Development of Low-Cost Prosthetic Using Circular Economy Approach for Disability in Indonesia

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Abstract

Indonesia has a large amputee population and persons with disabilities often face barriers in education, employment and social participation. Many of them face the complex challenge of having functional or aesthetic prosthetics that are affordable and inexpensive, and easy to repair or modify. This research examines the potential of combining 3D printing, open source design, penta-helix collaboration, and circular economy as a solution to improve the quality of life for persons with disabilities in Indonesia. The research method used is design thinking and participatory design. Data collection through stakeholder interviews and review of existing literature indicates that 3D printing technology can be used to make tools that are customizable, affordable, reduce costs, increase the availability of these products, and make these tools accessible. A circular economy approach can ensure sustainable and efficient use of resources, create opportunities for persons with disabilities to participate in the economy independently, and demonstrate the potential for collaboration between stakeholders in the public and private sectors to meet the needs of persons with disabilities. The research results show that a combination of 3D printing, open source design, penta-helix collaboration, and circular economy can provide innovative solutions for people with disabilities in Indonesia.

Keywords
Disability, 3D printing, Open-source design, Penta-helix, Circular economy.

1. Introduction
According to data released in the "Global Status Report on Road Safety 2018", lifelong disability ranks 8th due to road accidents, with deaths reaching 1.3 million people yearly or 3,562 people/day. The age of the victims who die from road accidents is close to 60% with an age range of 15-44 years. For Indonesia, when viewed from the types of road users who are victims of road accidents, the 3 largest are users of 2-wheeled vehicles (74%), bus drivers and passengers (7%), and pedestrians (16%). A moderate to severe type of injury from a road accident is usually accompanied by broken bones and injuries which, if severe, would result in amputation. The other data from UNICEF in 2022, there are nearly 240 million children with disabilities in the world (Unicef, 2021). Based on Indonesian Law no. 8 of 2016 concerning persons with disabilities, there are five categories of disabilities, namely physical, intellectual, mental, sensory, and multiple disabilities.

Meanwhile, based on data from the Indonesia Central Statistics Agency (BPS) for 2020, the number of persons with disabilities in Indonesia reached 22.5 million, or around eight percent. The data shows a significant increase in road accident victims from year to year. In addition to traffic accidents, work accidents, and genetic disorders, it is also the main cause of disabled people/patients in the community.
In Indonesia, persons with disabilities often face obstacles in education, employment, and social participation. Indonesia has a large population of amputees, many of whom face significant challenges in accessing affordable, functional prosthetics. Traditional prosthetics can be expensive and difficult to repair or modify, which can limit their accessibility and usability. This condition needs more strategic handling that involves all levels of society, because this problem is our shared responsibility, according to the UN's sustainable development goals (Abd Razak et al. 2013; Piazza et al. 2017; Schweitzer et al. 2018; Seppich et al. 2022; Vujaklija et al. 2016).

In recent years, 3D printing technology has shown great potential to address the challenges faced by people with disabilities (Dannereder et al. 2018; Koprnický et al. 2017; Ramkumar et al. 2021; Sidher 2017). By leveraging the open-source design and circular economy principles, it is possible to create affordable and customized tools that can improve the quality of life for persons with disabilities in Indonesia and serve as models for other developing countries. On the other hand, the Department of Industrial Design at Institut Teknologi Sepuluh Nopember (ITS), in this case, the Integrated Digital Design Laboratory/iDIG laboratory, has conducted product design research development that has a Level 6 Technology Readiness Level and has large potential market demand. The iDIG Laboratory already has the capability in terms of mastering technology, making prototypes, testing required; and product fabrication readiness to be marketed to the public to build regional self-reliance (see Figure 1).

1.1 Objectives
This study aims to propose the concept of a sustainable ecosystem by combining digital fabrication based on 3D printing, open-source design, penta-helix collaboration, and a circular economy that offers continuous training for young people, as a solution to overcoming disabilities, while creating jobs in developing countries.

Figure 1. An example of an open-source shoulder disarticulation prosthetic design-based 3D printer that has been developed by iDIG Laboratory (Kuswanto et al., 2019)

2. Literature Review

2.1 Conditions of Disability in Indonesia

Some several challenges and problems need to be addressed to improve the situation of individuals with disabilities in Indonesia (Ministry of Social Affairs of the Republic of Indonesia, 2008; National Team for the Acceleration of Poverty Reduction (TNP2K), 2020):

1. *Access to education*: Many children with disabilities in Indonesia face barriers to accessing education, including a lack of specialized schools and support services, as well as discrimination and stigma. This can lead to lower rates of enrolment and completion among students with disabilities, limiting their opportunities and potential.
2. *Access to healthcare*: Individuals with disabilities in Indonesia often face challenges in accessing healthcare services, including a lack of specialized medical facilities and trained healthcare providers. This can lead to a higher prevalence of health problems among people with disabilities, as well as a lack of support for managing existing conditions.
3. *Access to employment*: Individuals with disabilities in Indonesia often face discrimination and stigma in the workforce, which can limit their opportunities for employment and career advancement. This can lead to lower rates of employment and income among people with disabilities, as well as a lack of financial independence and stability.
4. *Inadequate infrastructure*: Many areas of Indonesia lack the necessary infrastructure to support individuals with disabilities, including accessible transportation, buildings, and public spaces. This can create barriers to mobility and independence for people with disabilities, limiting their ability to participate in society.
5. *Government health insurance/BPJS Kesehatan support is minimal*: BPJS Kesehatan funding to support individuals with disabilities is Rp. 2,500,000, -/disable people/5 years, and applies to whatever prosthetics a disabled person needs. This requires appropriate and sustainable solutions.

2.2 Open-source Product

The open-source design concept for 3D-printed prosthetics offers a powerful tool for addressing disability in developing countries, as it allows for the creation of customized, low-cost solutions that can be easily adapted and improved upon by local communities (Cano-Ferrer and Gómez, 2020; Hand, 2007). There are several advantages of using open-source design for prosthetic problems for the disabled in developing countries:

1. *Cost-effectiveness*: Open-source designs are freely available, which means that they can be easily accessed and used without incurring any additional costs. This makes 3D-printed prosthetics much more affordable, especially

for individuals in developing countries who may not have the financial means to access traditional prosthetic options.

2. *Customization*: Open-source designs can be easily customized to fit the specific needs of each individual. This allows for a better fit and increased functionality, as the prosthetic can be tailored to the unique anatomy and abilities of the user.
3. *Accessibility*: Open-source designs can be accessed and downloaded by anyone with a 3D printer. This means that individuals in remote or underserved areas can still access the technology, even if they do not have access to traditional prosthetic providers.
4. *Innovation*: Open-source designs are developed and shared by a global community of designers and users. This means that there is a constantly evolving pool of ideas and improvements, which can lead to more advanced and effective prosthetic options.

The use of open-source designs for 3D-printed prosthetics in developing countries can help to improve the accessibility and affordability of these important assistive devices, ultimately enabling individuals with disabilities to live more independent and fulfilling lives. 3D printing and open-source design can significantly reduce the cost of producing prosthetics and other assistive devices. This makes this technology especially valuable in developing countries where access is limited.

2.3 The Capabilities of 3D Printers

Several potential solutions could be implemented to upgrade the capabilities of 3D printers in developing countries, including (Dannereder et al. 2018; Quigley, 2015; Ramkumar et al. 2021; Said et al. 2020):

1. *Providing training and education*: Providing training and education to individuals and organizations in developing countries on the use of 3D printing technology can help to increase their understanding of the capabilities and limitations of 3D printing and enable them to use the technology more effectively. This could include workshops, seminars, and online courses on topics such as 3D printing fundamentals, design and modeling, and advanced 3D printing techniques.
2. *Establishing partnerships and collaborations*: Establishing partnerships and collaborations with other organizations, companies, and institutions that are involved in 3D printing can help to share knowledge, expertise, and resources, and facilitate the development and deployment of 3D printing technology in developing countries. This could include partnerships with research institutions, 3D printing service providers, and other organizations that are working on 3D printing projects in developing countries or elsewhere.
3. *Supporting research and development*: Supporting research and development on 3D printing technology can help to improve the capabilities of 3D printers in developing countries. This could involve funding research projects, providing grants and other forms of support to researchers and innovators working on 3D printing, and facilitating the exchange of ideas and knowledge among researchers and other stakeholders.
4. *Promoting the use of open-source 3D printing technology*: Promoting the use of open-source 3D printing technology can help to make 3D printing more accessible and affordable in developing countries. Open-source 3D printing technology allows users to freely modify, improve, and distribute 3D printing designs and software, which can help to drive innovation and democratize access to 3D printing technology. Overall, a combination of these and other strategies could help to upgrade the capabilities of 3D printers in developing countries.

2.4 The Penta-helix Concept

The penta-helix concept was offered as a solution because it required the cooperation of all parties to work together. This model of collaboration can be beneficial for addressing prosthetic problems for the disabled in developing countries because it brings together a diverse range of perspectives and expertise, which can lead to more effective solutions.

One key advantage of penta-helix collaboration is that it allows for a more comprehensive approach to problem-solving. By involving all five stakeholders, the penta-helix model ensures that all relevant perspectives and concerns are considered when developing solutions to prosthetic problems. This can help to ensure that the solutions developed are appropriate and effective for the specific needs of the disabled community in a given developing country.
Another advantage of penta-helix collaboration is that it can facilitate the sharing of knowledge and resources among the different stakeholders. For example, academia and industry can work together to develop new technologies and materials that can be used in prosthetics, while government and civil society organizations can help to provide funding

and support for research and development efforts. This sharing of knowledge and resources can help to accelerate the development of new and better prosthetics for the disabled in developing countries.
Additionally, penta-helix collaboration can help to build strong partnerships and networks among the different stakeholders. This can facilitate ongoing communication and coordination among the stakeholders, which can help to ensure that the needs of the disabled community are addressed in a sustainable and continuous (Pereira & Vence 2016).

3. Methods

Through stakeholder interviews and a review of existing literature, our results demonstrate that this approach has the potential to improve the lives of persons with disabilities in Indonesia, discovering that 3D printing technology can be used to make customized assistive devices affordable, reduce costs, increase the availability of these products and their ease of use accessible. Further research is needed to explore its feasibility and effectiveness.

The role of academics as initiators is needed to mobilize all stakeholders in their respective regions. Collaboration between universities without dividing their interests can be accommodated in the form of commitment to priority community service programs as part of the "Tri-Dharma" of Indonesian higher education. With advances in technology that already exists, as well as ongoing scientific research and development according to their respective roadmaps, do not rule out the possibility of implementing industry 4.0 and continuing with the concept of society 5.0 which can be a solution that needs to be built together.

3.1 The Design Thinking Process

The design thinking process method is used in this research, starting from the understanding stage (empathize and define), the explore stage (ideate and prototype) and the materialize stage (test and implement). Empathize and define location through primary data collection (observation, interview, questionnaire, shadowing, customer journey mapping) and secondary (literature study, benchmarking of existing products and reference products, mood board analysis, and persona analysis) (Katoppo and Sudradjat, 2015).
After the understanding stage gets the required criteria, it is followed by the exploration stage, namely the idea stage and the prototype stage. The ideate stage includes shape sketches, 3D parametric concepts, design system analysis (joining, production, molding, maintenance, distribution, etc.), integrated design, material experiments, molding experiments, and production.

3.2 Participatory Design

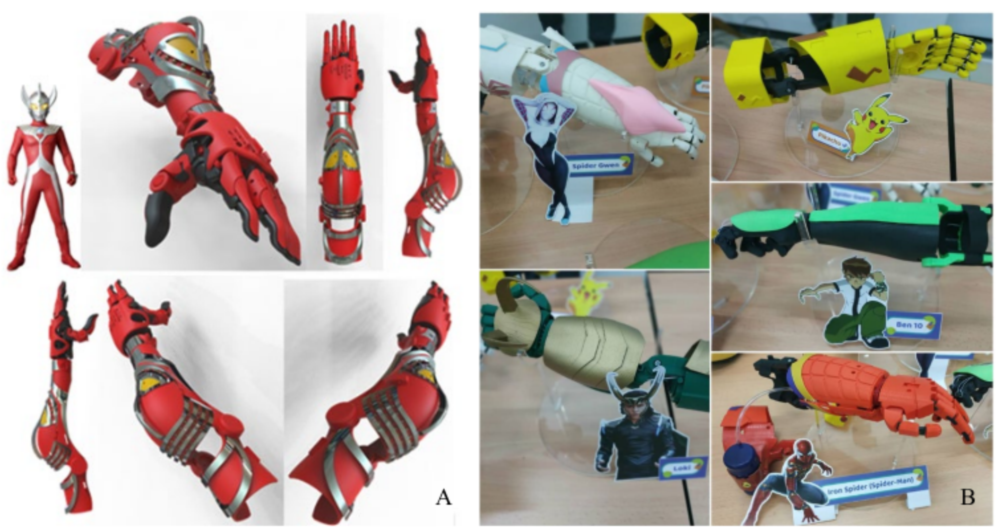

Figure 2. An example of an open-source 3D printer-based prosthetic design that has been developed by iDIG Laboratory using a participatory design approach (Amirullah et al., 2021; Wijaya and Kuswanto, 2019)

Participatory design for the development of a low-cost prosthetic based on 3D printing technology in Indonesia would involve engaging people with disabilities, prosthetic professionals, and local communities in the design process (see Figure 2). The goal of this approach is to co-create solutions that are responsive to the needs and perspectives of those who will use them (Chen et al. 2016; Cumbo and Selwyn, 2022; Drain et al. 2021; Gibson et al. 2010). The use of 3D printing technology can help make the development of low-cost prosthetics more accessible, as it can allow for the rapid prototyping and iteration of designs, as well as the customization of prosthetics, to fit the unique needs of each user.

To incorporate participatory design, stakeholders could be engaged through workshops, focus groups, or other forms of engagement that allow their perspectives and needs to inform the design of the prosthetics. This could include input on the design of the prosthetics themselves, as well as feedback on the manufacturing process and the overall accessibility of the technology.

4. Data Collection

The data collection process could involve the following steps:

1. *Identifying the target population*: The first step would be to identify the target population of people with disabilities who need prosthetics in Indonesia. This can be done through various sources such as government records, disability organizations, and healthcare facilities.
2. *Understanding the needs and preferences of the target population*: This would involve conducting surveys and focus group discussions with the target population to understand their needs and preferences for prosthetics. This information will be used to design a prosthetic that is suitable for the local context.
3. *Collecting data on available materials*: The next step would be to collect data on the availability of materials that can be used for the prosthetic, such as recycled plastics and metals. This data could be obtained from local recycling facilities, waste management companies, and manufacturers.
4. *Gathering data on manufacturing and distribution processes*: Data on the processes involved in the manufacturing and distribution of prosthetics would be collected to understand the challenges and opportunities in implementing a circular economy approach.
5. *Monitoring and evaluating the effectiveness of the prosthetics*: Once the prosthetics have been distributed, it is important to monitor and evaluate their effectiveness in terms of usage and user satisfaction. This information can be collected through follow-up surveys and interviews with the users.

It's important to keep in mind that the data collection process should be ethical, transparent, and respectful of the privacy of the individuals involved. All data collected should also be properly stored and protected to ensure its confidentiality.

5. Results and Discussion

5.1 The Integration of Industry 4.0 Technology and The Principles of Society 5.0

The integration of Industry 4.0 technology and the principles of Society 5.0 can potentially offer a range of benefits for individuals with disabilities in developing countries:

1. The improvement of access to information and services for individuals with disabilities. This technology, which includes advancements in areas such as artificial intelligence, the internet of things, and automation, has the potential to enable individuals with disabilities to access information and services more easily and quickly. For example, the use of smart devices and assistive technology can help individuals with disabilities to communicate, navigate, and access information more easily.
2. The improvement of healthcare for individuals with disabilities. This technology has the potential to enable the development of new treatments and therapies for individuals with disabilities, as well as improve the delivery of healthcare services. For example, the use of telemedicine and remote monitoring can enable individuals with disabilities to access healthcare services more easily, even in remote or underserved areas.
3. The integration of the principles of Society 5.0, which focuses on creating a society that is inclusive, sustainable, and resilient, can also help to improve the lives of individuals with disabilities in developing countries. This approach emphasizes the importance of collaboration and cooperation among different stakeholders, including individuals with disabilities, to create solutions that address the challenges faced by these individuals. For example, the principles of Society 5.0 can help to create a more inclusive and accessible built environment for individuals with disabilities, as well as support the development of policies and programs that promote their inclusion and empowerment.

Here are a few possible ways that technology can be used to support people with disabilities in Indonesia and serve as a model for other developing countries:

1. *Assistive technology*: Many different kinds of assistive technology can help people with disabilities live more independent, productive lives. This could include things like mobility aids, hearing aids, and speech-generating devices.
2. *Telehealth services*: Advances in technology have made it possible to deliver healthcare services remotely, which can be especially useful in rural or hard-to-reach areas. This could include things like teletherapy, telemedicine, and remote monitoring.
3. *Educational technology*: Technology can also be used to support the education of children with disabilities. This could include things like adaptive learning software, assistive technology for reading and writing, and virtual reality tools for therapy and rehabilitation.
4. *Online support groups*: The internet can provide a valuable platform for connecting people with disabilities, their families, and other support networks. Online support groups can provide a space for sharing information, advice, and support.
5. *Crowdfunding and microfinance*: The internet can also be used to raise funds and support people with disabilities. Crowdfunding platforms and microfinance organizations can help to provide access to financial resources that can be used to purchase assistive technology, support education and rehabilitation, and more.

The integration of Industry 4.0 technology and the principles of Society 5.0 has the potential to offer a range of benefits for individuals with disabilities in developing countries, including improved access to information and services, better healthcare, and greater inclusion and empowerment (Collaborators, 2018; Pereira and Vence, 2016; Quigley, 2015; Raj and Aithal, 2020; Stoppa et al., 2018; Vence and Pereira, 2019; Vujaklija et al., 2016).

5.2 The Circular Economy

The circular economy is an economic model that is based on the principles of conserving resources and minimizing waste (Pereira and Vence 2016; Raj and Aithal 2020; Vence and Pereira 2019). This model is designed to create a more sustainable and efficient economy by reducing the need for raw materials and promoting the reuse and repurposing of resources.

Additionally, the modular design of open-source prosthetics makes it easy to repair and upgrade individual parts, rather than having to replace the entire prosthetic. This reduces waste and increases the lifespan of the prosthetic, while also making it more affordable for users. Another aspect of the circular economy approach that can be applied to developing open-source prosthetics is the use of shared knowledge and collaboration. By sharing knowledge and collaborating with others in the development of prosthetics, resources can be optimized, and duplication of effort can be avoided. This can help to accelerate innovation and improve the quality of prosthetics, while also reducing costs. Disability is a significant challenge in Indonesia, with an estimated 15% of the population living with some form of disability. Many disabled individuals require assistive devices such as prosthetics to improve their mobility and quality of life. However, the cost of prosthetics can be prohibitively high, making them inaccessible to many Indonesians. A circular economy is an approach that aims to create a sustainable and inclusive economy by designing our waste and pollution, keeping products and materials in use, and regenerating natural systems. The circular economy approach can also provide social benefits, such as the creation of job opportunities, the promotion of community engagement, and the improvement of public health. Circular economy initiatives can create new business models, such as product-as-a-service, where companies retain ownership of the products and provide a service to customers, rather than selling products outright. Circular economy principles can be applied to the development of low-cost prosthetics in several ways. Here are a few examples:

1. *Design for sustainability*: The design of low-cost prosthetics can be optimized to reduce waste and maximize resource efficiency. This can include designing products for disassembly, using locally available materials, and reducing the use of toxic materials.
2. *Using of recycled and repurposed materials*: By using recycled and repurposed materials, the cost of production can be significantly reduced. For example, plastic waste can be collected and transformed into filament for 3D printing prosthetic components.
3. *Product-as-a-Service*: Companies can retain ownership of prosthetics and offer them as a service to customers, rather than selling products outright. This can provide a more affordable option for people with disabilities, as they may not be able to afford the upfront cost of purchasing a prosthetic.

4. *Recycling and refurbishing*: End-of-life prosthetics can be recycled or refurbished to extend their useful life. This can reduce waste and provide a more sustainable and affordable option for people in need of prosthetic replacements.
5. *Collaboration with local communities*: By working with local communities, low-cost prosthetic production can support local economic development and job creation. This can help to build a more resilient and sustainable economy that benefits everyone.

Furthermore, the circular economy promotes collaboration and innovation among different stakeholders, such as government, academia, industry, civil society, and the media. This can help to foster a more inclusive and effective approach to addressing disability in developing countries, with the potential to create more advanced and effective assistive technologies.

5.3 Working Group

Figure 3. Seven work-based structures (WBS) for implementing activity

To realize the concepts and technical plans mentioned above, it is necessary to divide a working group to facilitate coordination and grouping of roles and responsibilities of each stakeholder. We propose the existence of seven WBS for implementing activity (see Figure 3).

1. *WBS 1, Ecosystem Data Collection*: patient; support hospital; orthotic prosthetic workshop; potential Vocational School; support industry; foundation/association/Non-Government Organization; support regulation; etc.,
2. *WBS 2*, *Product Planning*: marketing and competitor analysis; product planning; design requirements and objective; human factor engineering; reliability, availability, maintenance, and safety,
3. *WBS 3*, *Legal and Intellectual Property Right*: research and activity ethics approval, standard operation procedure, medical assessment, medical test permit, product classification, product registration; intellectual property rights; donation; cooperation agreement,
4. *WBS 4*, *Rapid Prototyping and Production Center*: preliminary design; reverse engineering; final design and detail engineering drawing; 3D model, animation and simulation; engineering mock-up; rapid prototyping and production,
5. *WBS 5*, *Distribution and After Distribution*: distribution system; after distribution service; service center; user database; monitoring use/assessment of medical rehabilitation,
6. *WBS 6*, *Training, Facilitator, and Incubation*: training module/curriculum; certification; workshop and the event training camp; incubation and collaboration; MBKM-Merdeka Belajar Kampus Merdeka is a policy issued by the Indonesian Ministry of Education and Culture by giving rights to students to take courses outside the study program for 1 semester and activities outside of higher education for 2 semesters. Universities are given the freedom to provide Independent Campus activities that suit the needs and interests of their students,
7. *WBS 7*, *Mark-Com, Scientific and Community Service Publication*: marketing and promotion; scientific publication; community service publication; image and video documentation; monograph/reference book.

6. Conclusion

There are several advantages to using 3D printing, open-source design, penta-helix collaboration, and the circular economy to address disability in developing countries. These advantages include:

1. **Cost-effectiveness**: 3D printing and open-source design can greatly reduce the cost of producing prosthetics and other assistive devices. This makes these technologies particularly valuable in developing countries where access to traditional options may be limited due to cost constraints.
2. **Customization**: The use of 3D printing allows for the creation of custom-fit prosthetics and other assistive devices that are tailored to the specific needs and abilities of each individual. This can improve the functionality and comfort of the devices, leading to better outcomes for the user.
3. **Accessibility**: The use of 3D printing and open-source design means that individuals in remote or underserved areas can still access assistive technologies, even if they do not have access to traditional providers.
4. **Innovation**: The use of penta-helix collaboration (i.e., bringing together stakeholders from government, academia, industry, civil society, and the media) can foster a collaborative and innovative environment for developing assistive technologies. This can lead to more advanced and effective solutions for addressing disability in developing countries.
5. **Sustainability**: The use of the circular economy (i.e., a system in which waste is minimized and resources are conserved through the use of sustainable practices) can help to reduce the environmental impact of producing assistive technologies. This can also help to ensure that these technologies are available for future generations.

Overall, the combination of these 5 elements can offer a holistic and sustainable approach to dealing with a disability in developing countries. This can help increase the accessibility and affordability of assistive technology, ultimately enabling people with disabilities to lead more independent and fulfilling lives. By incorporating circular economy principles into development of low-cost prosthetics for individuals with disabilities in Indonesia, we can create more sustainable, affordable, and accessible solutions. This can help improve their quality of life while also reducing the environmental impact of prosthetic production and disposal. Additionally, this approach can create job opportunities and support the growth of local business in Indonesia. In inclusion, by applying circular economy principles to development of low-cost prosthetics, we can create a more sustainable and affordable option for people with disabilities. This approach can help to reduce waste, promote resource efficiency, and support economic development, while improving the quality of life for people with disabilities.

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Adhi Dharma Wibawa is an Associate Professor in Signal Processing, in ITS. He started his career as a lecturer in 2002 when he worked at Hang Tuah University. In 2004, he finished the Master's program at ITS, and then since 2008, he moved to ITS. In 2009 he continued his study for a Ph.D. at the University of Groningen, the Netherlands, majoring in Biomedical Engineering. He finished his Ph.D. program in June 2014. Now he joins several professional organizations such as IEEE, APTIKOM (Nasional Association for Higher Education in Computer and Informatics), and BANPT (National Accreditation Board). For 2021-2022, he was the chief of the AI Research Center at ITS, and now he is the head of the Medical Technology Study Program at ITS.

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Gunanda Tiara Maharany is a researcher and lecturer in the field of industrial product design, with a focus on visual ergonomics, user experience, assistive design, and creative thinking. She is currently based at ITS. She obtained her bachelor's degree in Industrial Product Design and holds a Master of Design at the Bandung Institute of Technology in Indonesia. Presently, to support and promote excellence in his field, Gunanda has joined as a member of the ADPII and ACM CHI organizations.

Ahmad Rieskha Harseno is a lecturer at Institut Teknologi Sepuluh Nopember, Surabaya. He has completed his master's degree in design at Institut Teknologi Bandung. Previously, he has experience in immersive design, product decoration, and roto molding industries. His research areas include industrial design, digital innovation, design immersion, infant support products, and human-centered design.

Ahmad Nur Firmansyah has been a Integrated Digital Design lab. member since 2019. He graduated with a bachelor's of product design and continuing his master's degree studies in Department of Innovation Design Management at ITS until now. As a member of the lab, he is in charge of supportive medical device design, product prototyping, reverse engineering, and supervision of 3D printer machines with FDM and SLA technology. Currently, he is still doing research on hand prosthetics and alternative materials for prosthetics.

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