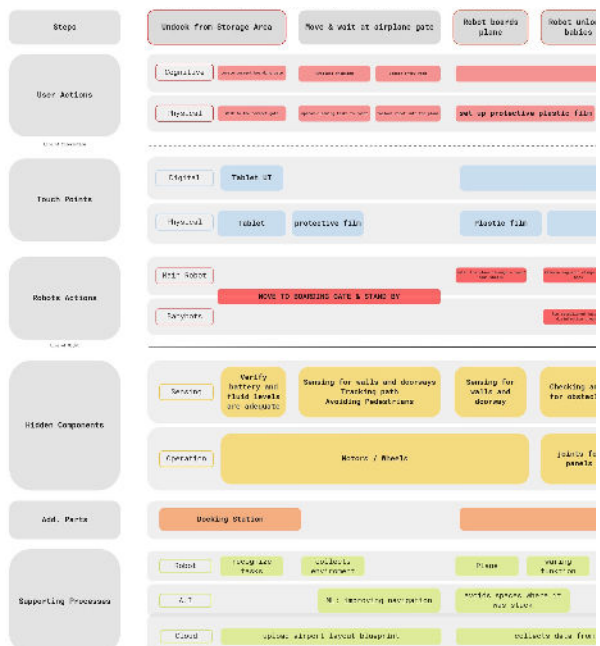
The context research and analysis phase involved understanding the current situation of the area of interest through primary and secondary research on users and stakeholders, the physical space, and technological and socio-cultural trends, particularly with a focus on the analyses of the task and information flow. Students were asked to create two task flow diagrams based on their research, one in a time sequence and another on a physical space layout. These flow diagrams helped to clarify the system components as well as interactions and relationships between customers, employees, the environment, and other service elements. Figure 3-a illustrates part of a task flow diagram created by a student team about the current procedure of boarding an aircraft and all related activities, interactions, and exchange of information and materials that occur during the procedure.

3.2. SYSTEM DESIGN

The system design phase began with exploring ideas for introducing robots to the area of interest. Students generated preliminary ideas for robots and various system elements, such as user interfaces, spatial arrangements, supporting items, and service scenarios. As ideas at this point were fragmented and lacked a cohesive story, students were asked to create concept sheets with more developed sketches and written descriptions. The concept sheets were then grouped and organized into sub-topic areas to create a cohesive story of robots working in a larger product-service system. The resulting ideas for the system were translated into a robot service blueprint, which was adopted from the service blueprint and modified to include specific physical elements of robots. The robot service blueprint helped to define the overall procedure of a robot's operation and interactions, as well as specify touchpoints, interaction modalities, functional components, and supporting processes. Figure 3-b shows part of the robot service blueprint for an airplane disinfection system developed in the studio. Here, frontstage actions are replaced with touchpoints and robot actions. The touchpoints are not limited to the elements on a robot but also include interfaces outside the robot, such as a mobile application. The elements below the line of sight represent what robots and the supporting system do, supposedly conducted by machines instead of humans. Backstage actions are replaced with hidden components, representing the physical functional components inside the robot, including sensors and actuators. Additional parts indicate any hardware that supports the robot's operation, such as a charging station or a storage unit. Finally, supporting processes are algorithms that drive the whole operation of the robot, occurring both inside the robot with data gathering and processing and in the cloud with machine learning. The four interaction elements of the human-machine interaction model (Ghim, 2021) are incorporated into the robot service blueprint to clarify the means of interactions and define sensors and actuators. Cognition and action on the human side are translated into cognitive and physical user actions respectively, and on the machine side, the hidden components are divided into sensing and operation. As the final step in this phase, a storyboard was created to visually narrate the context, tasks, workflow, interactions, and the robot's basic form and features.



3-a. Task Flow Diagram



3-b. Robot Service Blueprint

Figure 3. Task Flow Diagram (3-a) and Robot Service Blueprint (3-b)

3.3. PRODUCT AND INTERFACE DESIGN

This phase involved the concurrent development of a robot's physical appearance and functional features, as well as digital interfaces on both the robot and mobile devices. Based on the robot service blueprint, product architecture and information architecture were defined first. Then, the robot's specific form was explored and developed through iterations of sketches and initial CAD modeling. At the same time, students developed the UI design of a mobile application that supplements the robot's operation in the system. Students were also asked to design interactive elements on the robot, considering how to make robots more understandable of their status and intentions through expressive lights (Baraka, Rosenthal, & Veloso, 2016) and facial expressions (Thomaz, Hoffman, & Cakmak, 2016). Finally, students built and tested low-fidelity prototypes representing robots and interfaces to assess human factors and interactivity (Figure 4). Although in low-fidelity, prototypes enabled the students to view their designs more objectively and gain insights about the size, interactivity, and human factors. They could get a sense of how the robot would be perceived when it operates and moves around in physical space. The prototypes also provided an opportunity to ideate on new features.

Figure 4. Low-Fidelity Prototypes and Testing.

3.4. INTEGRATION

Based on the findings from the prototype testing, students further refined their designs by adjusting the size and form, adding new features, and considering materials. Functional components, such as sensors, motors, wheels, and other internal components were examined and arranged inside the CAD model, and the appearance of the robot was modified subsequently. Some teams came up with new ideas to make their robot work better in the intended environment and implemented the mechanisms in their CAD models. At the same time, interface design on the robot and mobile devices was further refined. In particular, students worked on more detailed interaction scenarios for the expressive lighting and the facial expressions on the robot, specifying the colors and animations. These interactive elements were finally integrated with the physical design of the robot.

3.5. STORYTELLING

The final phase was storytelling. As the project focused on designing a product-service system in which multiple system elements are interrelated both in time and space, it was essential to visually narrate the story behind this system. First, students were asked to create a system map using isometric composition to display the operation, workflow, and interactions of the robots in context. The paths of the robots were drawn on an isometric drawing of the physical space, along with other system elements and people. Next, the previous storyboard was revised to accommodate design changes and to fully communicate the story behind the product-service system of the robot. This led to the creation of a storybook, a collection of in-context rendering images (Figure 5), and a short animation.

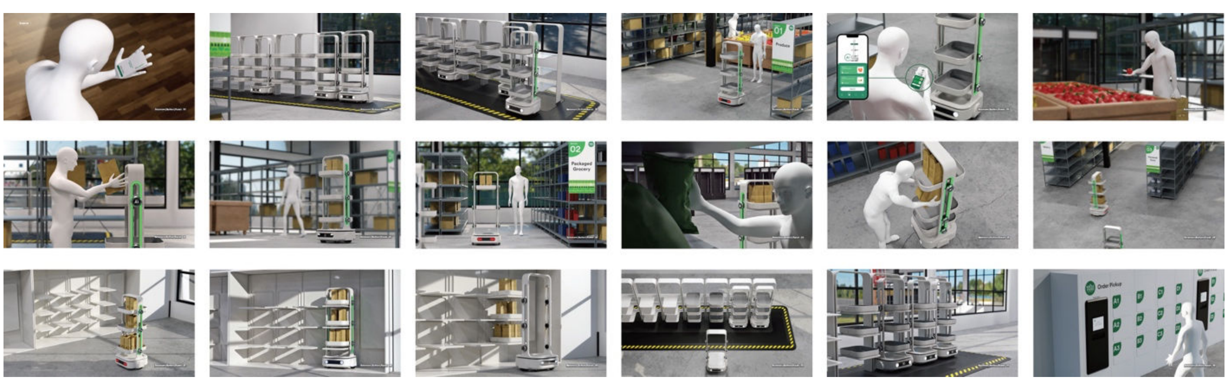
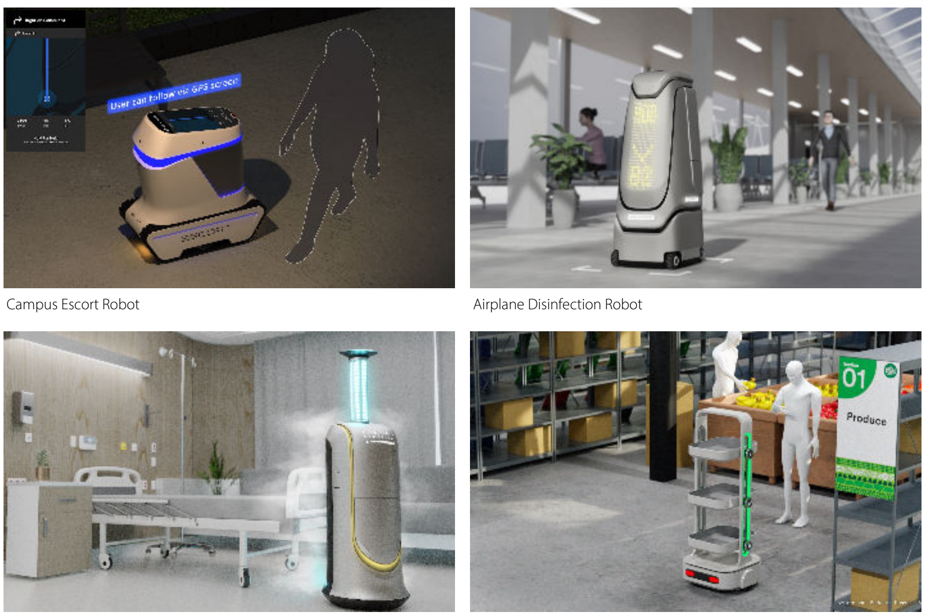


Figure 5. Storybook for a Grocery Fulfillment Robot.

Students were asked to communicate not only the robot's features and interactions but also the context and the benefit through the storybook and the animation. Robots are dynamically moving objects, and how people perceive them in their movement is different from what people see from still images. In that sense, animations were found to be effective in communicating the robot's operations and interactions in a specific environment, particularly when the robot's main feature is executed by manipulators.

4. PROJECT OUTCOMES AND CHALLENGES

The studio has produced 19 concepts of mobile robots in various application areas over the past three years, including airports, supermarkets, hospitals, and more. Figure 6 shows design renderings from the studio, each of which exemplifies an emphasis on the visualization of the context and the lights/display effects to communicate the robot as part of a large product-service system where it operates.



Campus Escort Robot — Airplane Disinfection Robot — Hospital Hygienic Robot — Grocery Fulfillment Robot

Figure 6. Examples of the Robot Designs from the Studio.

As discussed so far, the project outcomes of each team were not a single product but a system of product and service and a visualized storytelling of the system. All the teams endeavored to integrate the service aspect of a robot by designing interfaces and the workflow of the entire system. Students expressed in their course evaluation that learning systems thinking was helpful and one of the most valuable aspects of the course.

While an effort was made to cover the multiple aspects of designing robots from holistic systems thinking, team collaboration, and a clearly structured design process, several challenges were identified:

- **Form Development:** Students expressed a need for more time for form development. Students were given three weeks for initial form development, which includes product architecture definition, a human factors analysis, and low-fidelity prototype building and testing. However, the complexity of designing a robot and its system required the students to work on many things at the same time, causing them to lose focus and time on form development.

- **Robot Morphology:** Though not planned initially, it has been brought up to the attention of both the instructor and students about robot morphology, for example, opening up discussions about how much a robot should resemble humans. While existing robots show a huge variety of their appearances, from functional to zoomorphic or anthropomorphic robots (Kunold, Bock, & Rosenthal-von der Pütten, 2023), and although there has been much research done in HRI on the relationship between a robot's appearance and people's expectations (Phillips et al., 2017), it is still unclear what level of a robot's anthropomorphism is most acceptable to people in a particular use context. Robot morphology needs more serious attention and investigation from industrial designers and a better way of accommodating this topic inside the studio is necessary.
- **Engineering integration:** As robots are highly dependent on sensors to function properly, choosing the right type of sensors and placing them in the right spots is critical in robot design. Also, the choice of the drive system (motors, gears, and wheels) depends on the nature of the physical space, affecting the robot's locomotive behavior and the overall form factor. If a robot has manipulators like arms, it requires consideration of additional internal components, their placement inside the robot, and the workings of their mechanism. While all these engineering aspects affect the appearance of a robot, constraining design choices and sometimes even dictating the design, design educators lack the capability to provide engineering knowledge to students without help from engineers. Though overall guidance on engineering components was provided, students had to rely on resources on the web or leave out certain engineering aspects. This remains one of the biggest challenges, and collaboration with engineering should be considered to overcome this challenge.

5. CONCLUSION

The unique nature of mobile robots, including their autonomous and dynamic behavior, service aspects, and connectivity to larger systems, requires a holistic product-service system approach when designing them. Visual mapping tools adopted from interaction design and service design, such as task flow diagrams and a robot service blueprint, have been helpful for students in the early stages of the project to analyze and define the complex system elements of the robot and their interactions, although some students expressed dealing with various diagrams was confusing. Concurrent design of the product and interface in the middle stages, and their integration later in the project, have been found to contribute to designing the system more cohesively. Storytelling through a series of in-context rendering images or animations has been an effective means of communicating the larger system surrounding the robot. This paper has outlined an ongoing endeavor to teach robot design in an industrial design studio, with future research opportunities highlighted, including form development, robot morphology, and engineering integration.

6. REFERENCES

Baraka, K., Rosenthal, S., & Veloso, M. (2016, August). Enhancing human understanding of a mobile robot's state and actions using expressive lights. In *2016 25th IEEE international symposium on robot and human interactive communication (RO-MAN)* (pp. 652-657). IEEE.

Bartneck, C., Belpaeme, T., Eyssel, F., Kanda, T., Keijsers, M., & Šabanović, S. (2020). *Human-robot interaction: An introduction*. Cambridge University Press.

Cruickshank, L., & Trivedi, N. (2017). Beyond human-centred design: Supporting a new materiality in the Internet of Things, or how to design when a toaster is one of your users. *The Design Journal*, *20*(5), 561-576.

Ghim, Y. G. (2021). Allocated Flow Diagramming: A Structured Process and Methods for Teaching Interactive Product Prototyping in Industrial Design. *Archives of Design Research*, *34*(4), 7-21.

Harris, K., Kimson, A., & Schwedel, A. (2018). Why the automation boom could be followed by a bust. *Harvard Business Review*, *13*.

Huang, M. H., & Rust, R. T. (2018). Artificial intelligence in service. *Journal of service research*, *21*(2), 155-172.

International Organization for Standardization. (2021). Robotics - Vocabulary (ISO Standard No. 8373:2021). Retrieved from https://www.iso.org/obp/ui/#iso:std:75539:en.

Kunold, L., Bock, N., & Rosenthal-von der Pütten, A. (2023). Not All Robots Are Evaluated Equally: The Impact of Morphological Features on Robots' Assessment through Capability Attributions. *ACM Transactions on Human-Robot Interaction*, *12*(1), 1-31.

Lee, H., Kim, H. J., & Kim, C. (2007). Autonomous behavior design for robotic appliance. In *Proceedings of the ACM/IEEE international conference on Human-robot interaction* (pp. 201-208).

Lee, M. K., Forlizzi, J., Rybski, P. E., Crabbe, F., Chung, W., Finkle, J., Glaser, E., & Kiesler, S. (2009). The snackbot: documenting the design of a robot for long-term human-robot interaction. In *Proceedings of the 4th ACM/IEEE international conference on Human robot interaction* (pp. 7-14).

Mende, M., Scott, M. L., van Doorn, J., Grewal, D., & Shanks, I. (2019). Service robots rising: How humanoid robots influence service experiences and elicit compensatory consumer responses. *Journal of Marketing Research*, *56*(4), 535-556.

Mononen, L. (2017). Systems thinking and its contribution to understanding future designer thinking. *The Design Journal*, *20*(sup1), S4529-S4538.

Norman, D. A. (2009). Systems Thinking: A Product Is More Than the Product. *Interactions*, 16(5). pp. 52-54

Phillips, E., Ullman, D., de Graaf, M. M., & Malle, B. F. (2017). What does a robot look like?: A multi-site examination of user expectations about robot appearance. In *Proceedings of the human factors and ergonomics society annual meeting* (Vol. 61, No. 1, pp. 1215-1219). Sage CA: Los Angeles, CA: SAGE Publications.

Scholtz, J. (2003). Theory and evaluation of human robot interactions. In *36th Annual Hawaii International Conference on System Sciences, 2003. Proceedings of the* (pp. 10-19). IEEE.

Simon, M. (2020, April 16). *The Wired Guide to Robots.* Retrieved from https://www.wired.com/story/wired-guide-to-robots.

Thomaz, A., Hoffman, G., & Cakmak, M. (2016). Computational human-robot interaction. *Foundations and Trends in Robotics*, *4*(2-3), 105-223.