Human Augmentation Consortium White Paper

-Future Scenarios Unlocked by Human Augmentation Technologies-

Human Augmentation Consortium
December 2025

Table of Contents

1. Introduction.

The proliferation of smartphones and wearable devices, advances in robotics, the practical application of virtual reality (VR), augmented reality (AR) and artificial intelligence (AI), coupled with the development of high-speed, high-capacity communication networks, have driven rapid progress in information and communication technology. These changes are fundamentally transforming our daily lives, work, and the very fabric of society. Within this trend, "Human Augmentation" has garnered significant attention in recent years. Human Augmentation is a concept that aims to realize richer, more fulfilling lives and societies. It achieves this by using the power of information and communication technology to complement and extend the physical, cognitive, and perceptual capabilities inherent to humans, or to extend human existence beyond temporal and spatial constraints.

The growing interest in human augmentation stems from both social and technological factors. Social factors include modern society facing challenges such as labor shortages due to declining birthrates and aging populations, the decline of traditional skills, and depopulation in rural areas. Human augmentation holds potential as a solution to these societal challenges. For example, wearable devices like power assist suits that augment physical capabilities can support the labor participation and quality of life (QOL) of elderly and disabled individuals. Furthermore, remote operation combining robotics technology with ultra-low latency communication enables professionals with specialized knowledge and advanced skills to contribute regardless of their location. Furthermore, by using sensors to record the advanced techniques and tacit knowledge of skilled craftsmen and technicians as data, and then reproducing them via VR or AR, it becomes possible to effectively pass down traditional skills to the next generation. In this way, human augmentation possesses the potential to provide effective solutions to the various challenges facing modern society.

Additionally, from a technical standpoint, the rapid advancement of cutting-edge technologies such as AI, robotics, AR and VR, 5G, and 6G is noteworthy. Next-generation communication technologies like 5G Advanced, 6G, and All-Photonic Networks (APN), enabling low-latency, high-capacity data transmission, form the essential foundation for real-time interaction. This allows users to experience events in remote locations or virtual spaces with a sense of presence, as if they were right before their eyes. AI's advanced data analysis and learning capabilities dramatically extend human cognitive abilities, supporting faster and more accurate decision-making. Furthermore, the development of increasingly compact and lightweight high-performance sensors and actuators, coupled with battery technologies enabling extended operation, is accelerating the practical application of wearable devices and robots. Through these diverse technological innovations, human augmentation is transitioning beyond an abstract concept to the stage where it is being delivered as concrete products and services in reality.

Against this backdrop of heightened interest in human augmentation driven by social and technological factors, the Human Augmentation Consortium (hereinafter referred to as the Consortium, https://human-aug.com/) was established in December 2024. This initiative forms part of the third phase of the Strategic Innovation Promotion Program (SIP), a national project led by the Cabinet Office, specifically under the initiative "Development of Foundational Technologies and Rules for Expansion of the Virtual Economy[1]." This Consortium aims to solve societal challenges by promoting the social implementation of human augmentation and expanding its ecosystem. Participants engaged in R&D and business development from diverse industries, universities, and research institutions are working together through cross-industry and industry-government-academia collaboration. Their activities include creating use cases, demonstrating applications, devices, and platforms while verifying connectivity, promoting international standardization of human augmentation technologies, and disseminating information through symposia and other events.

1.1 Purpose and Overall Structure of the White Paper

This consortium has published this white paper to accelerate the societal implementation of human augmentation, its founding purpose. Human augmentation comprises diverse technological elements, with applications spanning broad fields including healthcare, education, industry, and entertainment. Implementing such a concept with extensive application domains into society requires the entire society to share a common understanding of human augmentation. Furthermore, it is necessary to carefully advance dialogue about the changes human augmentation will bring to life and society, objectively presenting both its benefits and risks. This white paper aims to serve as an aid in promoting this understanding and facilitating such dialogue. The intended readers are students and working professionals interested in solving societal challenges through human augmentation.

[1] https://sip3.nedo.go.jp/virtual/en/index.html

The structure of this book is as follows. First, Chapter 2 defines terminology. Chapter 3 then defines the concept of human augmentation, illustrates the changes it brings to daily life and industry through various use cases, and provides an overview of the entire range of supporting technologies. Chapters 4 through 6 then introduce initiatives by consortium members regarding elements enabling human augmentation—such as devices, cloud applications, and platforms—from perspectives including physical, perceptual, cognitive, and existential augmentation. Chapter 7 covers the consortium's efforts to foster the creation and demonstration of use cases, while Chapter 8 addresses the international standardization of technologies and specifications essential for ecosystem expansion. In addition to the efforts of existing international standardization bodies, this chapter also introduces the consortium's own standardization activity policies. Chapter 9 discusses the ethical, legal, and social issues (ELSI) that are crucial for achieving societal acceptance. Finally, future challenges and prospects are presented.

Note that this document is a living document and will be revised periodically based on discussions within the consortium and with other stakeholders.

2. Definition

The main terms used in this document and their definitions are listed below (Table 2-1).

Table 2-1 Definition

terminology	Definition.
Use case	・ A series of scenarios realized through human augmentation technology (see Chapter 3) that contribute to solving societal challenges.
System	・ A combination of devices, platforms, applications, etc. that work together to realize use cases.
End user	・ Humans interacting with the system. ・ Users include end users who directly benefit from the benefits provided by the use cases and administrative users who manage the system in whole or in part.
Device	・ A device that grasps the situation in the real world (e.g., sensing the state of the environment and objects, human movement and condition, etc.) and works on objects in the real world (e.g., working with robots, supporting human movement with actuators and exoskeleton suits, etc.).
Device applications	・ Software installed in devices to control device behavior (sensing, actuation, etc.) and user interface according to use cases.
SDK	・ A set of libraries, tools for application development, and documents that provide common functions for device applications.
Cloud applications	・ Software that delivers services and content from the cloud. ・ In this document, it refers to data collection and analysis services in metaverse (3D space, objects and agents), online shopping sites, cloud computing, etc.
Platform	・ Software that aggregates functions common to multiple use cases and provides them in the cloud. ・ Common functions include authentication, device management, management of user data (body data, operation logs, etc.), relaying of sensing/actuation data and operation data transmitted by devices, and absorption of individual differences in body size and sensation during relaying.

Session	・ A place established by a device-to-device or device-cloud application pair or group to send and receive data in real time. ・ The data transmitted and received includes sensing/actuation data, remote control instructions and response data, etc. ・ Sessions may be relayed on the platform.
Interface	・ Messages exchanged between devices, platforms, cloud applications, device applications, SDKs and hardware, and rules for data formatting and the order in which messages are sent and received. ・ The interface between the device application and the SDK is specifically called the API (Application Programing Interface).

3. Overview of Human Augmentation

3.1 What is Human Augmentation?

Human augmentation holds the potential to solve various challenges facing modern society. Consequently, diverse players from academia, industry, and both domestic and international spheres are engaged in research, development, and commercialization efforts. Human augmentation encompasses not only "enhancement"—dramatically improving inherent human capabilities to enable previously impossible activities and experiences—but also "compensation"—restoring functions impaired or lost due to illness, accidents, or aging.

Today, multifaceted discussions are underway regarding how to augment and supplement human capabilities and existence. These approaches can generally be categorized into four types: "enhancement of physical capability," "perceptual enhancement," "cognitive enhancement," and "extension of existence" (Figure 3-1) [1].

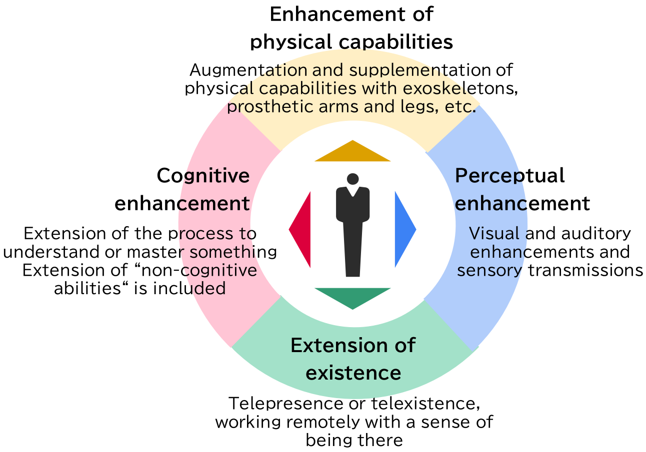


Figure 3-1 Typology of human augmentation

- **Enhancement of physical capabilities** refers to the artificial enhancement of physical strength, athletic ability, endurance, and similar capabilities. Specific examples include enhancements using powered suits, assistive suits[2], exoskeleton robots, and prosthetic devices such as artificial limbs. These technologies hold potential as effective solutions to challenges like the shrinking workforce and increasing physical strain in caregiving and medical settings.

[2] Powered suits and assist suits are both exoskeletal or garment-type devices worn by humans to enhance and support physical capabilities. The former utilizes power sources such as motors to provide powerful assistance, while the latter employs mechanical elements like springs and rubber, or pneumatic systems, to deliver relatively minor assistance.

- **Perceptual enhancement** refers to enhancing the sensitivity of human senses (vision, hearing, smell, taste, touch) and proprioception (such as the sense of force and proprioception), or transmitting sensory information from virtual spaces or remote locations for recording or sharing with other people or objects. It also includes using devices that assist vision and hearing to support individuals with visual or auditory impairments in acquiring information, thereby further promoting their social participation.

- **Cognitive enhancement** refers to supplementing and enhancing cognitive functions such as memory, calculation ability, thinking ability, and learning ability. Furthermore, it includes supporting the very process by which humans achieve understanding and mastery by expanding "non-cognitive abilities"[3] such as perseverance and self-control toward achieving goals, and the ability to persistently pursue objectives.

- **Extension of existence** refers to expanding the scope of human activities beyond the constraints of time and space, including into virtual environments. Examples include teleoperation—manipulating objects in distant locations in real time while experiencing them as if present (telexistence)—interacting with others through avatars in virtual spaces, and recording and sharing personal abilities and experiences via wearable sensors.

[3] 1) Goal achievement, 2) Collaboration with others, and 3) Emotional control abilities [41], encompassing elements such as 1) perseverance, self-restraint, and passion for goals; 2) sociability, respect, and compassion; and 3) self-esteem, optimism, and confidence.

3.2 Use Cases

Each type of human augmentation has various use cases and can be an effective means of solving a wide range of social issues. The following table shows the classification of use cases for each type, their overview and specific examples, and how they contribute to solving social issues (from Table 3-1 to Table 3-4).

Table 3-1 Use cases for enhancement of physical capabilities

Assistance in exercise and reduction of physical load		
	Summary	Assist physical exercise or reduce physical strain from heavy lifting or prolonged work.
	Example	• Powered suits and assist suits reduce the physical burden of carrying heavy and repetitive materials and improve work efficiency at construction sites and logistics warehouses. At nursing care sites, they assist in lifting and moving those in need of care, greatly reducing the physical burden on caregivers. • Prosthetic legs for athletes (plate spring type) to assist people with disabilities to participate in sports. Enables patients who have difficulty moving their limbs to operate robotic prosthetic arms and legs by sensing brain waves and myoelectric potentials. 
	Social issues	In **response to labor shortages caused by the declining birthrate and aging population, the** project will support the employment of people who have had difficulty finding work due to physical limitations and **promote further social participation of diverse human resources**. It will also contribute to reducing the number of occupational accidents and the burden on caregivers.
Support for rehabilitation and training		
	Summary	Support rehabilitation for recovery of physical functions and training of athletes to maximize their effectiveness.
	Example	• For patients with paralysis in their limbs due to the aftereffects of a stroke, a rehabilitation program adjusted in difficulty according to their individual conditions is provided, and an assist suit is used to aid movement and promote effective functional recovery. • Precisely analyze players' movements with motion capture and provide feedback on areas for form improvement and muscle areas that need to be strengthened; simulation training in a VR environment and instruction on correct movement using an assistive suit. For example, real-time analysis of running form and comparison with the ideal trajectory of a golf swing enable players to objectively grasp their own movements and improve them efficiently.  
	Social issues	It will improve the quality and efficiency of rehabilitation in an aging society and contribute to **extending healthy life expectancy**. It will also help professional athletes to improve their performance and prevent injuries, thereby **contributing to the improvement of their competitive performance**.

Table 3-2 Use cases for perceptual enhancement

Sharing and extending experiences and sensations		
	Summary	Beyond spatial and temporal constraints, the user shares various senses such as sight, hearing, touch, smell, taste, and even emotions, as if he/she were in the same place as others. In addition, the experience in the virtual space is reproduced not only visually and aurally, but also tactile, olfactory, and gustatory senses.
	Example	**Sharing experiences and sensations with others.** • In online conversations with family and friends who live far away from each other, sharing the sense of touch enables communication that involves physical contact, such as shaking hands or tapping each other on the shoulder. • By sharing the senses of sight, hearing, touch, smell, and taste in real time during a trip, others can also deeply experience the attractions of the destination. In addition, by recording and replaying data related to these five senses, it is possible to look back on the experience with a sense of realism after the trip. • By sharing with the audience the visual, auditory, and tactile senses of a professional musician during a performance or a professional athlete during a game, the audience can experience the performance or game from a first-person perspective. **Extended experience and sensory perception in virtual space** • In interacting with animals on the metaverse, the value of the experience is enhanced by reproducing the sensation of a bird perching on one's arm or a dog being pulled on a leash while being walked. • Confirm the feel of clothing or crafts on sale in online shopping with a handheld device to help make purchase decisions. Confirm the aroma and taste of food and wine with an olfactory/gustatory reproduction device prior to purchase.  
	Social issues	It alleviates the sense of isolation and lack of communication due to geographical separation, and strengthens bonds with family and friends. It also enables people who have difficulty going out due to illness or physical limitations to participate in society and enjoy a variety of experiences, thereby contributing to the promotion of social inclusion and improvement of quality of life (QOL). Furthermore , it may also promote cultural exchange and cross-cultural understanding.
Strengthening and complementing the senses		
	Summary	Enhancement of human perceptual abilities, such as the strengthening of sensory acuity in vision, hearing, and other senses, and supplementation of senses that have declined due to aging, disease, or disability.
	Example	**Strengthening of the senses** • Enables automatic selection and listening back to important information and announcements such as hospital calls, flight information at airports, train delay information, etc., when you are concentrating on something. • Enables the enhancement of certain sounds in noisy environments and the sensing of faint sounds in remote areas for disaster relief and security purposes. • Devices that augment vision are used to improve the efficiency and safety of inspection work in factories. This enables improved visibility in the dark and detection of minute defects that are difficult to identify with the naked eye. **Complementary to the senses.** • Smart glasses for the visually impaired recognize objects in their surroundings, read information aloud, and warn them of danger, helping them to be independent in their daily lives. • Cochlear implants and sophisticated hearing aids for the hearing impaired enable sound perception and reduce barriers to communication.  
	Social issues	It promotes social participation and improves the quality of life of the elderly and people with disabilities. In addition, in certain professions, such as disaster relief, security, acoustic engineers and geological surveyors, the detection of microtonal sounds will improve work accuracy and assist in early problem detection, contributing to reductions in working hours and man-hours.

Table 3-3 Use cases for cognitive enhancement

Support for the acquisition of skilled techniques and traditional skills	
Summary	To support the acquisition of skilled techniques based on long years of experience and intuition, and traditional skills that are difficult to pass on, in order to ensure their survival and development.
Example	• Sensors measure the hand movements and gaze of tea ceremony instructors, professional cooks, and skilled craftsmen, and reproduce them in a VR/AR space. Facilitate efficient learning by allowing learners to observe and relive the experience. • In training for playing a musical instrument, a glove-shaped exoskeleton device is worn, and the device's feedback guides the player to correct movements and points out inappropriate finger use, helping the player to improve in a short period of time. 
Social issues	Contribute to solving social issues **such as the decrease in the number of skilled technicians due to the declining birthrate and aging population, and the discontinuation of traditional skills due to a lack of successors**. This will **support the maintenance and improvement of industrial competitiveness and the inheritance and development of culture**.
Support for school education	
Summary	Reproducing the learning object on the metaverse enables intuitive learning that is difficult to achieve in classroom learning. Enable the progress and challenges of learning for children and students through digital ink.
Example	• 3D models of facilities to be studied, such as power plants, are faithfully constructed in the metaverse space, allowing students to explore the facilities and observe them from various perspectives, enabling them to intuitively learn how the facilities work.  • By having students work on tests and practice problems by handwriting with digital ink, the timeline logs of the digital ink can be used to track learning time, identify issues during learning, and improve instruction. 
Social issues	Enable students to **improve their learning effectiveness**, especially **in promoting independent learning**.
Increasing creativity	
summary	Supporting the power of imagination and idea generation to accelerate innovation in diverse fields such as design, the arts, and scientific research.
Example	• The pressure, speed, angle, and time of drawing, as well as biometric information (e.g., pulse and brain waves) during drawing, are recorded by digital pens and biometric sensors when writing down art creations and ideas. By analyzing these data with AI, it will be possible to extract relevant information that is effective for creation and ideation. The process of creation and conception can be shared with others and feedback can be obtained, leading to the creation of further creations and ideas. 
Social issues	Contribute to the **creation of new methods of expression in art and culture**.

Table 3-4 Use cases for extension of existence

Skill sharing and remote work (telexistence)

summary	Enable the use of expertise and technology and the execution of work from remote locations. Enables work that requires advanced skills and expertise, and work in/from hazardous locations that are difficult for people to access or where transportation access is limited.
Example	**Work requiring a high level of skill and expertise.** • Engineers in remote locations use robots to maintain and repair specialized machinery. Doctors and nurses remotely provide first aid to people with sudden illnesses in places where medical personnel are not available, using robots. • Experienced surgeons in remote locations will perform remote surgeries and provide guidance to junior doctors via robotic arms and VR/AR systems. • Professional chefs, instrumentalists, and tea ceremony adepts will remotely demonstrate cooking, performance, and tea ceremony via robot, providing local residents with opportunities to experience skills.  **Working in/from hazardous areas or areas with limited access to traffic** • Underwater repair and maintenance work on offshore wind power generation equipment and submarine cables, as well as repair and maintenance work on the moon and other space facilities, is performed remotely from the ground. • Robots are used to operate construction machinery and perform various tasks (assembly, harvesting, customer service, nursing care, etc.) at factories, farms, stores, and nursing care facilities by remote control. 
Social issues	Contribute to solving issues **such as the aging of skilled engineers, technical succession** problems **due to uneven regional distribution**, and the **shortage of human resources with** specific **expertise**. It will also contribute to correcting regional disparities and maintaining and improving industrial competitiveness. Furthermore, it will contribute to solutions to ensure the safety of human life in hazardous work and to the decrease in the number of skilled engineers.

Telepresence

Summary	It enables users to perceive remote situations in real time, act as if they were there, and interact with others even if they are not physically there. *It is envisioned that this will be done in combination with "sharing and expansion of experience and sensation" in the enhancement of perception.
Example	• It enhances the presence and immersion of online meetings and online calls with family members, providing an environment as if you were having a face-to-face meeting even between remote locations. 
Social issues	Create opportunities for everyone to freely participate in society, transcending physical limitations and social barriers. This will **contribute to the elimination of social isolation and the promotion of interaction with a diverse range of people**. It will also improve the efficiency of collaborative work between multiple people in remote areas.

3.3 Architecture

The various use cases of human augmentation will be realized through the integration of a wide range of technologies, including sensors, actuators, wearable devices, robots, VR/AR, and communication technologies. This section describes the technological architecture envisioned by the Consortium and its components as a means to realize various use cases of human augmentation.

3.3.1 Components and Examples of Operation

Figure 3-2 shows the overall architecture envisioned by the Consortium.

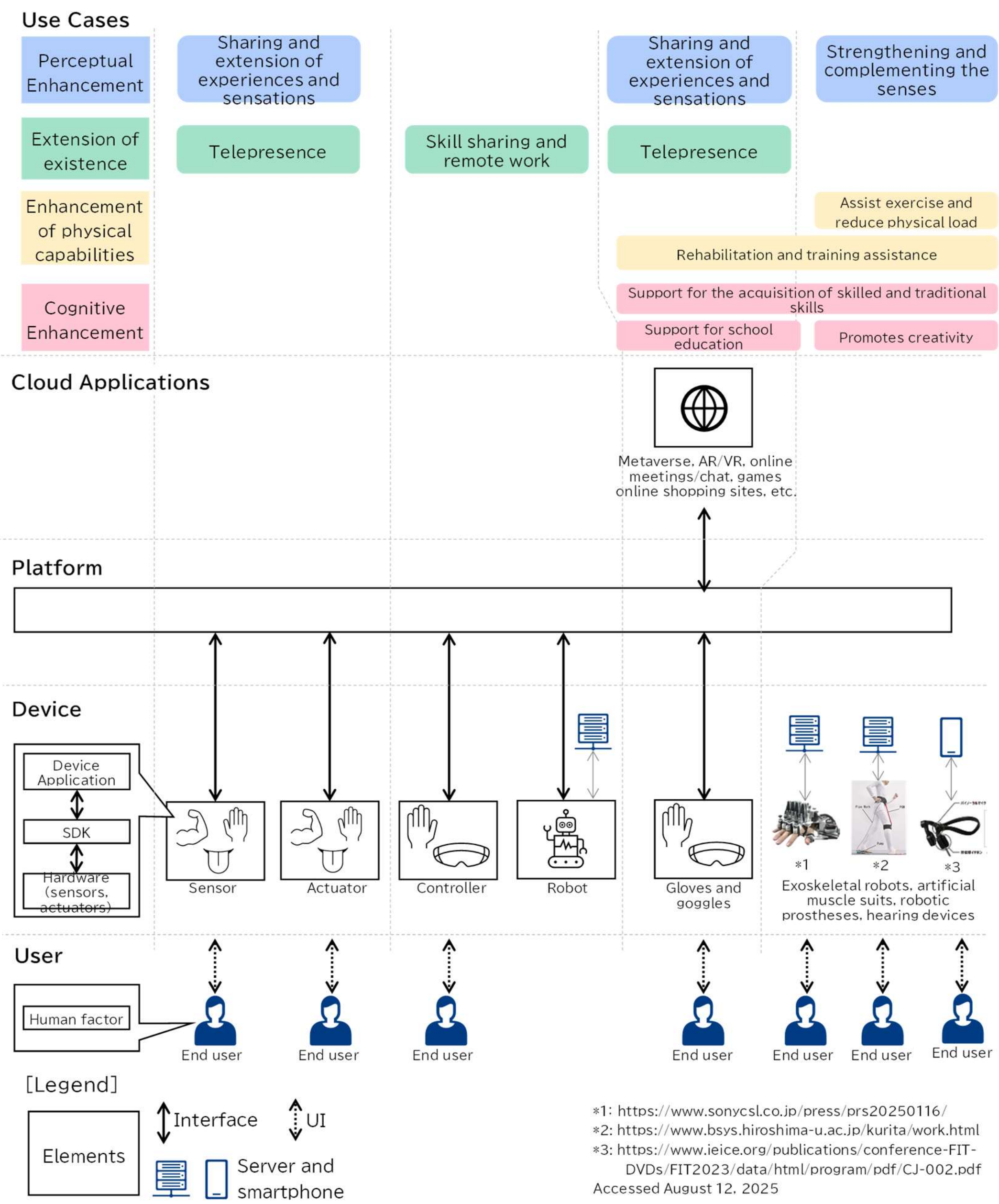


Figure 3-2 Overall architecture

The architecture shown in the figure is comprehensively configurable for various use cases of human augmentation. The components of the architecture are as follows

① **End users** benefiting from use cases
② **A platform that** consolidates functions common to multiple use cases
③ **Cloud applications that** provide services and content in cyberspace
④ **Devices for** understanding and working with real-world situations
⑤ **Interfaces** between the above elements, including user interface (UI)
⑥ **Communication networks where** devices, platforms, and cloud applications send and receive data

In the following, we provide examples of typical operation of each component to illustrate how this architecture realizes the Human Augmentation use case.

(1) Operation Example 1 - Unidirectional communication between devices

As a use case for sharing and extending experience and sensation, we envision a scenario in which a professional pianist's hand movements are shared with learners to help them learn to play the piano. An example of the operation of each component in this scenario is shown below. In this scenario, hand movement data is sent in one direction from the professional pianist to the learner (Figure 3-3 and Table 3-5).

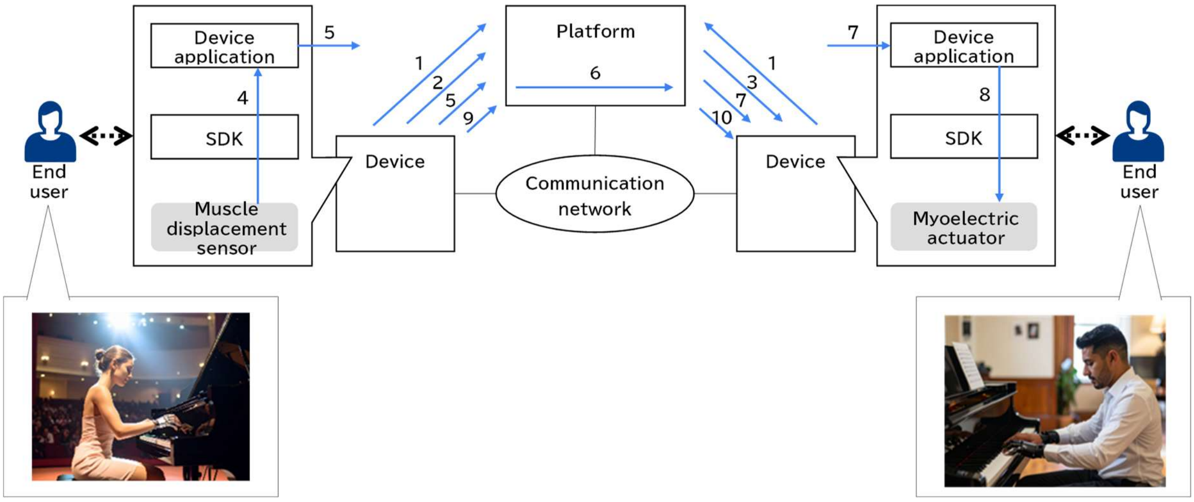


Figure 3-3 Operation flow of Example 1

Table 3-5 Operation flow of Example 1

No.	Operation Summary	Operation Details
1	Registering user and device information	・ Register user and device information to the platform in advance
2-3	Establishing a session	・ Specify who you want to share the performance experience with and request the platform to initiate the session ・ Platform discovers sharing partner and forwards session start request ・ Session is established when the other party grants the session initiation request
4-5	Reading and transmitting sensing data	・ Sensor reads muscle displacement data during performance and sends it to the platform
6-7	Conversion to and transmission of actuation data	・ Converts muscle displacement data into myoelectric actuation data on the platform and transmits it to the other side.
8	Actuator drive	・ Drives myoelectric actuators using data received from the platform
9-10	End of session	・ Session ends at the end of the sharing of performance experiences

(2) Operation Example 2 - Bidirectional communication between devices

As a use case for skill sharing and remote work (telexistence), we assume a scenario in which a medical professional wearing goggles and gloves operates a robot in a remote location to provide treatment. An example of the operation of each component in this scenario is shown below. In this scenario, hand movement data is sent from the medical worker and video data is sent from the hand robot side, and two-way communication is performed (Figure 3-4 and Table 3-6).

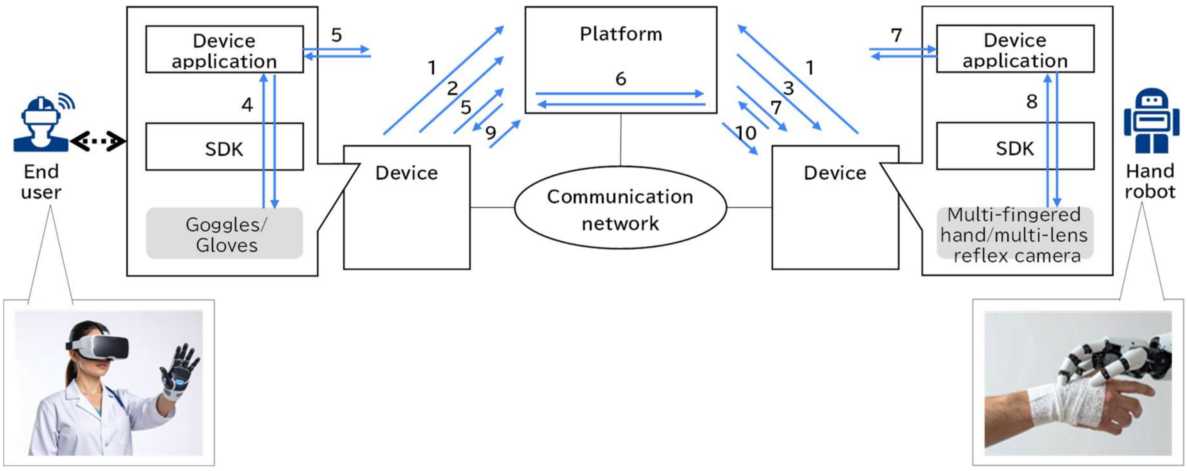


Figure 3-4 Operation flow of Example 2

Table 3-6 Operation flow of Example 2

No.	Operation Summary	Operation Details
1	Registering user and device information	・ Pre-register end-user and device (end-user goggles, gloves, and hand robots) information with the platform
2-3	Establishing a session	・ Specifies a hand robot to be remote-controlled and requests the platform to start a session ・ Platform discovers the hand robot to be operated, confirms operating authority, and forwards a request to start a session ・ Session is established when the hand robot receives and responds to a request to start a session
4-5	Reads and transmits hand movement data Video data reception and playback	・ Reads hand movements from end-user's glove and sends data to platform ・ In addition, video data from the hand robot onboard camera is received from the platform and played back on the goggles.
6	Relay of hand movements and video data	・ Platform relays hand movement and video data between end-user and hand robot
7-8	Driving hand robots and transmitting camera image data	・ Estimates end-user intent from hand movement data received from the platform, generates control signals, and drives the hand robot ・ Transmission of camera image data to the platform
9-10	End of session	・ Session ends after completion of remote work

3.3.2 Interface and Data

A list and overview of interfaces (IFs) between each component is shown below: a and b are IFs via the communication network, and c and d are IFs inside the device, which are API and hardware (HW) IFs, respectively. Although a and b are assumed to have the same functions at present, they are defined as separate IFs in anticipation of future expansion (Figure 3-5 and Table 3-7).

One of the reasons for clearly defining IFs in this architecture is that standardization of IFs is essential for the social implementation of human augmentation and the expansion of the ecosystem. As a result, it will be easier for new players to enter the market and for existing assets (devices, platforms, etc.) to be used for new use cases. The standardization efforts of the Consortium are described in Chapter 8.

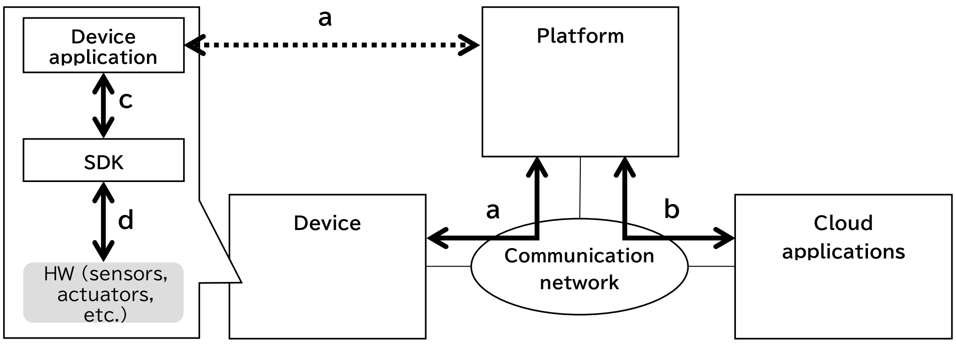


Figure 3-5 Interface list

Table 3-7 Interface overview

Location	IF	Purpose	Data to be sent and received on the IF
a, b	a/b-1	Register/update/ delete end user information	・ End user attribute information (sex, age, physique, etc.) and authentication information such as ID
	a/b-2	Device, cloud application Register, update, delete information	・ Information about the ID and capabilities of the device/cloud application (e.g., format of data that can be sent and received)
	a/b-3	Session management (build/close)	・ IDs of end users and devices/cloud applications comprising the session
	a/b-4	Sending and receiving session data	・ Sensing actuation data*. ※ data on sensory (audiovisual, taste, smell, touch) and end-user physical actions, equipment operation, etc. ・ Application data for content service provision*. ※ For example, data on buildings, avatars, objects, etc. in the metaverse
c	c-1	Hardware control (e.g., reading data from sensors, instructing actuators to move)	・ Sensing actuation data ・ Information on hardware capabilities and status
d	d-1		

3.3.3 Platform

A platform is software that provides common functionality needed for multiple use cases of human augmentation. It operates in the cloud and provides functionality to devices and cloud applications via the network. Figure 3-6 shows an overview of the functions and interfaces provided by the platform.

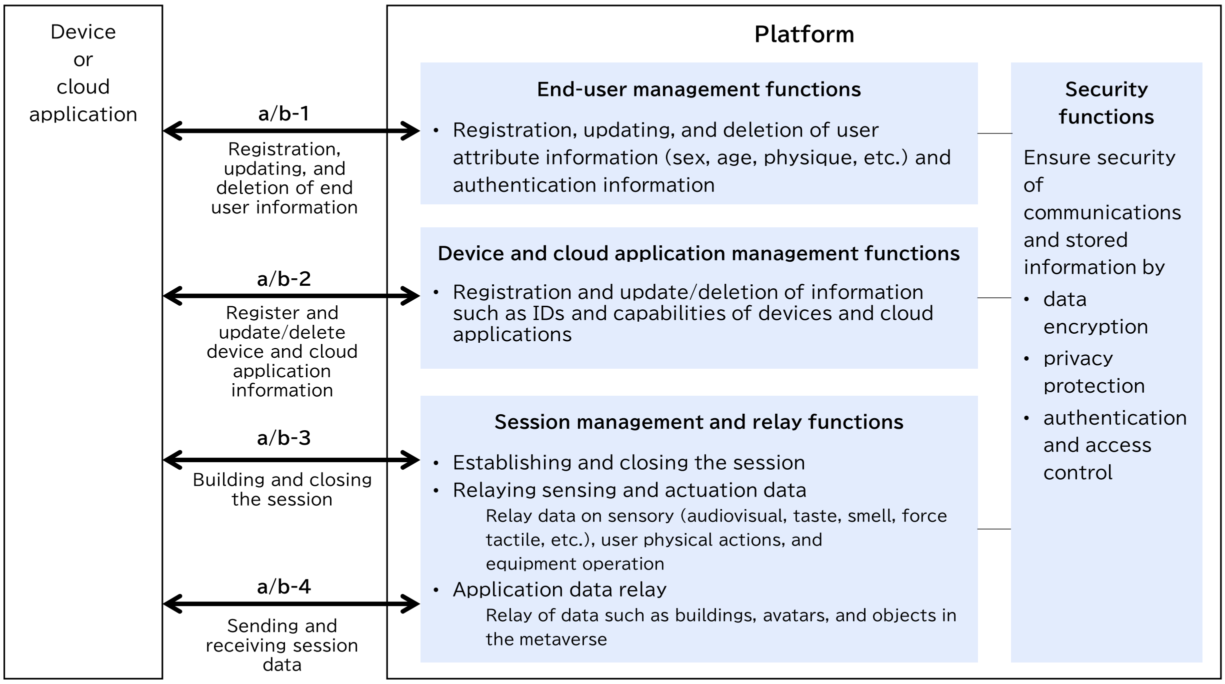


Figure 3-6 Platform functionalities and interfaces

One primary purpose of establishing a platform as an architectural component is to reduce service development and operational costs. The functions shown in Figure 3-6—such as managing end users, devices, cloud applications, and sessions, along with ensuring their security—are common requirements across a wide range of human augmentation use cases. By centrally providing these functions in the cloud, the need for new development and operation in each use case is eliminated, thereby controlling related costs.

Additionally, the platform's role in relaying sessions offers the advantage of facilitating seamless interoperability between diverse devices and cloud applications. Given the wide variety of devices and cloud applications used in human augmentation, it cannot be assumed that both parties involved in data transmission support common data formats or communication protocols. For example, in remote robot operation, it is conceivable that the controller and robot vendors differ, each using their proprietary standards. Even in such cases, the platform can enable data exchange by relaying the transmission, converting the source format into a format compatible with the receiver during the relay process. This expands the range of interoperable devices and cloud applications, broadening the spectrum of achievable use cases.

Furthermore, the platform's session relay function can be equipped with capabilities that go beyond data format and communication protocol conversion. For example, in the remote operation of robots shown in Figure 3-4, a function could be implemented to scale human movements up or down before transmission. This enables natural motion sharing even between humans and robots with differing ranges of motion, physical dimensions, and skeletal structures. Furthermore, for use cases involving the sharing of senses such as taste, smell, touch, and proprioception (e.g., weight and resistance sensations), a function could be considered that adjusts data to account for individual sensory differences (e.g., some people perceive spiciness or sweetness more strongly than others when eating the same food) before transferring it to the reproduction device. In this way, by having the platform perform data conversion during session relay that accounts for the characteristics of the transmitting/receiving devices and their users, the range of achievable use cases can be further expanded.

One of the efforts of the Consortium members is the "Human Augmentation Platform" of NTT DOCOMO, Inc. Details are provided in Chapter 6.

3.3.4 Device

In human augmentation, devices play two main roles. One is the sensor function that grasps the situation in the real world, and the other is the actuator function that acts in the real world. The sensor function includes the ability to grasp the state of the environment and objects, as well as the movement and physiological state of a person. Actuator functions include the execution of physical tasks by robots and motion support by exoskeleton suits and other wearable devices.

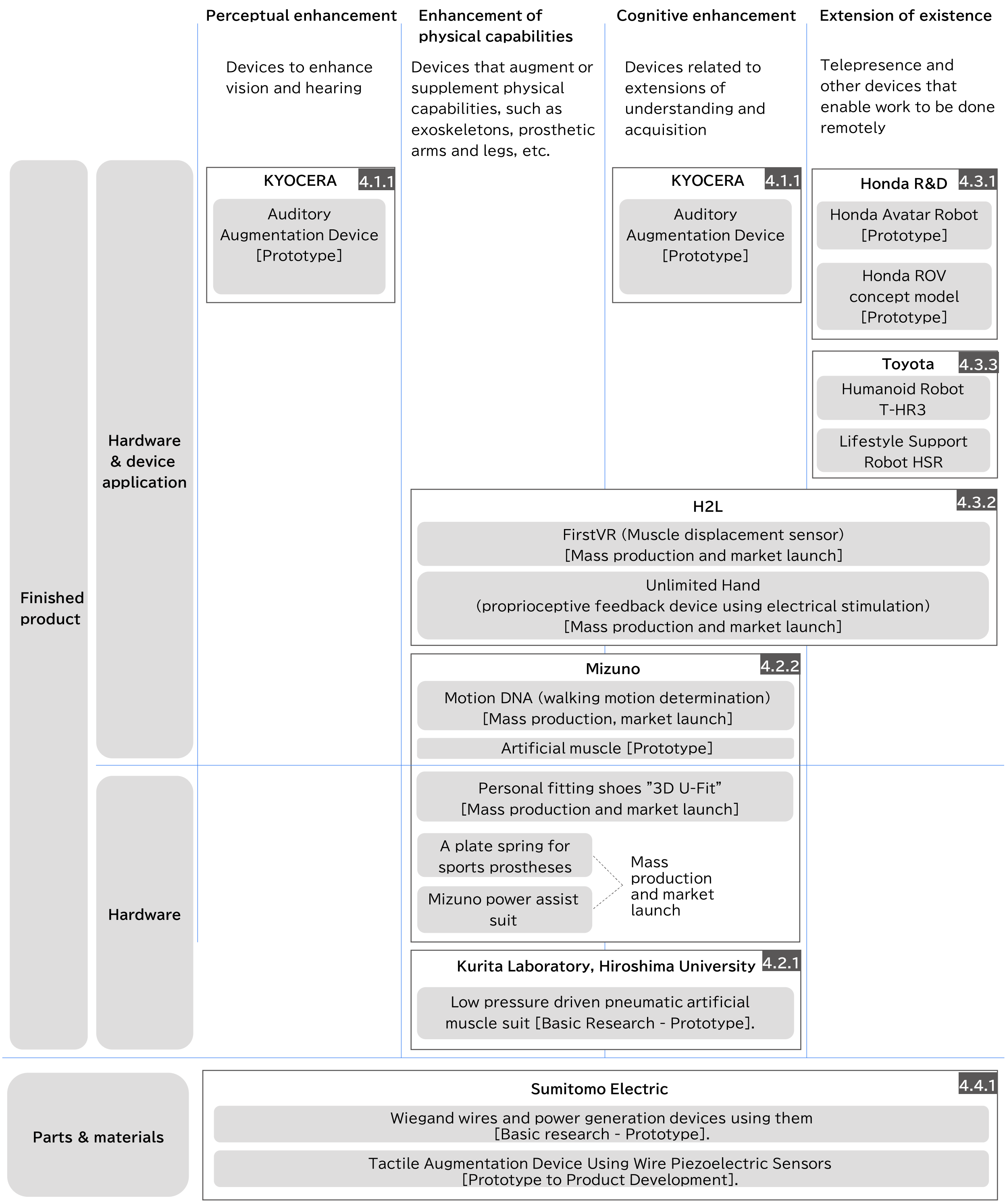
Devices used for human augmentation vary widely. Below are examples of the main devices used for each type of human augmentation.

- Enhancement of physical capabilities
  Examples are powered suits/assistive suits, exoskeletal robots, and prosthetics such as artificial limbs and feet to improve muscle strength and motor skills. These devices directly enhance the physical capabilities of humans, enabling them to carry heavy objects and perform precision movements.
- Perceptual enhancement
  Augmentation of vision includes devices such as smart glasses and VR/AR goggles that superimpose digital information on the real world or allow users to experience virtual spaces. Augmentation of hearing includes devices that amplify and extract specific sounds, such as ultrasonic and directional microphones, as well as hearing aid-type devices. Haptic augmentation includes haptic devices that generate tactile feedback. These devices enhance our understanding of the real world by making visible and audible information that is not directly perceivable or difficult for humans to perceive.
- Cognitive enhancement
  Examples are EEG (Electroencephalogram) sensors that measure brain waves, eye trackers that track eye movement, and other devices that can grasp the state of cognition, such as human thought, judgment, and memory. By using these devices to understand cognitive status, AI and cloud applications can provide appropriate information based on this information to support efficient decision-making and learning.
- Extension of existence
  Examples are remotely operated robots and controllers that operate them (e.g., glove-type devices that grasp hand and finger movements), and goggles that check images from robot-mounted cameras. These devices enable communication and activities with others beyond the constraints of time and space.

Companies in various industries and research institutions such as universities are currently engaged in the research and development of such devices, some of which have already been commercialized and introduced to the market. Figure 3-7 shows a list of devices being developed by members of the Consortium. The figure is classified mainly by the type of human augmentation targeted and by whether it is a finished product/component/material (i.e., whether it functions as a stand-alone product or is incorporated into another finished product). For finished products, the classification was further divided into those that include device applications and those that are hardware-only.

As shown in Figure 3-7, the consortium members cover a wide range of devices. However, there are also devices that are not covered by the current membership. For example, EEG sensors used to monitor brain status in cognitive enhancement, and robots used for specific purposes such as telemedicine robots and teleoperated construction machinery in existence enhancement are not included. The more diverse the devices that members are working on, the more active the discussions within the consortium will be, leading to the creation of new use cases and the acceleration of interface standardization. Therefore, it is hoped that more members will join the consortium to work on the development and commercialization of such devices.

The devices of each member shown in the figure are explained in Chapter 4.



The number on the right shoulder of each member's box indicates the section of detailed description. The number in [ ] indicates the development phase of the device. The meaning of each phase is as follows

1. Basic research	2. Prototype	3. Product development	4. Mass production and market launch
Scientific principles are being elucidated, new concepts are being explored, and research into basic technical elements is being conducted.	Stage of exploring the feasibility of specific devices based on findings from basic research	Stage of enhancing the product's degree of perfection with a view to mass production, based on the knowledge obtained from the prototype.	The product enters mass production and is introduced to the market.

Figure 3-7 List of consortium members' devices

3.3.5 Cloud Applications

Cloud applications refer to software that provides services and content from the cloud. Services and content include three-dimensional virtual spaces such as metaverse, online shopping sites, and data analysis and visualization services. In the following, we describe the main types of cloud applications used along the Human Augmentation typology.

- Enhancement of physical capabilities
  An application is envisioned in which data on human physical movements collected by a device is analyzed in the cloud to support improvements. For example, in sports training, an application could analyze a player's movements with a motion capture system and compare them with an ideal form to provide objective feedback on points for improvement in form and muscle areas that need to be strengthened. In rehabilitation, a possible application would be to generate rehabilitation programs on the cloud with a level of difficulty appropriate to the individual's condition, and link them to an assistive suit to promote effective functional recovery.
- Perceptual enhancement and extension of existence
  An application that reproduces experiences in a remote location or in a virtual space as if they were happening there
  is envisioned. For remote experiences, applications that share tactile information such as a handshake or a tap on the shoulder through a haptic device in addition to audiovisual information in communication with family and friends who live far away are conceivable. Another possible service would be to record and replay sensory information during a trip in the cloud and reproduce it in the metaverse.
- Cognitive enhancement
  Applications utilizing VR/AR are envisioned in skill transfer and school education. In supporting the acquisition of skilled and traditional skills, an application that analyzes the instructor's movement and gaze data on the cloud and reproduces them in a VR/AR space is conceivable. In school education, there could be applications that reproduce 3D models of learning objects such as power plants and plants in the metaverse and allow students to enter, rotate, zoom in and out, and observe them, so that they can intuitively learn about mechanisms that are difficult to understand only through classroom learning.

Figure 3-8 shows a list of cloud applications that members of the Consortium are working to develop. The cloud applications shown in the figure are described in Chapter 5.

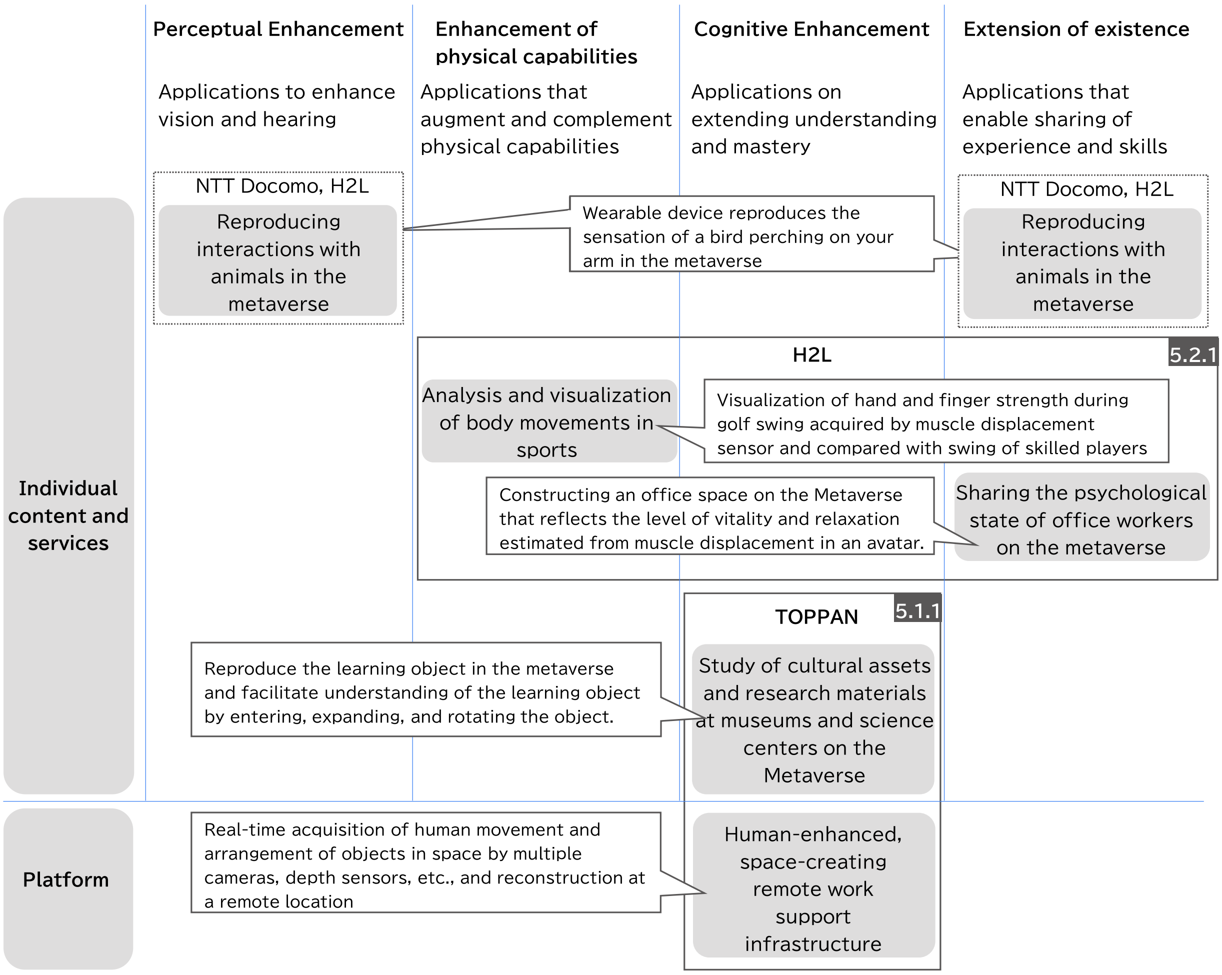


Figure 3-8 List of consortium members' cloud applications

3.3.6 Communication Network

In systems that enable human augmentation, the communication network acts like a nervous system that connects devices, cloud applications, and platforms and transmits information. The performance of the communication network has a significant impact on the quality of the end-user's experience with the system. Below we describe the main requirements for communication networks in human augmentation.

- Low latency, low jitter

  Delay and jitter (fluctuations in the timing of data reception) are factors that affect safety as well as the quality of the end user experience. For example, in teleoperation of a robot in telexistence, control data and sensor data are transmitted bidirectionally between the operator and the robot, and feedback control is sometimes performed to adjust control based on sensor measurements. In feedback control, the communication delay greatly affects the control performance such as the control cycle, etc. Therefore, the reduction of end-to-end delay and jitter between the operator and the robot is required for safe robot operation.

- Synchronization of multiple data communications
  This is an important requirement for use cases where multiple sensory information such as visual, auditory, and force-tactile information is transmitted in coordination, such as the aforementioned telexistence and experience/sense sharing/extension. For example, when operating a robot in a remote location, if video, audio, and force-tactile feedback are not synchronized (e.g., video and tactile information that should be received simultaneously is delivered out of sync), smooth operation becomes difficult. Even in the sharing and extension of experiences and sensations, the quality of the user experience will deteriorate if they are not synchronized. In cases where multiple end-users work together remotely (e.g., when multiple teleoperated robots jointly move heavy objects), synchronization of data communication is also required between end-users.
- Guarantee of communication reliability
  Low packet loss rate and uninterrupted communication are essential for stable system operation. In telexistence, especially in use cases such as telemedicine and lifesaving, high reliability must be guaranteed because communication interruptions or missing data can have fatal consequences. Otherwise, if control signals do not reach the robot, there is a risk of unexpected system behavior or loss of control. In addition to this safety perspective, a communication environment with guaranteed reliability is desirable from the perspective of improving the quality of the end-user experience.
- Wide communication area
  Securing a wide communication area will lead to diversified and attractive use cases, especially in telexistence and telepresence. For example, if stable communication can be established in hazardous areas and areas with limited access to transportation, as well as at sea, underwater, in space, and on the moon's surface, it will be possible to operate robots to perform rescue operations and inspect infrastructure without humans having to go there directly.
- Security
  Security is a requirement regardless of the use case. Since human

augmentation deals with data directly related to the human body, perception, and cognition, unauthorized access or data leakage can lead to physical harm and psychological effects as well as invasion of personal privacy. Improved security in communication networks is fundamental to ensure system reliability and to ensure that end-users can use human augmentation technology with confidence.

4. Device

4.1 Perceptual and Cognitive Enhancement

4.1.1 KYOCERA Corporation

(1) Auditory Augmentation Device

While concentrating on work, for example at an airport, have you ever missed an important announcement? Among the many sounds we hear each day, we naturally focus on those that seem most relevant, shifting our attention to understanding their meaning. An auditory augmentation device can alert you to important sounds you may have missed and give you peace of mind, knowing you can replay them at any time. For instance, you might want to replay instructions or conversations during work at nursing care facilities or hospitals, catch announcements or calls during telework, in passenger terminals or hospital waiting rooms, or replay foreign language conversations or quick memos for better understanding. In all these situations, the device ensures you can listen again, helping you stay informed and reassured [2] [3].Figure 4-1 shows the device and system of the Auditory Augmentation Device prototype [4]. The device has bone-conduction earphones and binaural microphones*. The AI system includes a "Ring buffer" that stores sounds over a certain period of time, "Event detection" that automatically detects sounds that the user does not want to miss, "Replay control" that allows the user to listen back to missed sounds, and "Sound processing" that performs noise reduction and speed adjustment during replay.

Recently, earphones are equipped with a range of features, including listening to music, people's conversations, and assisted hearing. In the future, we believe that the auditory augmentation device can be integrated into existing earphones. It will also help people maintain concentration and memory, as well as improve their health by monitoring their physical condition, and listen to only the sounds they want to hear from a wide variety of sounds [5] [6].

*Binaural microphones: two microphones are placed at the position of both human ears for recording to reproduce the condition of listening to sound with the human ear.

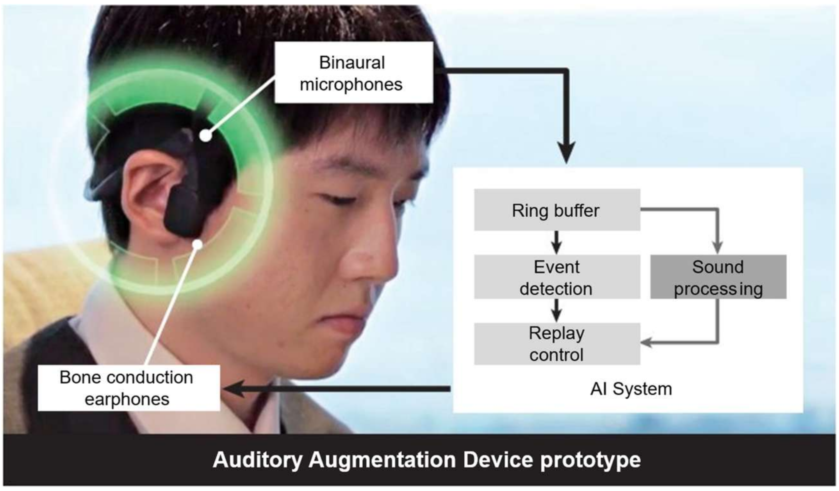


Figure 4-1 Auditory Augmentation Device prototype

4.2 Enhancement of Physical Capabilities and Cognitive Enhancement

4.2.1 Prof. Yuichi Kurita, Graduate School of Advanced Science and Technology, Hiroshima University

(1) Low-pressure-driven pneumatic artificial muscle suit

Motion support devices are generally classified into two categories: active devices equipped with actuators and passive devices incorporating spring or elastic elements. Active devices provide robust support and precise control; however, they require an external energy source—such as a battery, compressed gas tank, compressor—which increase bulk and weight and elevates installation and maintenance costs. Passive devices, in contrast, are typically more cost-effective and lightweight, and many configurations do not require an external energy supply. Although this makes them user-friendly and less prone to mechanical failure, passive mechanisms may, in certain applications, restrict rather than support natural motion. Consequently, next-generation exercise support suits should combine the advantage of both active and passive systems while reducing their limitations.

This section introduces the Pneumatic Gel Muscle (PGM), a low-pressure-driven artificial muscle developed to realize an exercise support suit that integrates these advantages. The PGM is structurally similar to conventional McKibben-type[4] artificial muscles, consisting of a pneumatic receptor that expands under pressure and a pantograph-shaped restraining structure made of orthogonally arranged, non-stretchable fibers (Figure 4-2). In traditional McKibben-type actuators, the pneumatic receptor and restraining section share the same natural length, causing radial and longitudinal expansion forces that oppose contraction, and as a result the actuator lacks elasticity when depressurized.

The PGM exhibits elasticity even without applied pressure by incorporating a pneumatic receptor whose natural length is shorter than that of the restraining section. Defining the fully extended configuration as the initial state enables operation with minimal circumferential elongation and longitudinal contraction, thereby reducing interference with the restraining section's contraction motion. The air receptor is fabricated from a highly elastic foamed styrene gel with a low

[4] The MacKibben type refers to a representative structural form of pneumatic artificial muscles. It consists of a rubber tube covered by a knitted sleeve, designed to allow air to be injected and expelled.

Young's modulus [5]. The foaming process enhances surface deformability, preventing obstruction of the pantograph structure's movement [7]. These material and structural characteristics have been applied in gait support systems [8], upper-limb assist devices (Figure 4-3) [9], and motion-training support technologies used in sports such as tennis, soccer and baseball (Figure 4-4) [10] [11] [12] [13].

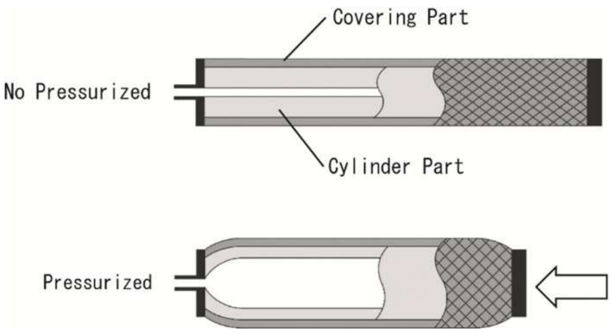


Figure 4-2 Structure of McKibben-type pneumatic artificial muscle

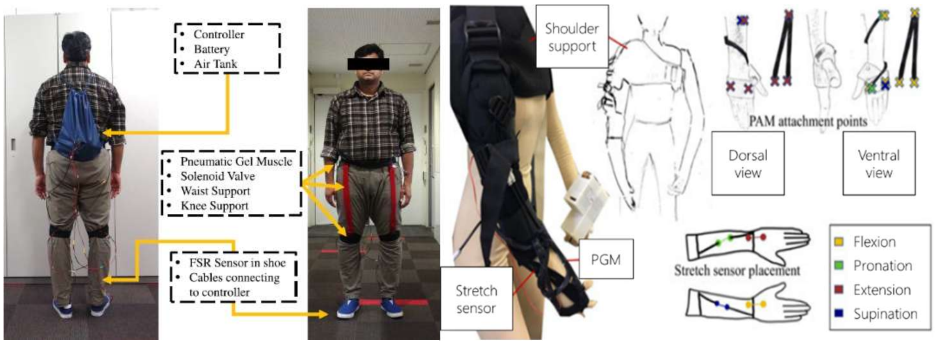


Figure 4-3 Examples of utilizing artificial muscles for gait support (left) and upper limb movement support (right)

[5] Young's modulus is the proportionality constant between stress and strain when a material is stretched or compressed by an external force.

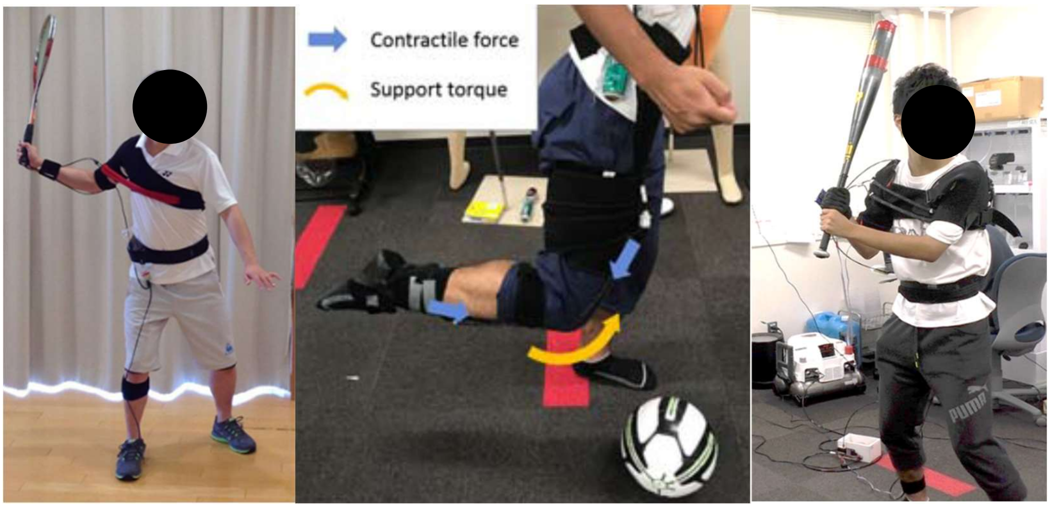


Figure 4-4 Example of application to support movement in sports

4.2.2 Mizuno Corporation

Through the fusion of Mizuno's sports technology and human augmentation technology, MIZUNO aims to realize a vibrant society in which everyone, including healthy persons, seniors, persons with disabilities, pregnant women, and children, can manipulate their own bodies freely, do what they could not do before, and adopt a positive attitude of trying everything that they want to do. (Figure 4-5) [14].

Figure 4-5 Attempts at social implementation of human augmentation technology in Mizuno

(1)　A plate spring for sports prostheses

We are working with Imasen Engineering Corporation (Gifu, Japan), a welfare equipment manufacturer, to develop a plate spring for sports prostheses(Figure 4-6) [15]. Plate springs for sports prostheses need to be fitted in various ways depending on the type and degree of disability and performance of the athlete who wears them. By making full use of the carbon processing technology that we have cultivated over the years through the development of baseball and golf equipment, as well as our expertise in various other competitive sports, we are developing springs that enable para-athletes to achieve higher performance.

In addition, by utilizing its expertise in manufacturing competitive a plate spring, the company has newly developed a lightweight, easy-to-handle plate spring as an entry-level model for first-time runners. By attaching a special sole to this plate spring, performance that can be used in top-level competition situations has been achieved. In addition, it is easy to replace the daily-use prosthetic foot and is less expensive than previous models.

Figure 4-6 Development of a prosthetic foot plate spring for sports use

(2) Mizuno Power Assist Suit

Many people working in the logistic and agricultural industry struggle with back pain. Lifting and moving heavy objects, especially from a position low to the ground, requires a massive exertion of force on the lumbar spine and pelvis, and can lead to injuries such as hernias, disk slippage and stress fractures. Mizuno developed the Power Assist Suit to reduce the daily physical strain on working people (Figure 4-7) [16].

First, focusing on heavy lifting, the load on the lower back caused by the lifting motion was analyzed using musculoskeletal simulation. Based on the analysis results, we identified the assist force required to reduce the load on the lower back by about 15%. Furthermore, by visiting sites where existing power-assistive suits are used and surveying the issues and needs, we identified three issues: "heavy," "difficult to move," and "expensive," as well as needs at sites where it is difficult to replace people, such as agriculture and logistics.

The Mizuno Power Assist Suit is characterized by its comfort. The suit itself is light and slim, weighing only 3.2 kg, and the wearable type feels as light as wearing a haori, while the non-electric mechanism using a spring power spring makes it so easy to wear that you will want to wear it every day.

Figure 4-7 Mizuno Power Assist Suit

(3) Motion DNA (scientific determination of walking motion)

It is generally said that there will be greater individual disparities in walking ability from 75 years old and beyond, and the number of people requiring assistance and care also increases from this age onward. However, there are also some who begin to experience a decline in walking ability from around 50 years old. In view of that, Mizuno has developed "Motion DNA" as a core theory that scientifically assesses and determines the walking motion. This will enable people to put in place measures to effectively maintain our walking ability from an early stage, so that we can live actively for a longer time.

The core theory of "Motion DNA" is the result of collaborative research between Mizuno and Professor Akira Iwata from the Department of Rehabilitation Science, School of Medicine at the Osaka Metropolitan University. Its most distinct feature is that it classifies the human walk into four categories based on their standing posture. The "walking characteristics" and "functions/parts needed for walking" vary between each type of walk, so knowing your walking category can help you to learn about the functions and parts that are required for walking(Figure 4-8) [18].

By analyzing the types of walks and walking abilities, Mizuno teaches training methods for strengthening one's walking ability efficiently and effectively, and provides products and services that provide optimal support for maintaining and enhancing walking ability.

Figure 4-8 Determination of walking motion by Motion DNA

(4) Personal fitting shoes "3D U-Fit"

Mizuno has developed the sports industry's first 3D printer technology to design and manufacture exclusive one-piece soles tailored to the individual.

It is known that many people have trouble choosing shoes because of wide or narrow feet, or different sizes from left to right, etc. However, the manufacturing process to date has been technically limited in that the sole, which carries most of the function of the shoe, cannot be easily changed to suit the individual.

"3D U-Fit" measures an individual's foot shape and creates an integrated sole according to that data, enabling the creation of original shoes that fit each individual foot. The sole also has a unique structure that reduces load by distributing the load on the sole and provides a unique cushioning sensation, offering a next-generation fit that is a step different from conventional fits (Figure 4-9) [19].

Figure 4-9 Personal fitting shoes "3D U-Fit"

(5) Artificial Muscle

Artificial muscle technology under research and development aims to play a key role in helping athletes improve their performance in competition and older adults maintain or improve their physical capabilities by enjoying healthy activities. Mizuno's approach focuses specifically on "dynamic adaptability" and aims to optimize the assistive force by taking into account the timing and location of the body in relation to its movements during sporting activities and daily life (Figure 4-10).

This approach overcomes the problems of conventional active and passive devices and enables more natural motion support. Specifically, by individually adjusting the support force according to the muscle strength and movement patterns of athletes and the elderly, it will be possible to support daily life and sports without excessive strain.

In addition, this artificial muscle is designed to be lightweight and compact, providing a high degree of convenience in daily use and in assisting exercise in sports situations.

Figure 4-10 Application of artificial muscle technology to the golf swing

4.3 Extension of Existence and Cognitive Enhancement

4.3.1 Honda R&D

Honda is developing avatar robots [20] [21] and ROVs (Remotely Operated Vehicles: remotely operated unmanned submersibles) [22] with the aim of extending oneself beyond by the constraints of time, location, and capability.

(1) Honda Avatar Robot

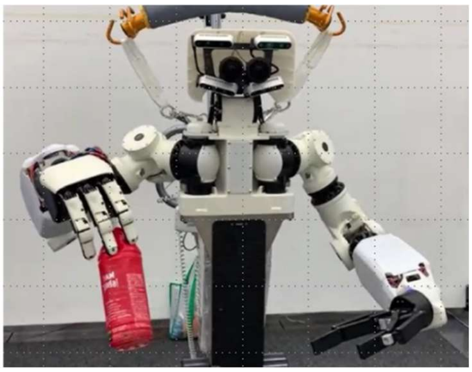


Figure 4-11 Avatar Robot

Avatar Robot Features and Technologies

High-precision operation with multi-fingered hand: Honda Avatar Robot is equipped with a multi-fingered hand whose structure closely resembles that of a human hand. Through devising and precisely controlling the drive system of the mechanical mechanism, it achieves 12 types of grasp taxonomies that cover 80% of daily-life tasks, as well as fingertip forces of up to 50N. As shown in Figure 4-12, the robot can now perform a wider range of tasks using the multi-fingered hand, thereby expanding the range of operations achievable by robots.

Figure 4-12 Daily-life tasks with a multi-fingered hand

AI-Supported Remote Control:

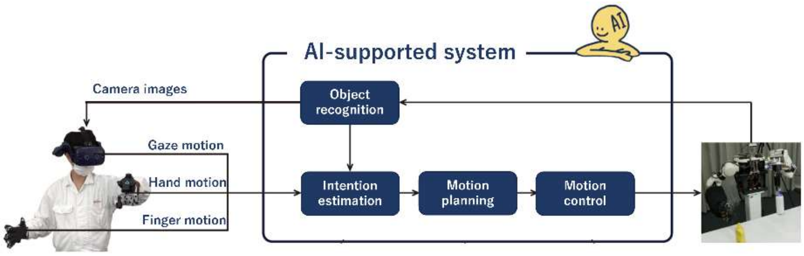


Figure 4-13 AI-supported remote control

Teleoperation using simple user interfaces such as HMDs and sensor gloves suffers from limited depth perception and lack of haptic feedback, making precise operation difficult for the operator. To address this problem, Honda developed AI-supported remote control, in which AI estimates the operator's intentions and supports operation. For example, when the operator brings the hand close to an object to grasp it, the system infers the operator's intent and automatically adjusts the hand pose, shape, and grasping force to ensure a stable grasp, even if the operator performs a rough grasping motion. This technology realizes smoother and easier execution of remote tasks through adaptive human-robot cooperation.

Case Studies

Honda's avatar robot enables the creation of free time for people to engage in creative work and allows activities in remote or hazardous environments. Since users can demonstrate their expertise without physically traveling, applications are expected in emergency medical care and high-priority equipment maintenance. Moreover, the robot can operate in disaster sites, outer space, and other environments that are difficult for humans to access, making its potential applications highly diverse.

(2) Honda ROV Concept Model

Figure 4-14 Honda ROV System Overview

ROV Features and Technology

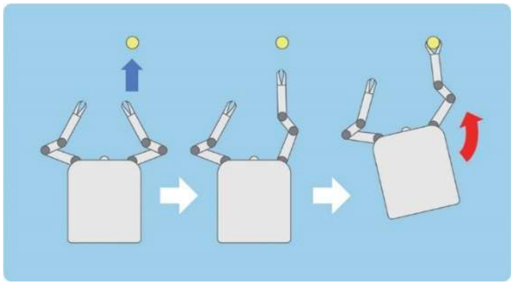


Figure 4-15 Manipulator and ROV Cooperative Control

Manipulator-ROV Cooperative Control: "Manipulator-ROV cooperative control" was developed by applying ASIMO's "Manipulator body cooperative control" technology. The main body automatically moves forward and adjusts its attitude in response to arm manipulation, thereby improving maneuverability. A deadband is introduced, and when the arm leaves this region, the vehicle is commanded to follow the arm based on DVL and IMU measurements. This technology stabilizes the hand position even under tidal currents and improves the accuracy and efficiency of cleaning and other operations.

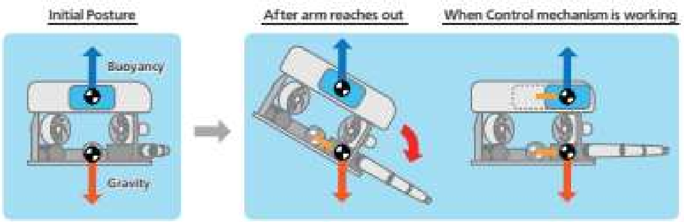


Figure 4-16 Mechanism to Control Center of Buoyancy and Center of Gravity

Mechanism to Controle Center of Buoyancy and Center of Gravity: In underwater environments, the ROV's attitude constantly changes due to currents and shifts in its center of gravity, requiring stable control. Traditionally, attitude was maintained using thrusters, but this posed issues such as response delay and the disturbance of seabed sediment.

Honda has developed a *center-of-buoyancy/center-of-gravity control mechanism* that adjusts the position of the buoyant material mounted on the upper part of the main body in the forward/backward and lateral directions to control attitude. By estimating changes in the center of gravity from IMU data and arm motion, and moving the buoyant material to generate restoring force, the system achieves energy-efficient and highly responsive attitude control.

Case Studies

The ROV performs offshore wind power maintenance tasks such as attaching and removing lifting gear(e.g., shackles) and cleaning underwater structures. This will help solve the shortage of divers and the difficulties of working in deep water, and enable efficient operations.

4.3.2 H2L Corporation

(1) FirstVR - Intrinsic Sensory Estimation by Muscle Displacement Sensor

Device Overview

H2L has developed a technology that uses optical muscle displacement sensors to estimate "proprioception," which forms the basis of human motor control and body sensation, from muscle status information in real time and as input to external systems. The wearable device "FirstVR" (Figure 4-17), equipped with this muscle displacement sensor, captures the bulging of the forearm and upper arm muscles (muscle displacement) in a non-contact manner to visualize the force level and intensity of movement in specific finger and arm movements.

Figure 4-17 Wearable device with muscle displacement sensor "FirstVR" by H2L

Device Features

The optical muscle displacement sensor in FirstVR estimates muscle displacement by the reflection of light, thus achieving stable sensing without being affected by sweat or electromagnetic noise (Figure 4-18) [23] [24]. In combination with an acceleration gyro and vibration mechanism, the sensor collects and transmits multidimensional body information.

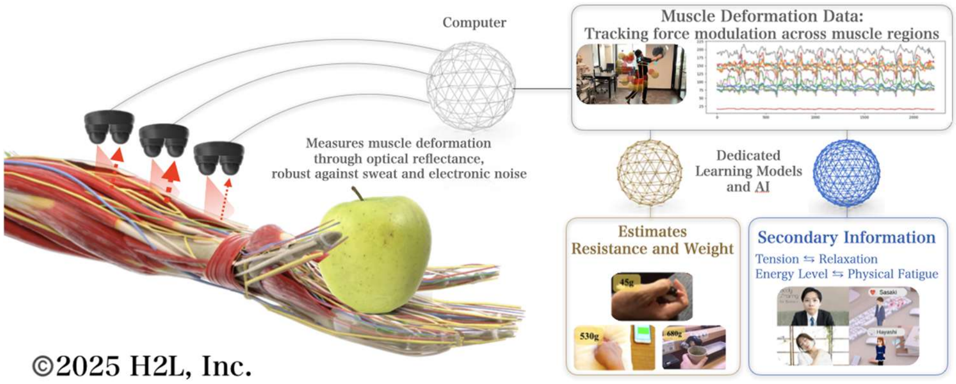


Figure 4-18 Principle of muscle displacement sensor and flow of estimating intrinsic sensory-related information from muscle displacement data

Demonstration of Use Cases and Characteristics

Analysis and Sharing of Sports Experiences (e.g., archery and golf)

Differences in force between expert and novice players are visually presented to share the sports experience. For example, based on muscle displacement data obtained from the forearm muscles during a golf swing, the strength of each finger is displayed as a color-coded sphere (Figure 4-19) [25]. Red indicates the strength of the index and middle fingers, while yellow indicates the strength of the ring and little fingers. The force distribution is biased toward the ring and little fingers in the swing of an expert and toward the index and middle fingers in the swing of a beginner. By visually presenting these differences, specific instruction for improving motor skills can be established.

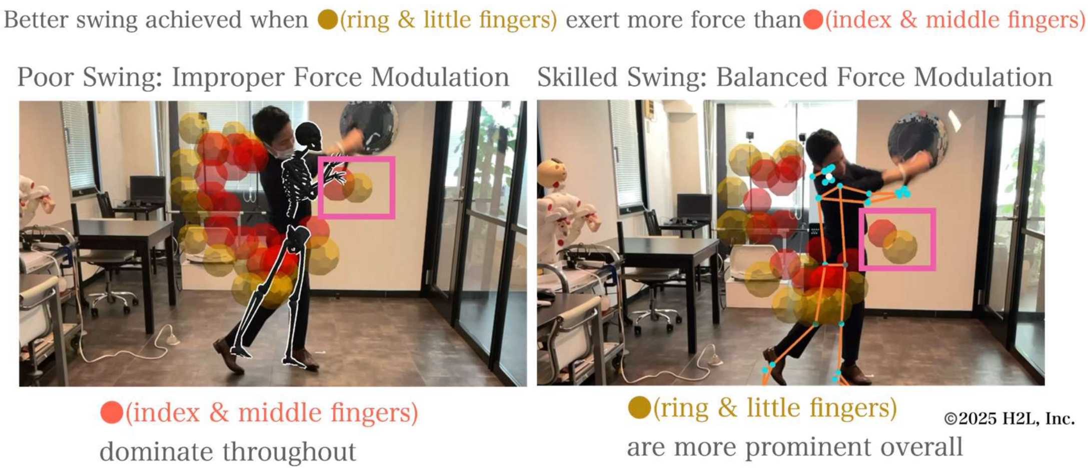


Figure 4-19 Visual presentation of the difference in force between skilled and novice sports experience

(2) UnlimitedHand - proprioceptive feedback via electrical stimulation

Device Overview and Features

UnlimitedHand is a wearable device developed by H2L for research purposes, which is worn on human limbs, body sides, front or back (Figure 4-20). In addition to the optical muscle displacement sensor described in the previous section, the device is equipped with an output mechanism (up to 8 channels) for proprioception through electrical stimulation, and is configured to handle proprioception from both input and output directions.

Figure 4-20 “UnlimitedHand” by H2L, equipped with an output mechanism of proprioception by electric stimulation in addition to muscle displacement sensor

Device Features

UnlimitedHand directly induces muscle contraction through noninvasive electrical stimulation, thus eliminating mechanical restraints while achieving the induction of fine movements (Figure 4-21) [26]. In addition, waveform control suited to the human body enables the reproduction of natural movements while reducing discomfort.

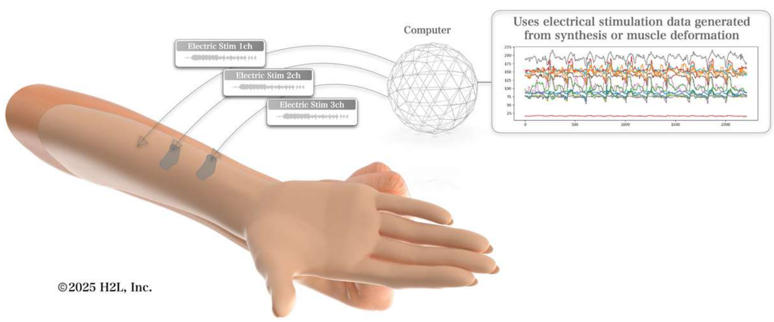


Figure 4-21 Principle of eigen sensory output from electrical stimulation and other eigen sensory outputs

"Sharing the Kayaking Experience in VR Space."

When the user wearing UnlimitedHand moves his/her arm, the paddle of the kayak displayed in the VR space moves in tandem, providing resistance feedback, one of the audiovisual and intrinsic senses, as if the user were paddling on the water in reality. In this configuration, the resistance sensation when the paddle is submerged in the water and the weight of the paddle pushing back the water are output as electrical stimulation to the forearms and upper arms.

For example, when the paddle is paddled deeply with the right arm, a moderate contraction signal is sent to the triceps muscle of the upper arm, followed by an interlocking stronger stimulus to the forearm flexor muscle group, which reproduces the action of pulling the paddle against the water pressure. Conversely, when the paddle is pulled out of the water, the stimulation is weakened as the muscle tension is released, and the body senses the end of the propulsive motion. In this way, the user's body receives information on the "weight of the water" and the "force applied to the propulsion" in a sensory way, which is integrated with the audiovisual information on the VR to enhance the sense of immersion (Figure 4-22).

Figure 4-22 Sharing kayaking experience on VR space by output mechanism of proprioception with muscle displacement sensor and electrical stimulation

4.3.3 Frontier Research Center, Toyota Motor Corporation

Frontier Research Center, Toyota Motor Corporation is conducting research and development of partner robots using robotics technology to realize “Mobility for All”. Using remotely piloted robots from a distance, research and development is being advanced with a variety of use cases in mind, including solving future social issues such as labor shortages, work support in harsh environments like extreme temperatures and disaster sites, where people cannot or find it difficult to go directly, enabling remote employment for people with disabilities, as well as applications in remote medical care, and agriculture.

(1) HSR (Human Support Robot)

This robot was developed for the purpose of life support in the home (housework support and nursing care support). In addition to supporting various in-home tasks autonomously, research and development is also underway to support housework and nursing care by remote operation, and to realize remote employment for people with disabilities (Figure 4-23) [27].

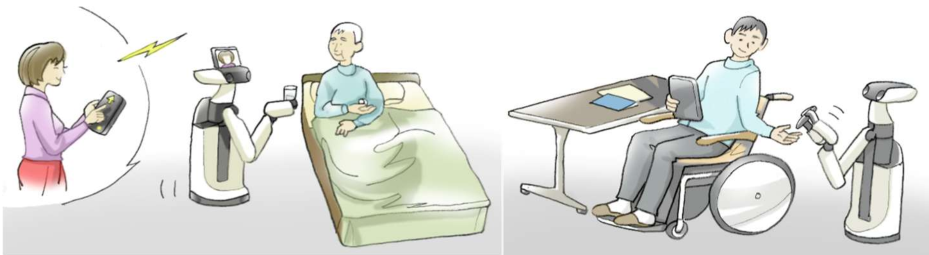


Figure 4-23 HSR remote support (left) / support for independence (right)

Hospitality Spectator Support Demonstration

As a demonstration for the realization of remote employment for people with disabilities, we conducted a demonstration in which people with disabilities communicated with visitors in wheelchairs to the event venue from remote locations through the robot to provide assistance in watching the games and photo services (Figure 4-24) [28].

Figure 4-24 Support for hospitality spectators (part of the figure was edited by Toyota Frontier Research Center)

The event site side and the remote control side were connected by a dedicated closed network to ensure security, while the robot side utilized temporary local wireless and 5G/LTE lines to achieve low latency, highly reliable communication and stable operation (Figure 4-25).

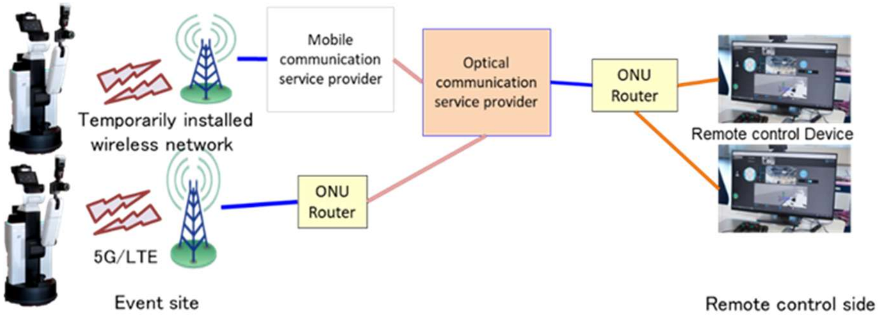


Figure 4-25 Hospitality spectator support system (communication system configuration)

After the event, one participant with a disability commented: "The entire period felt like a dream. Above all, it was my very first experience in customer service. I never imagined in my wildest dreams that I would one day be serving customers. Having resigned myself to pursuing only desk-based roles like clerical work when considering career options, I was astonished to discover that there is a path like this through robot-mediated work." Such robots can offer hope to those with limited job choices, transcending physical location. This confirmed not only the potential for daily living support but also the further possibility of creating employment opportunities.

Tele-operation AI assist by robot foundation model

A robot foundation model is a robot control model that can learn from robot motion data collected in diverse environments and can be used universally for a variety of tasks. While large language models learn from a large amount of text data, robot foundation models learn from sensor data and motion data in an integrated manner, enabling them to execute tasks in diverse real-world environments such as homes, factories, and medical care. They are expected to contribute to solving future social issues.

The development of this model requires a cycle of (1) large-scale data collection, (2) model training, (3) validation, and (4) additional data collection. For this large-scale data collection, teleoperation techniques are becoming especially important.

The resulting base model can be used to assist in teleoperation, and will be used to make the robot perform optimal behavior even with simple teleoperation [29].

Currently, the development of the basic model is being carried out in cooperation with the AI Robot Association (AIRoA) [30].

(2) Realistic Sensory Remote Control Robot System (HSR Telepresence Version)

Current robot remote control systems provide limited information to the operator and are far removed from the realistic sensation of direct operation by the operator. Therefore, we are conducting research and development to realize a remote-control system that can be applied to use cases where it has been difficult to achieve a realistic sensation as if the operator is working directly, even when working remotely via a robot from a distant location.


Figure 4-26 HSR telepresence version

To realize realistic sensation, we believe it is important to transmit various senses (five senses + α), improve the sense of presence and immersion, and reduce latency, and we are implementing these technologies in robots to verify their effectiveness (Figure 4-26).

Ultra Low Latency Video and Audio Transmission System

Figure 4-27 illustrates a system that transmits camera footage and microphone audio from a robot to the operator with minimal latency. The robot side uses a latency-free camera and microphone, along with an ultra-low-latency encoder, to convert the data into IP format. This is transmitted via a low-latency, low-jitter millimeter-wave band radio to the environmental radio, then relayed to the control unit via an optical network line. At the control unit, an ultra-low-latency decoder restores the original signal, outputting video and audio to the display and speakers. Currently, the delay from camera to display achieves performance well below one video frame. This realizes low-latency transmission where no perceptible delay is felt, even through the network.

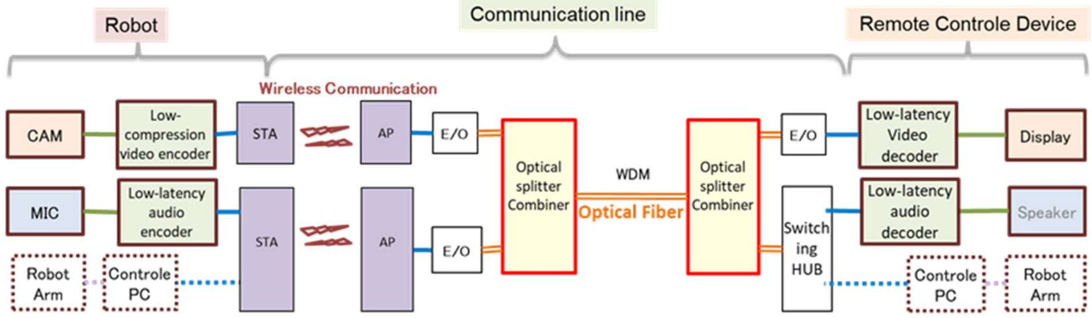


Figure 4-27 Ultra-low latency video and audio transmission system

When the camera image actually shown on the display is looped, it is repeated many times, demonstrating that there is extremely little delay (Figure 4-28).

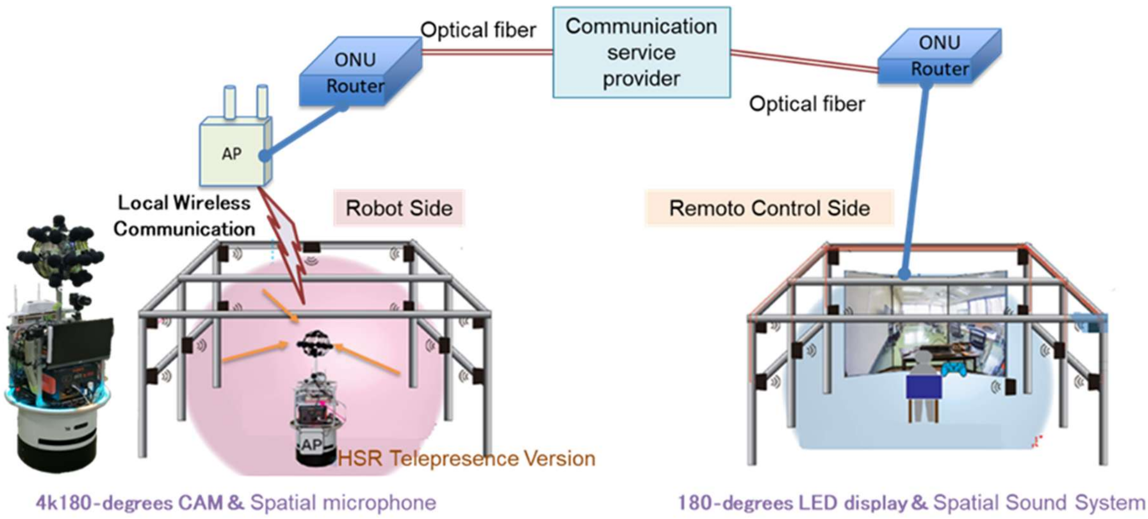
Figure 4-28 Ultra-low latency transmission of video (camera image is repeatedly displayed on the display)

Using this system, the operator is expected to be able to remotely control without experiencing any delay in video and audio. It is expected that this system will be effective for work with objects that move at high speeds and for use cases that require more precise movements.

However, there are currently performance issues such as delay and jitter in the radio system, and it is hoped that the next generation of radios to achieve even lower latency and jitter (required value of 1 ms or less).

Ultra-realistic and Immersive Experience System

This system transmits images from an ultra-wide-angle camera (180-degree field of view) mounted on the robot and sound from a 360-degree stereophonic sound harvesting microphone to a remote operator with ultra-low latency, greatly enhancing the sense of presence and immersion (Figure 4-29). The operator is provided with an unprecedented immersive experience through the wide field of view, large screen images, and immersive sound surrounded from 360 degrees. This creates the feeling that the operator is truly present at the robot's location [31].



This system was jointly developed with Mihal Communications Inc.
Figure 4-29 Ultra-realistic and Immersive Robot Remote Control System

Using this system, the robotic arm located remotely was operated to play a musical instrument and break a balloon, allowing operators to experience the sensation of being right there (Figure 4-31 and Figure 4-30).

This system was also capable of low latency two-way communication between remote locations using common optical lines, providing new remote communication possibilities.

Figure 4-31 Remote balloon-splitting operation

Figure 4-30 Remote Wind Chime Performance

Future plans

Currently, achieving a truly realistic control experience is still far from being realized. Going forward, efforts will focus on adding more sensory feedback that can be transmitted, enhancing immersion and presence, and improving the performance of wireless communication, which still faces many challenges.

(3) T-HR3 (Toyota Humanoid Robot 3)

This robot is a system that allows the operator to remotely control the robot while feeling external forces applied to the robot (Figure 4-32) [32]. A torque servo module (Figure 4-33), which can detect subtle torque, is built into each joint (Figure 4-34) of the robot, and the detected force is fed back to the operator in real time through the control unit that freely manipulates the robot's entire body. This allows operators to move the T-HR3 as if it were their own alter egos, enabling delicate work with its five-fingered hand.

Figure 4-32 Humanoid robot T-HR3

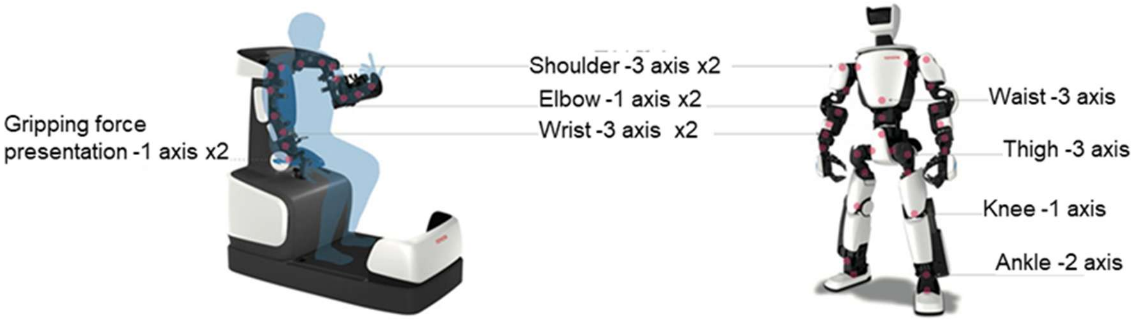


Figure 4-33 Torque Servo Module Layout

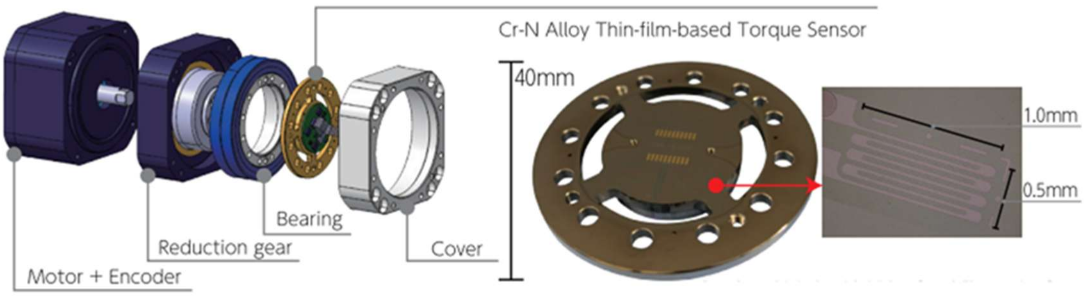


Figure 4-34 Torque Servo Module

4.4 Parts & Materials

4.4.1 Sumitomo Electric Industries, Ltd.

(1) Wiegand Wires and Power Generation Devices using them

Sumitomo Electric Industries, Ltd. (hereinafter referred to as "Sumitomo Electric") is focusing on power generation using changes in magnetic field as an energy source, particularly a method that utilizes Wiegand wire, which can generate power even with slow changes in the magnetic field, and is developing the wire, which is the key to this method. We believe that such power-generating methods can contribute to the realization of cable-free and battery-less devices for wearables and robotics.

The characteristic feature of a Wiegand wire is the rapid magnetization reversal (the Wiegand effect) that occurs when the magnetic field applied to it changes and exceeds a certain threshold value. By inserting a Wiegand wire into the center of a coil, this magnetization reversal generates a pulsed induced electromotive force through the coil. The magnitude of this pulsed power is almost independent of the rate of the magnetic field change, distinguishing it from the commonly used dynamo method of power generation, which has difficulty generating power at low speeds (Figure 4-35).

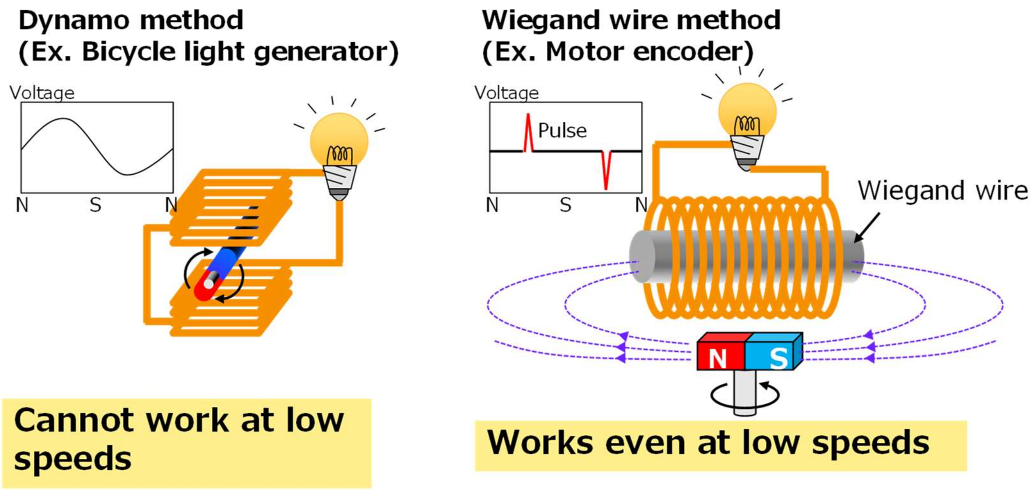


Figure 4-35 Comparison of power generation methods by magnetic field change (dynamo method and Wiegand wire method)

Daikoku Electric Wire Co.,Ltd., a subsidiary of Sumitomo Electric, manufactures and sells the Wiegand-wire type power generation device for servo motor encoders[6] under the name “Daikoku MG sensor™”(Photo 4-1). An example of its specifications is shown in Table 4-1. An encoder is a device that detects the rotation of a motor, and the Daikoku MG sensor™ is employed for this purpose. Permanent magnets attached to the motor shaft rotate with the shaft, generating pulse power to Daikoku MG sensor™, which serves as a signal for rotation information and provides the necessary power for integrated circuit (IC) writing (Figure 4-36). This setup allows the encoder to operate without requiring external power for IC writing. Encoders employing this technology have seen rapid adoption in recent years. Sumitomo Electric has successfully developed the Daikoku MG sensor™ by fully leveraging its alloy design technology and process design technology to control the metal microstructure in the development of high-performance Wiegand wires, combined with the advanced coil manufacturing and assembly technology of Daikoku Electric Wire. The sensor has received positive feedback from users and is regarded as being at the forefront of the industry in terms of size, performance, and reliability.

Looking ahead, we are exploring the possibility of using pulsed power for wireless transmission to broaden the range of application. We believe that this technology can be effectively used in wearable devices for monitoring human movement without the need for cables or batteries, and we will continue to advance the development of Wiegand wires to achieve the higher output power.

[6] A sensor that detects the rotational angle and speed of a motor shaft, used to perform precise position control.

Photo 4-1 Daikoku MG sensor™ made by Daikoku Electric Wire Co.,Ltd.

Table 4-1 Example of Daikoku MG sensor™ Specifications

	Item	Value	Conditions
Dimensions	External dimensions(mm)	W11.7max × D4.3 × H4.5	
Maximum rating	Operating ambient temperature(°C)	-30～110	
	Storage temperature (°C)	-40～125	
Signal characteristics (at ambient temperature 25° C)	Output voltage peak value*1	6 (Min)、7 (Typ)	
	Output voltage rise time (μs)	50 (Max)	
	Output voltage temperature coefficient (%/° C)	-0.1 (Typ)	
Electrical characteristics (at ambient temperature 25° C)	Inductance (mH)	7 (Min)、10 (Max)	15kHz:2V
	Resistance (Ω)	210 (Min)、230 (Typ)、250(Max)	1mA
	Resistance temperature coefficient (1/° C)	0.00393	

*1 : Guaranteed value at magnet rotational speed ≒ 0 rpm

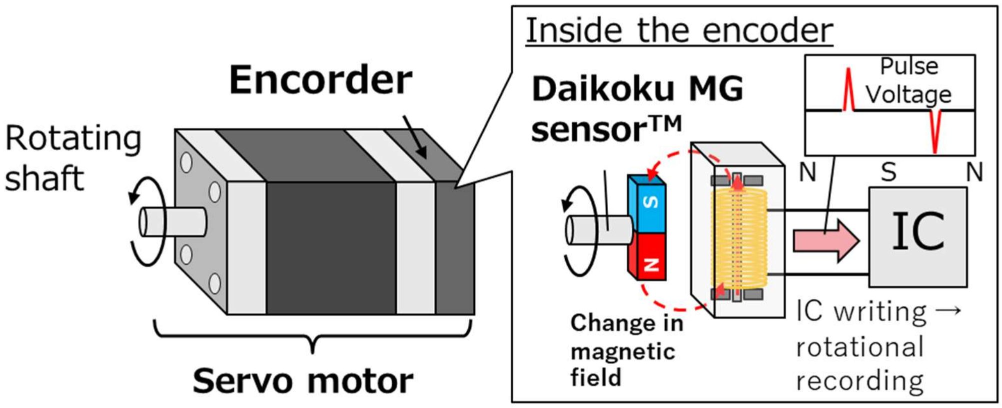


Figure 4-36 Role of Daikoku MG sensor™ in the encoder

(2) Tactile Augmentation Device using a Wire-shaped Piezoelectric Sensor

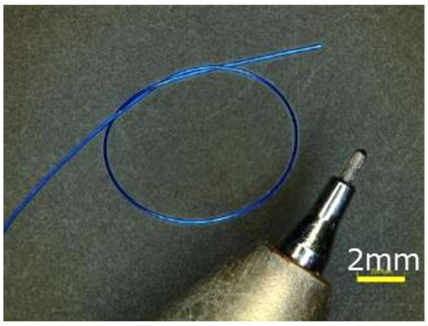


Figure 4-37 Wire sensor / Filasense™

Sumitomo Electric is a manufacturer of wires and cables. As the sensing target is becoming wider and wider, from points to lines and surfaces, the company is developing wire-type sensors that are easy to handle and install.

This product is a piezoelectric sensor in the form of an ultra-thin wire, a device intended for use on external surfaces and joints as a substitute for tactile sensation, and characterized by its high flexibility, which allows for minimal restrictions on mounting locations.

The change in the shape of the wire due to tension, bending, or compression causes the piezoelectric layer to deform, thereby generating voltage, which can be sensed (Figure 4-38). For example, it is envisioned to be applied to information completion such as “softness” that cannot be sensed by vision sensors, switches to activate augmented devices with small force, detection of vibrations, etc. of contact objects, and recording of sensations over distance and time.

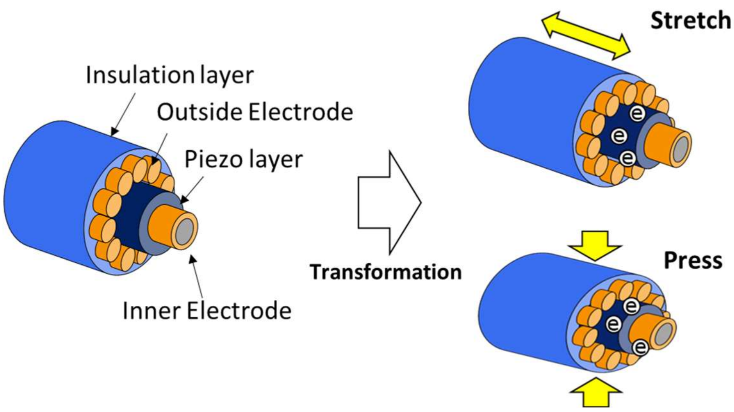


Figure 4-38 Detection principle of wire piezoelectric sensor

For installation in machines and equipment, the wire form makes sewing possible in addition to bonding, which may have the advantage of facilitating, for example, the installation of an outer skin. This is made possible by utilizing our high-strength steel wire technology, which is as strong as sewing thread or stronger.

Table 4-2 Standard Specifications and Manufacturing Scope of Wire Sensors

	Standard specification	Production range	
Wire diameter	0.13mm	0.10 to 0.30mm	* Custom specifications might be available upon request.
tensile strength	4N (0.4kgf)	2 to 60N	
outer skin material	PET	PET, PVC, etc.	
Possible temperatures of use	0 to 100°C	—	

5. Cloud Applications

5.1 Cognitive Enhancement

5.1.1 TOPPAN Inc.

(1) Human-augmentation, Space-creating Remote Work Support Platform

This research is a joint research project by the University of Tokyo and TOPPAN under a commission from the National Institute of Information and Communications Technology (Grant Number: 02901) [33]. It enables the acquisition, transmission, and reconstruction of 3D real-world environments of remote locations in real time, allowing for the sharing of spatial information as if one were at the remote site. Currently, 2D video is generally shared through videoconferencing; however in the future, it will be possible to share 3D spaces in real time, contributing to the expansion of the user perception.

This spatial information is generated by the real-time fusion of static geometric data (such as buildings measured in advance) and 3D data of human bodies and dynamic objects captured by multiple cameras and depth sensors. However, because of the massive data volume required, real-world deployment is planned in anticipation of the next-generation mobile communication system called Beyond 5G (hereinafter referred to as 6G), which will be put into practical use in the 2030s.

The establishment of such an ICT infrastructure is important to support flexible work styles—such as teleworking, balancing childcare and work, and working regardless of disabilities—and contributes to regional development as well as building a disaster-resistant society.

As a use case, we produced skill transfer content that allows users to experience a professional pianist's performance from various perspectives. Based on user evaluations and transmission test in an ICT testbed environment, activities for societal adoption and dissemination are currently underway.

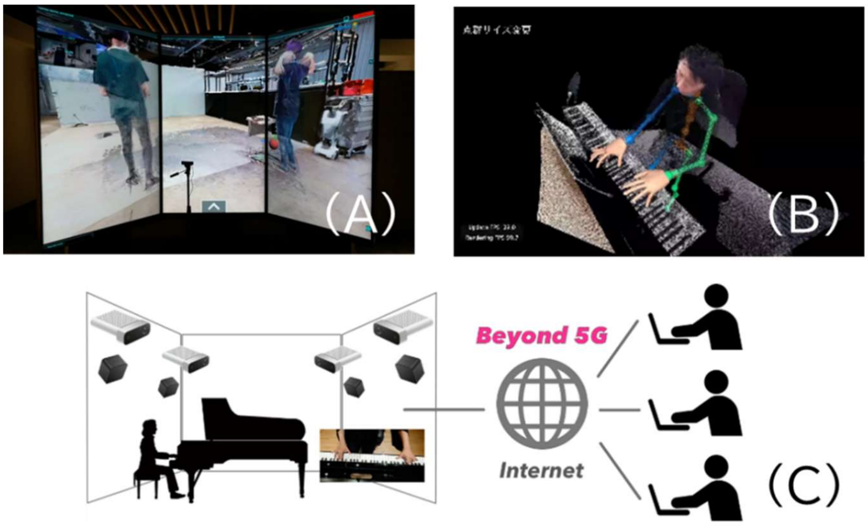


Figure 5-1 Human-augmentation, space-creating remote work support platform
(A) Example of remote collaboration using an immersive large display
(B) Skill transfer content of performance by professional pianists
(C) System configuration. Because spatial information is a huge amount of data, it is assumed to be used in anticipation of Beyond 5G (6G).

(2) Theater to Learn about Museum and Other Exhibits on the Metaverse

TOPPAN has developed a "stadium theater" in the Metaverse that enables visitors to learn about cultural properties and research materials held by museums and science centers. Through interactive communication with curators, visitors can engage with the content in a lecture-style format.

This theater, named "Da Vinci Stadium," is offered as a comprehensive package. It includes a virtual space where a science communicator (facilitator) and a researcher (commentator) provide explanations, as well as high-definition 3D content production that faithfully reproduces cultural assets. Institutions can utilize this stadium theater to conduct educational programs, such as special events and seminars.

①時間と空間を超えて学ぶ　②自分の好きな角度から対象物を見る　③学芸員や生徒とのコミュニケーション

Figure 5-2 Stadium Theater Type Education System by Metaverse

In this educational program, participants entered the interior of a fig reconstructed using 3DCG under the supervision of a researcher. They observed the flight trajectory of the fig wasp, the pollination process , the roles of males and females, and egg-laying scenes up close.

Using a controller, participants could shrink to the same size of a wasp and observe the symbiotic relationship between the fig and the wasp from various angles. Furthermore, by combining magnified views of fruit cross-sections, supplementary materials, videos, and discussion, the project is developing next-generation science communication methods that allow users to experience microscopic ecosystems.

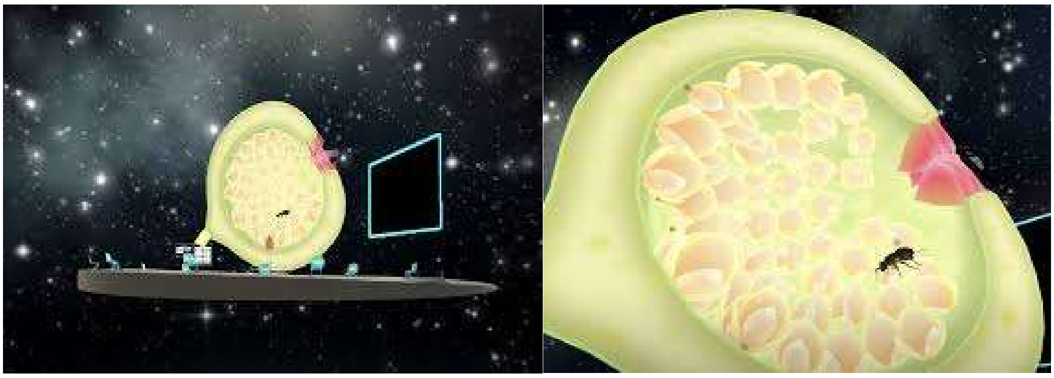


Figure 5-3 Educational program on the subject of the symbiotic relationship between figs and copepods

5.2 Enhancement of Physical Capabilities and Extension of Existence

5.2.1 H2L, Inc.

(1) Analysis of the Experience using Muscle Displacement Sensors and Visual Communication of Analysis Results -Analysis and Feedback of Sports with BodySharing

Application Overview and Features

This application converts the analysis results of real-time muscle displacement data obtained from muscle displacement sensors into visual form and presents them as feedback. Especially in sports, the physical sensation, which has conventionally relied on verbalization and indirect guidance through images, is made explicit through numerical and visual representations and fed back to the user (Figure 5-4) [25] [34].

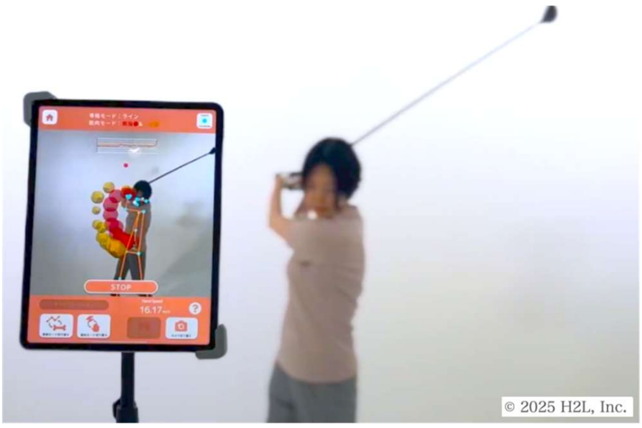


Figure 5-4 "Visualization" of analysis results of proprioception (force) during sports experience

(2) Analysis and Communication of Work Experience Using Muscle Displacement Sensors -BodySharing for Business

Application Overview and Features

"BodySharing for Business" is a business support application developed to visualize physical sensation and psychological state at the workplace. It estimates the user's muscle tension and fatigue in real time. By reflecting these biometric data to avatars in the metaverse space, nonverbal sharing of the working state is realized (Figure 5-5) [35].

Conventional business communication has limited means of sharing workers' internal states, such as fatigue and tension, making it difficult to detect uneven workloads and overloads at an early stage, often resulting in delays in management and care within the organization.

BodySharing for Business addresses this issue by providing a status-sharing function using intrinsic sensory measurement with muscle displacement sensors. The measured physical information is converted into abstract categories such as "energy level" and "relaxation level," which are visually reflected in icons around avatars installed in the office space.

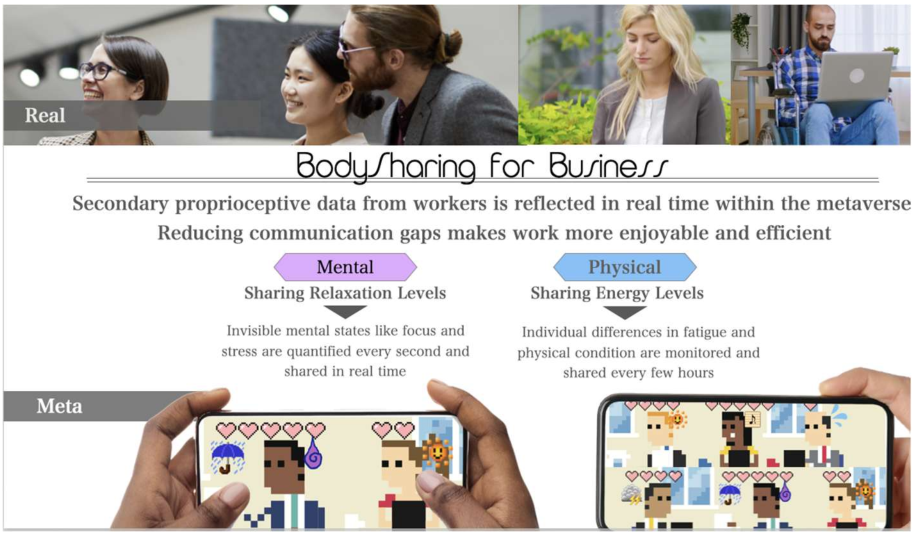


Figure 5-5 Avatar and Metaverse Space in BodySharing for Business

Demonstration of Use cases and Features

Support for telework and telecommuting

In remote work, it is extremely difficult for supervisors to constantly monitor the work status of their subordinates. In this application, the tendency of the user's physical load and mental tension is clearly indicated by measurement at the beginning and end of the workday, and is used by the supervisor as a material for judging the allocation of workload. The visual display of the user's continuous state of tension during work promotes appropriate breaks and task reallocation.

On-site work management and remote support

In field operations such as construction sites and factories, there was a lack of a means for the head office to check the work load status of workers in the factory. Through this application, management at remote locations can see the status of workers based on muscle displacement data acquired from FirstVR worn by workers in the field, and can call out to them and adjust their work as necessary.

6. Platform (Human Augmentation Platform)

This chapter describes the "Human Augmentation Platform," a platform being developed by NTT DOCOMO, INC.

6.1 System Configuration

As shown in Figure 6-1, the system comprises a sensing device that captures movement and sensation, an actuation device that reproduces movement and sensation, the Human Augmentation Platform that connects over the network. Motion and sensation data acquired by a sensing device are transformed by the Human Augmentation Platform and conveyed in real time through an actuation device to a recipient, such as a person or a robot. The Human Augmentation Platform is notable for its capability to compare the physical data of persons and robots connected such as their size and skeletal structure as well as individual sensory sensitivities so that it can move persons and robots by considering the physical data differences between them or adjust the range and force of movements and the intensity of sensations as necessary. With this technology, it is possible to share movements naturally between humans and robots regardless of their differences in size and structure and to even share the sensations of touch and the taste of food, which are difficult to explain in words, with others.

In addition, as devices can access the Human Augmentation Platform via the network, it is possible to perform human augmentation in a variety of locations.

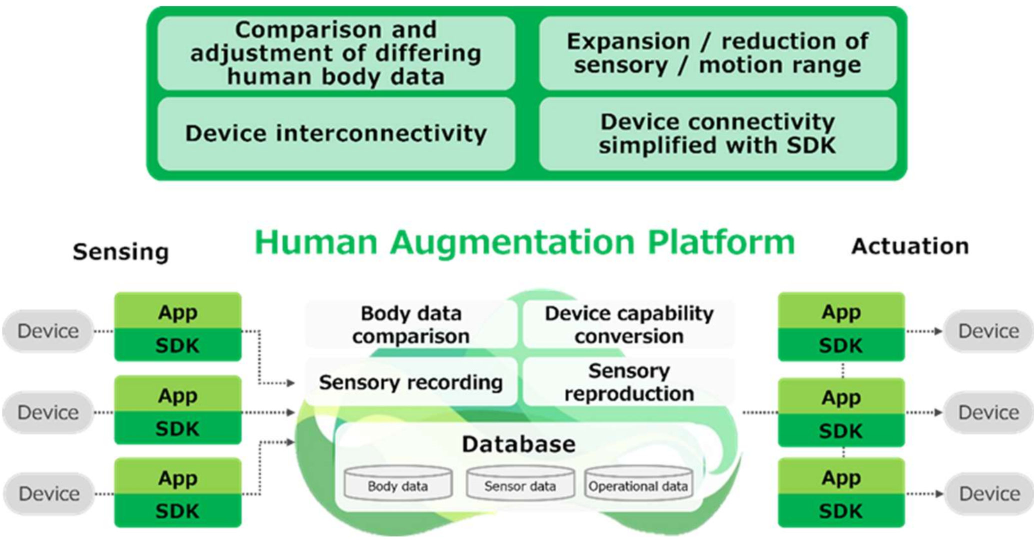


Figure 6-1 System configuration

6.2 Features

The following is a list of the features realized by the Human Augmentation Platform as of FY2024.

(1) Motion Sharing

Compare physical data between people and robots and share movements by considering the physical differences between them. It realizes the sharing of natural movements without strain and the reproduction of meticulous movements based on larger movements (Figure 6-2) [36].

Figure 6-2 Motion sharing

(2) Haptics Sharing

Share the sense of touch based on the recipient's tactile sensitivity characteristics. It enables people to feel subtle tactile differences only recognizable by professional craftsmen, to realistically recall past tactile sensations, or to feel the texture of products such as clothes on e-commerce site (Figure 6-3) [37].

Figure 6-3 Haptics sharing

(3) Taste Sharing

Share taste based on the recipient's taste sensitivity characteristics. It is possible to provide richer content by linking this feature to virtual experience in the metaverse space, or by adding the taste that anime or movie creators want to convey to the content of their works (Figure 6-4) [38].

Figure 6-4 Taste sharing

6.3 Milestones

The future milestones are shown in Figure 6-5. The goal is to share sensations, emotions, and eventually even thoughts with others without the use of words as showing in the figure. In addition, we hope to realize a world in which we can share multiple senses simultaneously although currently it is limited to only one sense at a time.

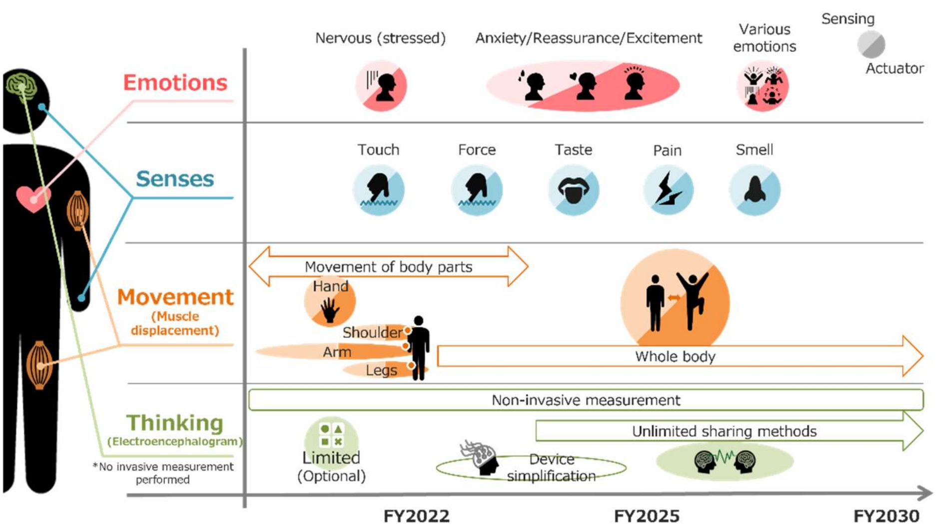


Figure 6-5 Milestones of the Human Augmentation Platform

7. Use Cases / PoC

The Consortium is engaged in activities to promote social implementation of human augmentation technology, such as creation of use cases and proof of concept (PoC) for new use cases. This chapter introduces such activities.

7.1 "Augmented Experience Design Session"

As an activity for the creation of use cases, the Consortium is conducting a workshop for member participation, the "Augmented experience design session" (hereafter referred to as the "Session"). The following describes the first session held in August 2025.

7.1.1 Objective

As described in Chapters 4 through 6, members of the Consortium are engaged in research and development of a diverse range of assets, from devices and cloud applications to platforms. In addition, members include not only companies but also researchers engaged in academic research at universities, and the industry sectors to which the corporate members belong include automotive, sports, telecommunications, electronic media, materials, and many others. By combining the knowledge of members with such diverse backgrounds, this session aimed to explore solutions to unprecedented social issues and new experiences, to create new attractive use cases for human augmentation, and to provide an opportunity for PoC for social implementation.

7.1.2 Methodologies

This session was conducted using the "Design Thinking" method. The following is an explanation of the characteristics of Design Thinking based on the paper by Tim Brown et al. [39], proponents of Design Thinking, as well as the reasons why this session was conducted using Design Thinking.

- Human-centered thinking, emphasis on empathy
  The first characteristic of Design Thinking is that it is "human-centered" in that it approaches ideas from the user's feelings, experiences, and needs, and that it emphasizes "empathy" to empathize with and understand the feelings and actions of the user from his or her perspective. By addressing the creation of use cases through design thinking, we can design "meaningful augmented experiences for humans," rather than the

development of the technology itself. This enables human augmentation technology to be embodied not as a mere technology, but as an experience that enriches society and people's lives.

- Inter-disciplinary Co-creation through the Integration of Diverse Expertise
  Design thinking emphasizes "Integrative Thinking," which links knowledge from different disciplines across the board. In this session, participants including engineers, researchers, and business people will collaborate, and design thinking will promote collaboration among different disciplines and increase the likelihood of creating creative use cases.
- Creating practical results through trial and error and prototyping
  Design thinking includes a process of "trial and error, and prototyping," in which ideas are fleshed out, tested by users, and improved upon. This is an effective approach for quickly giving shape to hypotheses and empirically refining them in the conception stage of use cases where there is still ambiguity about the form of social implementation.

This session involved 23 participants from 15 member organizations, divided into four groups of four to five members each. It was conducted in person over one day (7 hours). Figure 7-1 illustrates the workflow undertaken by each group, while Figure 7-2 shows the proceedings on the day.

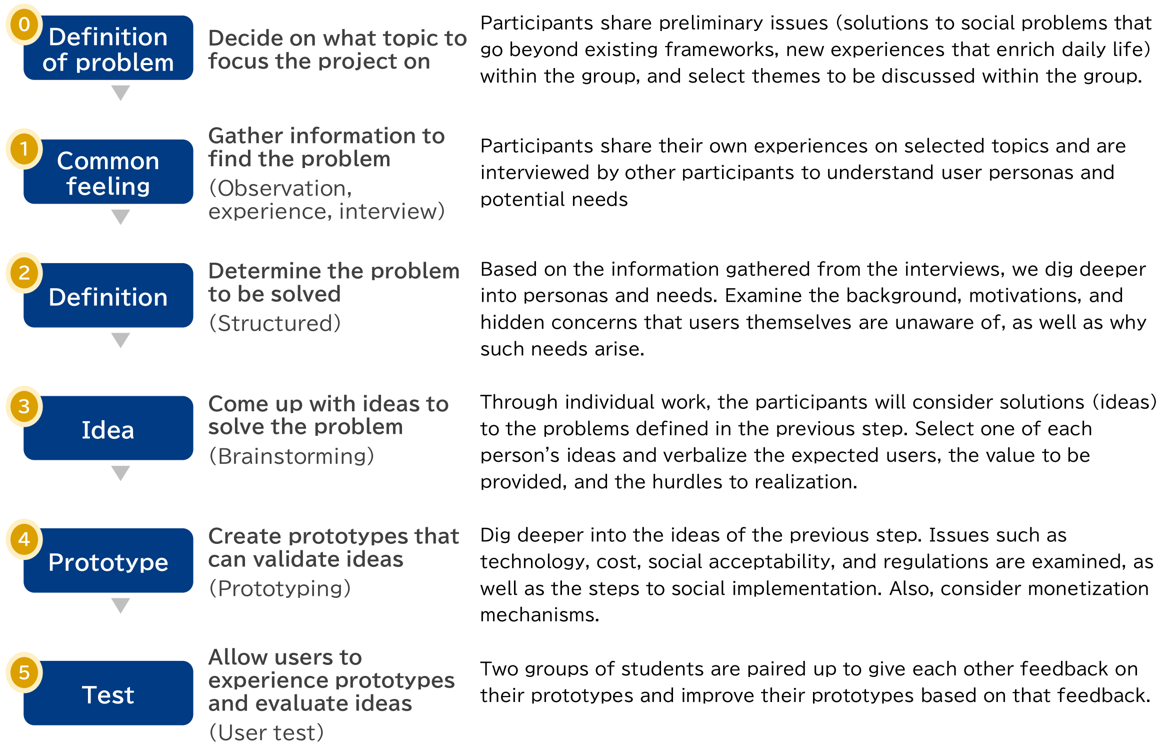


Figure 7-1 Flow of the augmented experience design session

Brainstorming session Prototyping

Figure 7-2 The day of the session

7.1.3 Results

Table 7-1 summarizes the outputs for each group, while Table 7-2 to Table 7-5 detail the outputs for each group respectively.

Table 7-1 Summary of Outputs for Each Group

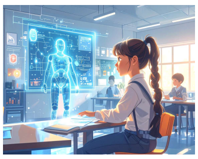
		Group 1	Group 2	Group 3	Group 4
Output	Social issue	• **Improving the quality of education** (personalizing education for each student) • **Utilization of Retired Workforce**	• **Improve the quality of life of the elderly, disabled, etc.** (enable them to play on the golf course with able-bodied people)	• **Health promotion**	• **Visualize and experience the pain of disease/disability to promote behavioral change/generate empathy**
	Type	Cognitive Expansion	Expansion of physical capabilities	Cognitive Expansion	Cognitive and Perceptual Expansion
	Use case overview	• Multiple types of teacher avatars trained with input from multiple teachers • Sensing student ability and status (comprehension, concentration, academic performance) • Matching teacher avatars to each student's condition and ability to provide education.	• High-precision sensing of club swings and ejection of golf balls from the launch pad accordingly • Moderately reflects mistakes and generates the feeling of actually hitting the ball. • Players go to the golf course and enjoy playing with able-bodied players	• Introduced bathtub-type exercise devices. • Sensing the user's health status while bathing and encouraging exercise by adjusting water pressure, electrical stimulation, etc. • Highly immersive entertainment elements will be incorporated through video projection in the bathrooms, etc.	• Using wearable devices, etc., reproduce and experience the pain of cancer and the aftereffects of stroke and myocardial infarction to promote behavioral change in health behaviors. • Sharing the pain can also lead to understanding and empathy with family members and coworkers who have illnesses or disabilities.
					

Table 7-2 Group 1 "Personalizing education with teacher avatars learned from retiree knowledge"

Persona, issue hypothesis, background, and needs		
	Persona	• Assume a group of students (mainly middle and high school students), especially those with varying learning abilities, knowledge, and interests. • Retirees who have a desire to educate young people but "want to teach but can't" due to age and geographical constraints.
	Problem hypothesis	• Interests and skill acquisition are influenced by coincidences such as "where I was born" and "the first teacher I learned from." • There are preferences and aptitudes in "how to communicate" and "how to teach" that, if not adapted, can hinder knowledge acquisition. • In the educational industry (e.g., entrance exam guidance), such as tutoring schools, compensation is paid for non-quantifiable values such as "popularity" and "fame," making it difficult to verify the appropriateness of cost-effectiveness.
	Contexts	• There is a gap in education level between urban and rural areas (especially private schools and tutoring schools). Remote classes and learning apps are becoming more widespread, but there are limits. • A "teacher who is popular among students" often depends on the way he or she looks and communicates. While there is a positive aspect of being able to learn human-to-human communication (e.g., building trust), there is also a fear that it will inhibit the essence of learning (knowledge acquisition) and reduce the effectiveness of learning. • These communication problems are one of the major reasons why skilled older adults "want to teach but can't."
	Needs	• (Educators) Adults of various ages and backgrounds can participate in education, even partially, and the information conveyed to children without stress. • (Educated person) Coincidence is eliminated, and students are able and willing to learn anywhere and in a teaching style that suits them.
Idea		• Avatars who use multiple teachers' lectures (how to tell the story, how to respond to questions, and the content of the lesson) as input and tailor their delivery to the students. • Sensing technology measures students' level of concentration, behavior change, and comprehension, and provides feedback to avatars (modifying the way they communicate and ask questions).
Prototype		
	Experience Value/Benefit	• Teachers can choose to maximize their skills by selecting the areas of communication (lectures, question answering, etc.) in which they excel as well as the areas in which they excel (knowledge). • The student side can enjoy content that is optimized for them in terms of the way it is communicated/content.
	Current state of technology and issues	• Techniques for modifying the appropriate way of communicating from the input on the part of the faculty member. • Integration and modification in case of different educational policies, ways of perceiving knowledge, study methods, etc. of the inputting teachers.
	Partners/Industries	• Introduced as an extension of distance learning content or used as a TA at a private university.
	Implementation and dissemination issues	• The hurdle is high for introducing it into compulsory education because it affects the existing culture of face-to-face education itself. • Compulsory education already tends to be neglected in urban areas, but if only children who can receive this service enjoy high educational benefits, the educational gap will rather widen.

Table 7-3 Group 2 “Sensing and reproduction of golf swing for wheelchair users”

Persona, issue hypothesis, background, and needs		
	Persona	• Seniors who enjoyed golf during their working years but are no longer able to play golf due to declining physical fitness.
	Problem hypothesis	• There is a need to enjoy golf with able-bodied friends and family members on the golf course, but it is difficult for the following reasons • One is difficulty in walking long distances. It is assumed that they will have to use electric wheelchairs, etc. to move and play. • Another is the problem of distance. With his physical strength declining, he is not able to hit the ball with any distance if he sits in a wheelchair even more.
	Contexts	• Golf is one of the sports that can be enjoyed by the elderly, especially baby boomers, and the market is large on a global scale. • Being able to play with able-bodied people on the golf course, even as they age, contributes to improving their quality of life.
	Needs	• To actually go to the golf course and play. • To produce the same distance as before the decline in physical fitness, while enjoying the feeling of hitting the ball by oneself.
Idea		
		• It senses the head speed and trajectory of the swung club and transmits that information to the golf ball ejector via high-speed communication to increase the output and launch the ball. • The actual angle of incidence is used to generate the sensation of actually hitting the ball, reflecting even a moderate amount of misses.
Prototype		
	Experience Value/Benefit	• Playing on the golf course, the feeling that you are hitting the ball. • The feeling of getting better, that skill improvement is not a black box, and a sense of self-initiative and self-efficacy will lead to higher repeat business.
	Current state of technology and issues	• Motion analysis of the club and sensing of the angle and orientation of the club face and reproduction on the ejector.
	Partners/Industries	• Sporting equipment manufacturer • Mobility manufacturers (e.g., wheelchairs that can be moved on golf courses, etc.)
	Implementation and dissemination issues	• Golf courses have about 8 million users per month, with an increasing number of seniors over the age of 70. • Golf course playing rules and practices need to be changed regarding wheelchair-accessible rounds and the installation of ejection devices.

Table 7-4 Group 3 “Behavior change and health promotion with tub-based exercise devices”

Persona, issue hypothesis, background, and needs		
	Persona	• People who are healthy (or unwell) but lack exercise
	Problem hypothesis	• There is a certain segment of the population that has had poor health checkup results and wants to normalize their numbers and become healthier, but does not want to do anything painful (diet restrictions, strenuous exercise).
	Contexts	• Time and money constraints are preventing them from using gyms and other facilities. • Future risks due to lack of exercise are difficult to visualize and motivate. • It is difficult to monitor one’s own health status outside of regular health checkups, and it is difficult to realize the benefits of exercise.
	Needs	• I want to be healthy while having fun and doing as little hard work as possible (I want to bring my health checkup results closer to normal).
Idea		
		• Bathrooms and bathtubs for fun, exercise and health sensing. • The water flow and electric current allow the user to exercise without strenuous physical exertion. It has entertainment functions such as games, sightseeing, and karaoke, allowing users to enjoy themselves while exercising. • A sensing device is also built in, allowing the health status to be monitored at the same time.
Prototype		
	Experience Value/Benefit	• By utilizing bathing as a daily habit, it can be continued without feeling burdened. • By adding entertainment elements to the bath, it is sublimated as a new experience space. • The closed space of the bathroom allows for a highly immersive experience.
	Current state of technology and issues	• Non-contact sensing (especially underwater) and control of water (fluids) are issues.
	Partners/Industries	• Gyms and public bathhouses (operator) • Sensing device developer (development partner of bath-type devices), actuator developer (development partner of bath-type devices), bath product manufacturer (development partner of bath-type devices)
	Implementation and dissemination issues	• Difficult to secure space for installation at home. And it costs a lot of money. • If it is to be installed in a gym or other facility, it is difficult to ensure ease of use.

Table 7-5 Group 4 "Visualization and experience of the pain of disease/disability to change behavior and evoke empathy"

Persona, issue hypothesis, background, and needs		
	Persona	• People who are in good health or in an unwell state and have little sense of urgency about unhealthy lifestyles such as lack of exercise.
	Problem hypothesis	• The importance of health cannot be realized without actually experiencing the pain (pain, numbness, state of mind) of being sick or having a disability. • If they can experience firsthand the pain of illness and disability, it may provide an opportunity to change their lifestyle and to empathize with those who are ill or have disabilities (which may help reduce the pain of caregiving).
	Contexts	• The high level of patients with cancer, stroke, myocardial infarction, and other diseases that can be prevented or alleviated to some extent by lifestyle modification, and the accompanying high/increasing burden of health insurance premiums. • Increase in the number of caregivers due to an aging society.
	Needs	• Reduce the burden of social insurance premiums and create an opportunity to improve lifestyle.
Idea		
		• Reproduce the vexation of illness and disability using wearable devices, VR goggles, etc. • Visualize what "life functions "* will be lost when a person has a future risk-based disease or disability. *Loss of ability to climb mountains, commute by train, etc.
Prototype		
	Experience Value/Benefit	• By instilling a sense of urgency, it provides an opportunity to improve lifestyle habits. • Improve communication with people with illnesses and disabilities (to be able to treat them with empathy).
	Current state of technology and issues	• It is unclear how far the technology for sensing, quantifying, and reproducing pain and vexation has developed. • In particular, there may be little sensing and reproduction of mental vexation.
	Partners/Industries	• Health insurance associations, insurance companies, and municipalities (medical cost containment)
	Implementation and dissemination issues	• The challenge is how to make them experience it, as they may not be willing to do so. Regular health checkups and during medical examinations (to convey the reality of the risks that may come if left unchecked) are realistic solutions. • Ethical hurdles to having the patient experience pain and vexation. Temporary pain can only replicate some of the vexation of being ill, but allowing the patient to experience persistent pain can be emotionally taxing.

At the end of the session, final outputs were shared from each group and feedback was provided by the participants. Suggestions from the feedback for future use case creation are listed below.

Needs Perspective

- Visualizing/experiencing the future "risk" of unhealthy living may lead to behavior change toward healthy behaviors (feedback to Group 3 and 4).
- The emphasis on the experience of actually going to the golf course and playing with friends, rather than a completely remote/virtual space experience, is unique and could be applied to other sports/activities (feedback to Group 2).

Technical Perspectives

- What is needed to make the participants realize the "risk" and change their behavior without making them directly experience pain, vexation, or discomfort (feedback to Group 4).
    - For example, if a person is unable to move his/her body well due to pain,

etc., it may be effective to take an approach to visualize what life functions are lost (e.g., inability to climb a mountain, etc.).
    - The damage caused by changes in life functions differs from person to person. We believe that a higher effect of behavior change can be achieved by visualizing and reliving, as a parallel world, how the life functions that each individual values are affected when physical or mental functions are lost, in relation to the individual's current physical condition and future aspirations.
- Emphasizing the feeling that the ball flew through one's own swing may create a sense of action and self-efficacy, leading to an increase in the value of the experience (feedback to Group 2).

7.1.4 Future Plans

The Consortium plans to continue conducting the Augmented Experience Design Sessions. This was the first time we implemented a session incorporating design thinking, with the majority of participants encountering design thinking methodologies for the first time. Repeating the sessions will enhance learning outcomes, improving participants' understanding and capabilities in design thinking. This is expected to refine ideas and foster the growth of participants. Furthermore, using the ideas conceived this time as a starting point, it is anticipated that iterative prototyping and testing will clarify the strengths and weaknesses of these ideas. Moving forward, we aim to conduct these sessions repeatedly to foster the creation of compelling new use cases.

8. Standardization

International standardization of components such as devices, cloud applications, platforms, and interfaces connecting them is essential to promote social implementation of human augmentation and to maintain and expand the ecosystem. Standardization will ensure interoperability among products from different countries, regions, and companies, enabling users to select the most suitable product from a variety of options without being aware of the country, region, or company. For companies, this will also reduce barriers to entry into markets in diverse regions. Furthermore, development based on standard specifications will reduce R&D costs and accelerate technological innovation.

Human augmentation consists of multi-layered technical elements such as hardware, software, communication protocols, and data formats. The design and implementation of these elements based on unified standards will enable the diffusion of the technology and the expansion of the market. Furthermore, international standardization clarifies quality and safety standards and contributes to gaining user trust and social acceptance.

This chapter provides an overview of the efforts of existing international standardization bodies on human augmentation, and then introduces the Consortium's activity policy.

8.1 Efforts of Existing Organizations

Figure 8-1 shows the organizations working on standardization related to human augmentation. Although several organizations are working on standardization related to human augmentation, they can be generally classified into the following three categories based on the technological domains they cover.

- Organizations working on standardization of APIs inside devices (c in the figure) and hardware interfaces (d in the figure)
  - Includes Khronos OpenXR group, W3C Immersive Web Working Group (WG), and IEEE Open Integration WG
- Organizations working on standardization of communication interfaces and data formats (a and b in the figure) between devices on the network and between devices and cloud applications/platforms.
  - It includes ITU-T SG21 Q8-ILE (Immersive Live Experience), ISO/IEC JTC1/SC29, and IETF Media Type Maintenance WG.
- An organization that compiles the requirements within the industry for standards required for services using haptics, metaverse, etc., without

limiting the technical domain, and provides input to other organizations.

➢ It includes the Haptics Industry Forum (HIF) and the Metaverse Standards Forum (MSF).

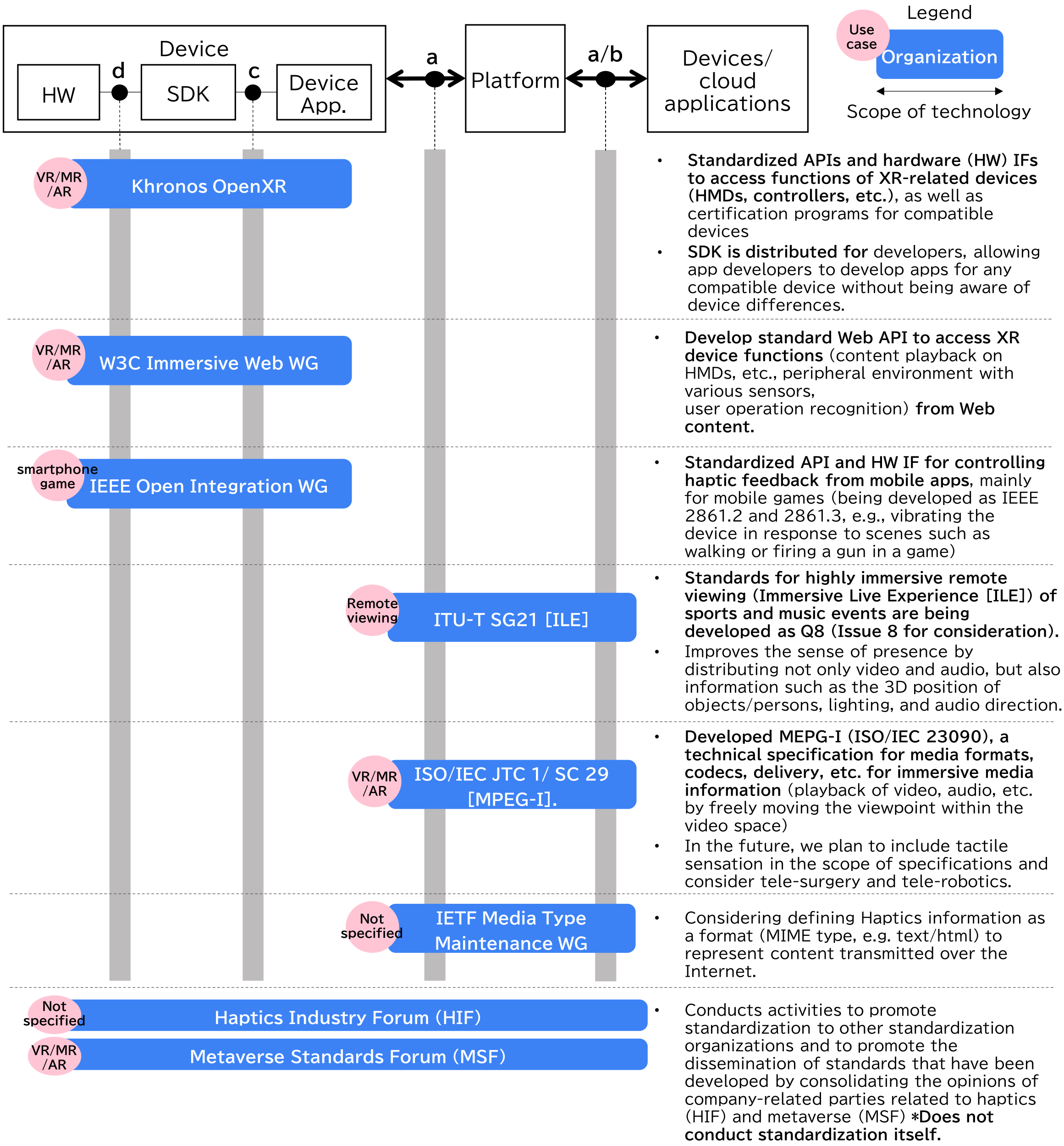


Figure 8-1 Existing international standardization organizations and their technical areas

Each standards body also differs in the way it is involved in the development of standard specifications. As shown in Figure 8-2, there are two types of organizations: (I) those that do not develop specifications, but rather summarize the standardization needs within the industry related to specific services such as haptics and metaverse, and then promote the development of standard specifications to other organizations (HIF and MSF fall into this category); and (II) those that develop standard specifications on their own (other organizations fall into this category). (II) those that develop standard specifications on their own (other organizations fall under this category). As shown in the blue box in the figure, the process from standard specification development to implementation and market deployment consists of multiple steps, and the extent to which each organization is involved in these steps differs within II.

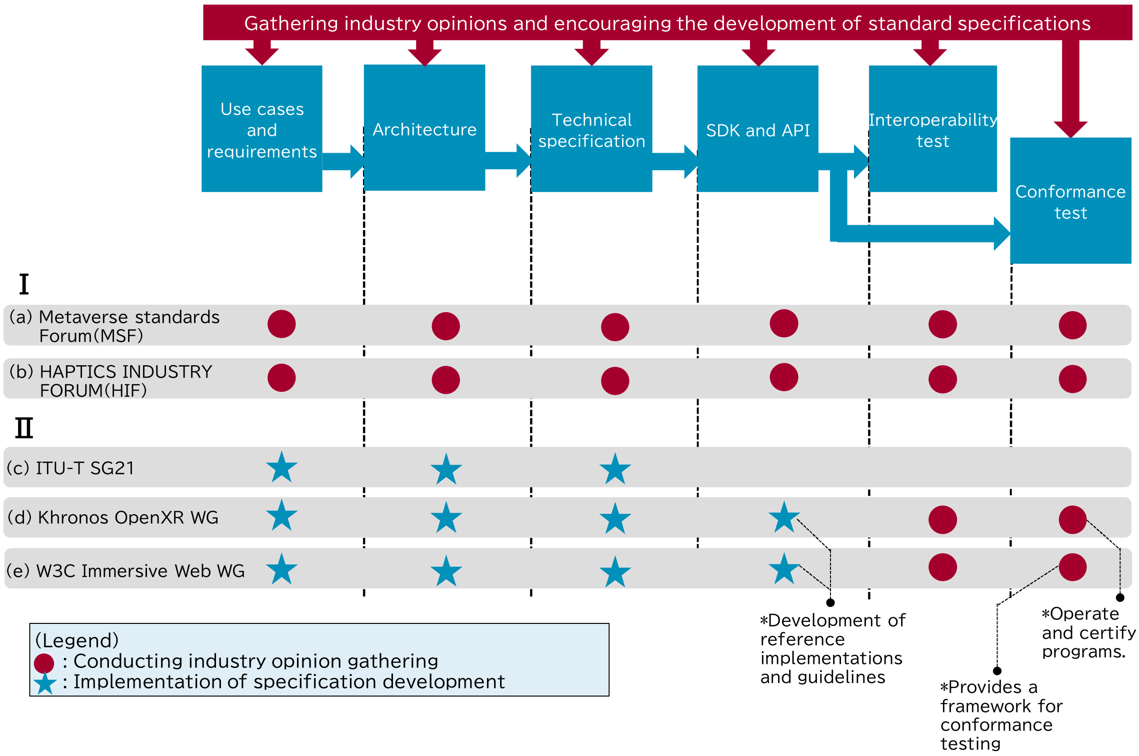


Figure 8-2 Approach to involvement in the development of standard specifications by existing international standardization bodies

8.2 Activity Policy of the Consortium

The Consortium has adopted a policy of promoting standardization of missing functions while utilizing existing standard specifications as much as possible in order to realize the assumed use cases. Based on the trends in international standardization described in the previous section, we are currently analyzing the gap between the assumed use cases and existing standards, in other words, we are investigating the standard specifications that have already been established or are scheduled to be established to realize the assumed use cases, and identifying the functions that are lacking in these existing standards.

Among the four types of human augmentation, for perceptual enhancement, cognitive enhancement, and extension of existence (excluding telexistence), relevant standard specifications are being developed by the standardization organizations listed in Figure 8-1. In particular, ITU-T SG21 Q8-ILE (Immersive Live Experience) is developing standards that can comprehensively support the use cases envisioned by this consortium. The sharing of experiences is not limited to concerts (e.g., playing a musical instrument in a concert hall) or sports games, but is expected to be used for a variety of use cases, including medical care, education, and remote work [40]. In the future, the consortium will analyze gaps in existing standard specifications, mainly in ITU-T SG21 Q8-ILE, compile missing functions within the consortium, and consider providing input to the ITU-T and other related standardization bodies as a request from the consortium.

On the other hand, with regard to telexistence for the enhancement of physical capabilities and the extension of presence, no relevant existing standardization bodies have been identified at this stage. Realizing these types of use cases in a multi-vendor environment requires standardization across a wide range of areas, including communication protocols and data formats for sending and receiving commands and responses when remotely operating robots, and architectures for managing robots. Whilst the consortium will continue investigating relevant standardization bodies, should it become apparent that none exist, consideration will be given to developing standard specifications within the consortium itself.

9. ELSI

With the development and diffusion of human augmentation technologies in society, issues such as invasion of privacy, widening disparities, and alteration of self-identity may become apparent. It is essential to address these ethical, legal, and social issues, or ELSI (Ethical, Legal and Social Issues), for the development and diffusion of human augmentation technology to be accepted by society.

- Widening Disparities
  If access to human augmentation technology is limited by economic power, a new digital divide, a qualitatively different disparity between those who have received enhancements by human augmentation technology and those who have not, may emerge.
- Safety and privacy invasion
  With the proliferation of wearable devices (wearable devices) and devices implanted in the body, the risk of physical damage from cyber attacks and the protection of personal data including biometric information become important issues.
- Identity change
  The increasing convergence of humans and technology may require a fundamental rethinking of the definition of humanity and the self-identity of the individual.

This consortium will conduct ongoing studies on ELSI with the aim of promoting the sound development of human augmentation technology and improving its social acceptability. The Consortium will refer to the results of studies on ELSI conducted by the Digital Haptics Consortium and the Meta Consortium for Promotion of Social Implementation of Interverse, both of which were formed as part of the SIP Virtual Economy Project of the Cabinet Office, as well as other related organizations and research institutes in Japan and abroad, to understand the impact of human augmentation technology on society from various perspectives and to promote ongoing discussions and studies on both technological development and social implementation, We plan to continue discussions and deliberations on both technological development and social implementation.

10. Future Issues

Advancing the social implementation of human augmentation technologies presents multiple challenges that must be addressed. This chapter outlines key challenges from technological, legal, and societal perspectives.

First, from a technological standpoint, standardizing and promoting interfaces—such as communication protocols and data formats—is essential to enhance interoperability among diverse players' devices, cloud applications, and platforms. As discussed in Chapter 8, existing standardization bodies are developing standard specifications related to human augmentation across diverse technical domains. However, no effort has been made to comprehensively review and organize these standard specifications within the context of "human augmentation." Consequently, current risks include human augmentation engineers "implementing solutions using proprietary technologies unaware of existing standards" or "using existing standard specifications for purposes differing from their original intent." Leaving these risks unaddressed could hinder interoperability between different vendors and become a factor impeding ecosystem development. To avoid this, it will be necessary to organize the standard specifications available for human augmentation by type and use case, and to widely publicize them to engineers.

Other technical challenges include the widespread adoption of ultra-low-latency communication technologies, such as 6G and APN, and the advancement of sensing technologies that accurately measure human perception and motor functions. For example, in use cases involving shared experiences and sensations, latency impacts immersion in those shared experiences and sensations, demanding real-time performance measured in milliseconds. Regarding the devices themselves, key challenges include wearability, miniaturization, weight reduction, and improvements in battery technology to enable extended usage.

Next, in terms of legal and institutional challenges, establishing a legal framework for handling personal data, protecting privacy, and safeguarding intellectual property rights is essential. Current systems have insufficient coverage in certain areas, necessitating the creation of flexible and effective rules that keep pace with technological advancements.

As a societal challenge, strengthening awareness campaigns to promote understanding of the technology and foster social acceptance is essential. For human augmentation to gain broad acceptance, society as a whole must discuss not only its benefits but also its potential risks and challenges. Particularly regarding Ethical, Legal, and Social Issues (ELSI), ongoing discussions within industry-government-academia partnerships and international frameworks are essential to address concerns such as widening disparities, privacy violations, and identity transformation, enabling swift and flexible responses. Furthermore, cultivating specialized talent and supporting the skill enhancement of existing engineers and researchers is indispensable.

11. Conclusion

This document provides an overview and summary of human augmentation technology as a whole, while introducing the initiatives of this consortium's members regarding devices, cloud applications, and platforms. It also organizes the efforts of existing standardization bodies concerning human augmentation technology standardization and explains this consortium's policy on standardization. Furthermore, it outlines the challenges involved in advancing the commercial implementation of human augmentation.

The Consortium will promote the commercialization and serviceization of human augmentation technologies. By achieving widespread societal adoption, we aim to deliver tangible value to our lives and industries while contributing to the creation of new markets. As explained in this book, human augmentation is not merely a tool for enhancing convenience; it holds the potential to transform our lifestyles, industries, societal structures, and even the very concept of "humanity" itself. To realize this transformation in a desirable manner, collaboration among stakeholders with diverse expertise is essential, in addition to the activities of this consortium.

Moving forward, we will continue to accumulate and share knowledge, promote standardization activities, and foster societal understanding through cooperation with diverse stakeholders from industry, government, and academia. By sustaining these efforts, we aim for human augmentation to spread safely and equitably, contributing to the development of a sustainable society.

We hope this white paper will spark greater interest in human augmentation among students and working adults alike, fostering lively discussion. The future opened by human augmentation will be shaped by each of our proactive engagement and cross-disciplinary "co-creation." We wish for this white paper to be the first step toward that co-creation.

References

[1] 暦本 純一, ”人間拡張が築く未来,” 情報学研究: 学環: 東京大学大学院情報学環紀要, 2021.

[2] E. Yamamoto, S. Nagao, J. Urakami and T. Kanaoka, ”Hearable device for auditory augmentation: Agile development to enhance user experience (UX) value,” Information Processing Society of Japan, Interaction 2023, 2023 (in Japanese).

[3] J. Urakami, A. Moriwaki, S. Nagao, K. Osumi, E. Yamamoto and T. Kanaoka, ”Augmenting Auditory Attention and Memory to Reduce Cognitive Load in Dual Task,” Extended Abstracts of the 2023 CHI Conference on Human Factors in Computing Systems, 2023.

[4] T. Kanaoka, S. Nagao, K. Osumi, E. Yamamoto and O. Hoshuyama, ”Proposal of a hearable device for auditory augmentation,” Information Processing Society of Japan, Interaction 2022, 2022 (in Japanese).

[5] K. Ohara, K. Osumi, E. Yamamoto, M. Morobishi and T. Arakawa, ”Real-time target speaker extraction using direction and voice features,” Information Processing Society of Japan, 2024 (in Japanese).

[6] K. Osumi, K. Ohara, K. Yamamoto, E. Yamamoto, M. Morobishi and T. Arakawa, ”Real-Time Simultaneous Estimation of Speaker and Sound Source Direction Using a Binaural Microphone,” Information Processing Society of Japan, 2025 (in Japanese).

[7] K. Ogawa, C. Thakur, T. Ikeda, T. Tsuji, and Y. Kurita, ”Development of a Pneumatic Artificial Muscle Driven by Low Pressure and Its Application to the Unplugged Powered Suit,” Advanced Robotics, Vol.31, Issue 21, pp.1135-1143, 2017.

[8] C. Thakur, K. Ogawa, T. Tsuji, and Y. Kurita, ”Soft Wearable Augmented Walking Suit with Pneumatic Gel Muscles and Stance Phase Detection System to Assist Gait,” IEEE Robotics and Automation Letters, Vol.3, Issue 4, pp.4257-4264, 2018.

[9] S. Das, C. Lowell, Y. Kishishita, K. Ogawa, T. Tsuji, and Y. Kurita, ”ForceHand glove: a wearable force-feedback glove with pneumatic artificial muscles (PAMs),” IEEE Robotics and Automation Letters, Vol. 3, Issue 3, pp.2416-2423, 2018.

[10] P. Ramasamy, G. Renganathan, and Y. Kurita, ”Force Feedback-Based Gamification: Performance Validation of Squat Exergame Using Pneumatic Gel Muscles and Dynamic Difficulty Adjustment,” IEEE Robotics and Automation Letters, 8(10):6371 - 6378, 2023.

[11] K. Ogawa, T. Ikeda, and Y. Kurita, "Unplugged Powered Suit for Superhuman Tennis," 12th France-Japan Congress, 10th Europe-Asia Congress on Mechatronics, pp.355-358, 2018.

[12] W. Sakoda, T. Tsuji, and Y. Kurita, "VR training system of step timing for baseball batter using force stimulus," AsiaHaptics2018, D1P11, 2018.

[13] W. Sakoda and Y. Kurita, "Coaching system of motion timing for a baseball batter using force stimulus," Worldhaptics DM1.06, 2019.

[14] ミズノ株式会社, "人間拡張技術の社会実装に向けた試み," [Online]. Available: https://corp.mizuno.com/jp/articles/0067. [Accessed 12 9 2025].

[15] ミズノ株式会社, "スポーツの楽しさ・価値をより多くの人たちにスポーツ用義足板バネ開発," [Online]. Available: https://corp.mizuno.com/jp/articles/0006. [Accessed 12 9 2025].

[16] ミズノ株式会社, "ミズノパワーアシストスーツで体への負荷を減らし、働く人を重力から解放," [Online]. Available: https://corp.mizuno.com/jp/articles/0036. [Accessed 12 9 2025].

[17] G. A. Van Kan, Y. Rolland, S. Andrieu, J. Bauer, O. Beauchet, M. Bonnefoy, M. Cesari, L. M. Donini, S. Gillette-Guyonnet and M. Inzitari, "Gait speed at usual pace as a predictor of adverse outcomes in community-dwelling older people an International Academy on Nutrition and Aging (IANA) Task Force," *The Journal of nutrition, health and aging,* vol. 13, no. 10, pp. 881-889, 2009.

[18] ミズノ株式会社, "「歩く」を科学した『Motion DNA』で健康意識を高め、「いつまでも歩ける身体作り」をサポート," [Online]. Available: https://corp.mizuno.com/jp/articles/0030. [Accessed 12 9 2025].

[19] ミズノ株式会社, "パーソナルフィッティングシューズ「3D U-Fit」の開発," 26 11 2024. [Online]. Available: https://corp.mizuno.com/jp/news-release/2024/20241126. [Accessed 12 9 2025].

[20] T. Hasegawa, H. Waita, T. Kawakami, Y. Takemura, T. Ishikawa, Y. Kimura, C. Tanaka, K. Sugiyama and T. Yoshiike, "Powerful and dexterous multi-finger hand using dynamical pulley mechanism," *2022 International Conference on Robotics and Automation (ICRA),* pp. 707-713, 2022.

[21] Honda R&D, "人に寄り添い、人の役に立つ Honda アバダーロボット," [Online]. Available: https://global.honda/jp/RandD/activity/rdtopics/advancedtech2025/multi_finger/. [Accessed 30 8 2025].

[22] Honda, "Honda ROV(遠隔操縦無人潜水艇)コンセプトモデル," [Online]. Available: https://global.honda/jp/tech/Honda_ROV_Remote_Operation_Vehicle_underwater_robot/. [Accessed 30 8 2025].

[23] S. Hosono, S. Nishimura, K. Iwasaki and E. Tamaki, "Pondushand: Measure user's weight feeling by photo sensor array around forearm," *SIGGRAPH Asia 2019 Posters,* pp. 1-2, 2019.

[24] T. Miyake, S. Yamamoto, S. Hosono, Z. Cheng, C. Zhang, E. Tamaki and S. Sugano, "Gait phase detection based on muscle deformation with static standing-based calibration," *Sensors,* vol. 21, no. 4, p. 1081, 2021.

[25] S. Shimabukuro, T. Miyake and E. Tamaki, "Time Series Analysis of Muscle Deformation During Physiotherapy Using Optical Wearable Sensors," *Sensors,* vol. 25, no. 11, p. 3507, 2025.

[26] E. Tamaki, T. Miyaki and J. Rekimoto, "PossessedHand: techniques for controlling human hands using electrical muscles stimuli," *Proceedings of the sigchi conference on human factors in computing systems,* pp. 543-552, 2011.

[27] Toyota Motor Corporation, "HSR Practical Demonstration," 16 7 2025. [Online]. Available: https://global.toyota/en/download/8725321. [Accessed 16 9 2025].

[28] Toyota Times, "HSR, the Omotenashi Robot: The Technology and People that Supported the Tokyo 2020," 23 3 2022. [Online]. Available: https://toyotatimes.jp/en/spotlights/supported_tokyo2020/057.html. [Accessed 16 9 2025].

[29] Toyota Motor Corporation, "Advancing the Integration of Robots and AI to Drive Technological Innovation," 27 3 2025. [Online]. Available: https://global.toyota/en/mobility/frontier-research/42394425.html. [Accessed 16 9 2025].

[30] 一般社団法人 AI ロボット協会, "一般社団法人 AI ロボット協会(AIRoA)AI×ロボット分野で、ロボットデータエコシステム構築を目指し活動を開始," 7 3 2025. [Online]. Available: https://prtimes.jp/main/html/rd/p/000000001.000158322.html. [Accessed 16 9 2025].

[31] COMNEXT, "ミハル通信とトヨタ自動車 未来創生センター トヨタ製ロボットの遠隔操縦デモを共同で実施 イマーシブ音声・映像の極低遅延伝送で操縦," 9 2024. [Online]. Available: https://www.miharu.co.jp/information/images/2024_9_newmedia_COMNEXT.pdf. [Accessed 16 9 2025].

[32] Toyota Motor Corporation, "Toyota Unveils Third Generation Humanoid Robot T-HR3," 21 11 2017. [Online]. Available: https://global.toyota/en/detail/19666346. [Accessed 16 9 2025].

[33] 情報通信研究機構, "革新的情報通信技術研究開発委託研究," [Online]. Available: https://www.nict.go.jp/collabo/commission/B5Gsokushin/B5G_02901.html. [Accessed 30 8 2025].

[34] S. Shimabukuro, T. Miyake, T. Akamine, C. Ookubo, D. Yanagihara and E. Tamaki, "Investigating the Relationship Between Anxiety, Depression, and Forearm Muscle Deformation in Amateur Athletes Using Time-Series Analysis," *Frontiers in Sports and Active Living,* vol. 7, p. 1561808, 2025.

[35] H2L 株式会社, "乃村工藝社と H2L が共同開発　感覚共有できるメタバースオフィス「BodySharing® for Business」正式リリース," 29 6 2023. [Online]. Available: https://prtimes.jp/main/html/rd/p/000000045.000006831.html. [Accessed 30 8 2025].

[36] 株式会社 NTT ドコモ, "あなたと常識を変えていく," [Online]. Available: https://www.docomo.ne.jp/corporate/anatatodocomo/changesociety/04/. [Accessed 7 9 2025].

[37] 株式会社 NTT ドコモ, "あなたと記憶の形を変えていく," [Online]. Available: https://www.docomo.ne.jp/corporate/anatatodocomo/changesociety/07/. [Accessed 7 9 2025].

[38] 株式会社 NTT ドコモ, "あなたと世界を変えていく," [Online]. Available: https://www.docomo.ne.jp/corporate/anatatodocomo/changesociety/08/. [Accessed 7 9 2025].

[39] T. Brown, "Design Thinking," *Harvard Business Review,* vol. 86, no. 6, p. 84, 2008.

[40] 長尾 慈郎, "グローバルスタンダード最前線 ITU-T SG16 参加報告," 21 6 2024. [Online]. Available: https://journal.ntt.co.jp/news/27077. [Accessed 10 8 2025].

[41] OECD, "OECD Skills Studies, Skills for Social Progress, THE POWER OF SOCIAL AND EMOTINAL SKILLS," OECD publishing, 2015.

List of Authors

This publication was written by the following members of the Human Augmentation Consortium:

Company/Organization Member

- H2L, Inc.
- Honda R&D
- KYOCERA Corporation
- Mizuno Corporation
- NTT DOCOMO, INC.
- Sumitomo Electric Industries, Ltd.
- TOPPAN Inc.
- Toyota Motor Corporation, Frontier Research Center

Individual Member

- Professor Yuichi Kurita, Graduate School of Advanced Science and Technology, Hiroshima University

(Listed in alphabetical order)

Revision History

Date	Ver.	Updates
October 7, 2025	1.0.(Japanese)	First edition
November 28, 2025	2.0.(Japanese)	Added the Consortium efforts to promote the creation and demonstration of use cases ("7. Use Cases/PoC")
December 25, 2025	2.0.(English)	Translated ver. 2.0 into English

*The figures and tables in Chapter 3 and 7 include images generated using Adobe FireFly. The use of these images as machine learning input data is prohibited.