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Exoskeleton and Humanoid Robotic Technology in Construction and Built Environment

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1. Introduction

The human being is the only living organism which steadily uses "tools". We have used tools to cultivate our land, grow our food, build up cities and communication infrastructures – tools are the basis for phenomena as culture and globalization. Some even argue that tools (and especially the wealth they are able to create for a huge amount of people) are the basis for today's global spread of freedom and democracy [1].

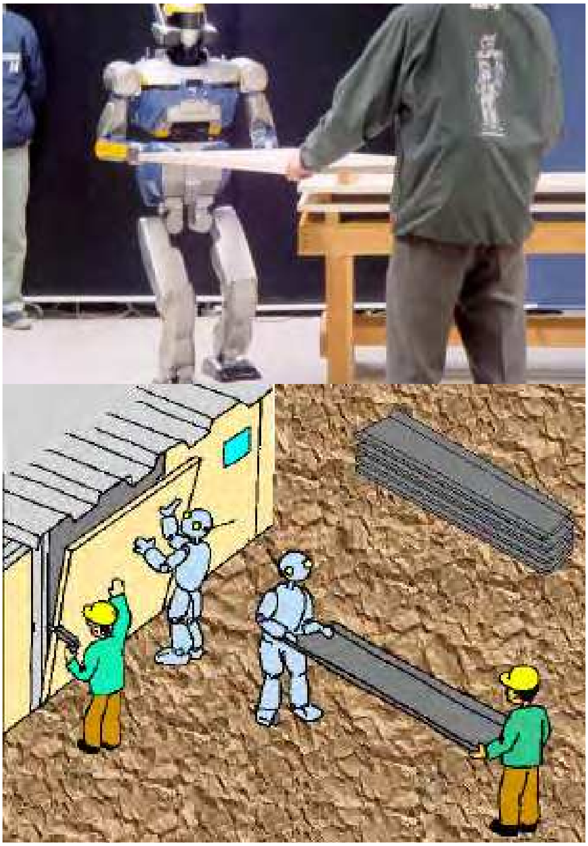
Especially tools which enhance our power in the field of mobility have played an important role in human history. The bicycle, an archetype of the assistance in physical ability and mobility, is based on the combination of human power and an artificial, technical system and was introduced by C. Drais in 1817. Later on, the car pressed ahead with this approach and supplemented human force by motor technology, a kind of actuator. Ergonomics and the research on efficient man-machine cooperation developed during First and Second World War in order to maximize the efficiency of man controlled artifacts as motor cycles, cars, airplanes, ships and other war equipment. After the Second World War, systematic science in improving man-machine systems led to airplanes and cars which more and more reduced the physical and cognitive workload of the human users. Today's cars take over driving maneuvers in critical situations and electric cars equipped with sensor-actuator systems provide a multitude of possibilities to assist the driver and driving efficiency. Within the scope of research on the next generation fighter jet control an autopilot is used which is able to set its degree of autonomy in real-time based on the measured cognitive workload of the pilot [2]. An even closer relation between man and machine is represented by so called mobile suits envisaged by Japanese technology visionaries (e.g. in Japanese Mangas) since the 60 's. In 1963, the Rancho Arm was developed by Rancho Los Amigos Hospital (California) as an artificial limb for handicapped and later on integrated with computer technology by Stanford University. Experiments with whole mobile suits and power assistance devices were conducted by Japanese robotic scientists since the 70 's. Today's version of HAL (Hybrid Assistive Limb) is controlled by bio-electric signals thus blurring the borders between man and machine. Further, modern power suits allow a stepwise regulation of the suits' assistive power according to user's individual needs. Finally, Toyota calls its next generation of downsized, personal, and electrical mobility devices like iReal and iSwing explicitly "Mobility Robots" and closely cooperates with top robotic researches to make them as intuitively operated as possible.

Meanwhile, the ICT (Information and Communication Technology) and robotic technology no longer only focus on upgrading devices for mobility on middle and long distance (e.g. mobility from city to city, within a city) [3] but enhance more and more devices for mobility on a short distance and on the level of centimeters (mobility in the neighborhood, within the building, and individual motions). Especially in ageing societies, aforementioned robotic power assisting "tools" might transform our way of thinking about how to utilize robot technology. A multitude of robotic devices able to restore, support, augment, and supplement human abilities has been developed up to now. In order to support a systematic development of future concepts, new application scenarios and technologies, we have mapped the state-of-the-art of robotic power assisted "tools" supporting and augmenting human abilities. Particularly, we will show in this article, that advancing robot technology has a growing potential to gain great influence in the construction and building sector and as assistants in our built environment.

Most major industries have already extensively made use of robotic technology. Robotics has transformed production system technology in automotive industry, aircraft industry and in the electrical appliances' sector. Rapid advancements are currently made in ICT (Information and Communication Technology) and robotics in the medical field. Furthermore, in the US companies, e.g. John Deer, make advancements in applying field robotics to partly and fully autonomous farming machines. In the future, we see a huge potential for robotics – wearable cooperative systems as well as fully autonomous systems to permeate the field of construction and building technology. As construction technology we define tools and processes needed to erect a building. Whereas building technology refers to the buildings' or environment's performance and stands for tools and processes that assist people within the built environment from the scale of individual buildings up to neighborhoods or cities.

1.1 Construction technology

Up to now, automation and robotic technology has been applied in construction mainly for processing raw materials and production of building parts and building modules. Parts and modules had to be prefabricated in a structured and standardized environment for a safe and robust operation of the robots. In unstructured and not-standardized environments as on the construction site or in service environments, autonomous humanoids or service robots were difficult to operate. However, robot technology advances. Scientists as e.g. T. Hasegawa find ways to structure environments for robots [4] and also cognition and control technology become more advanced. Shimizu Corporation, a big Japanese construction company, cooperates with Yasukawa Electric Corporation, Kawada Industries and the national research institute AIST for introducing Humanoid robots to construction work for more than eight years already [5]. It has already been shown that humanoid robots as HRP-2 can carry a joinery bench together with a construction worker, fit an interior wall, and drive forklifts or diggers. Groups of HRP-2s can cooperate, move over a gradient of around five degrees and compensate for up to two centimeters on uneven surfaces [6]. They can straighten up themselves when they fall over. When carrying a component with a human, they use an adaptive and flexible arm system. An image processing system with a mobile portable control system has been developed to allow location detection. When the robots move over uneven surface, a force sensor in the sole of the foot and a balance sensor in the body register the difference and so, the sole of the foot can adapt to the surface.



Yokoyama, K., Maeda, J., Isozumi, T., Kaneko, K. (2006) Application of Humanoid Robots for Cooperative Tasks in the Outdoors

Fig. 1. Humanoid Robot HRP-2 assisting in construction environment in carrying and installing building parts and building modules. [5]

1.2 Building technology and service tasks

Experts and masterminds, as for example Bill Gates, announce the era of service robotics and estimate that service robotics as part of assisted environments will undergo a similarly fast and rigid development as the spread of personal computers in private and economic areas since the nineties. In 1961, Joe Engelberger already wondered, whether using robotic technologies only as industrial applications makes any sense. “The biggest market will be service robots,” [7] asserted Engelberger, who started the industrial robotics era, when his firm Unimation delivered GM's first robot. Today, the application of robotics and distributed robotic sub-systems finally starts to extend into our home, office and town surroundings. This transformation, which has to be understood as a natural part of the evolution of robotics, will become visible especially when robots enter the field of service, assistance and care [8]. We think that modern robotics assisting and serving human beings will permeate into the “surroundings” of daily life and thus become an integral part of our built environment. Although building's interior environments and service environments tend to be less structured and standardized, increasingly autonomous robot systems can be applied to those environments. However, from a short term perspective, it will be easier to deploy not fully autonomous robotic systems as e.g. Suits for Power Assistance because they exploit human receptiveness and flexibility for robotic service.

2. Concepts and technologies

Exoskeleton and humanoid robot technology applied in construction and building technology demands for key concepts and technologies. At fists the degree of autonomy of the designed system has to be considered. Further, the fusion of speed, power and accuracy of robotic systems with human intelligence and flexibility within one system and the operation of humans and robots in dynamic environments can be supported by recent advancements in sensing and interface technology, actuator and control system technology and system design strategies. Further, a slow but continuous break up of strict borders between professions helps to create interdisciplinary cooperation and consortia which are able handling the complex challenges of man-robot cooperation. At the end of this chapter we present a categorization of exoskeleton and humanoid robot technology applied in construction and building technology based on the system complexity.

2.1 Exoskeletons, humanoids and autonomy

Robotic systems can have varying degrees of autonomy. Robots with a low degree of autonomy require detailed pre-programming or detailed real-time operation of a human person. Robots with a medium degree of autonomy only require supervision and an operator only has to assign tasks for which the robot autonomously finds sufficient solutions. Robots with a high degree of autonomy are capable of performing tasks and making decisions without major human interference. Especially in the area of construction and building technology the degree of autonomy of a system plays an important role as e.g. construction sites and service environments within buildings often provide dynamic environments and unstructured, complex work tasks. One can address this problem by modifying or structuring the environment or work task on the one hand or by advancing robot control technology or the application of artificial intelligence on the other.

2.2 Interface technology for human-robot cooperation

In task oriented systems where humans and robots closely cooperate a close link between the man's sensing and motion system and the robot's sensors and actuators is created ideally. With every advance in sensing technology and signal interpretation methods, these cooperative approaches become more practical. Following control strategies based on sensing human motions, feelings and intentions can be distinguished:

Conventional Control

- Steering Wheel
- Joystick
- Buttons
- Touch Screens

Intuitive Control

- Motion
- Gesture
- Eye Movement
- Force

Control by Bio Signals

- Bio-electric Signals
- Vital Data (EKG, Blood Pressure, Respiration Frequency)
- Brainwaves
- Electrons transmitted from Nervous System

2.3 Tele-existence & Tele-Control

Concepts of Tele-Existence and Tele-Control to be used in the field of construction and building technology were advocated by Prof. Susumu Tachi at the University of Tokyo, already in 1980s. Tele-existence can be seen concept of advanced Tele-operation. Real world applications for tele-operated construction machinery as e.g. excavators and trucks had been developed in Japan since the Mount Unzen incident in 1991. A Vulcan eruption covered a large area with dust which would be health threatening for humans removing it. Thus a number of construction machines with the ability to be remote controlled from a save place had to be developed. Mt. Fugen is the main peak of Unzen Volcano, which is the collective name of a group of volcanic cones constituting the main part of the Shimabara Peninsula. Its phreatic eruption on 17 November 1990 caused a number of pyroclastic flows, which killed 44 people and destroyed 820 houses. The area around Mt. Fugen was deadly damaged by debris flow and pyroclastic flow. The restoration works to remove much stone and sand and the bank protection works were done by unmanned construction machines in order to avoid the risk of further catastrophes. Tele-operators manipulated machines from the operation room, which was more than 2km apart. Wearing special goggles, operators were watching 3D-images of the site sent by cameras equipped with machines. The efficiency of these remote-controlled works was estimated to be 70 percent of usual works [9]. Due to this incident Japanese researchers and construction companies realized the importance of tele-operation technology.

Today intelligent excavators with the ability for tele-operation and even partly autonomous operation capability are under development in the R&D sections of all major Japanese and Korean contractors. Further Japanese researchers and construction companies have tried to control construction machinery by teleported humanoids (Figure 02). This approach has the advantage that standard construction machinery can be used without modification.

Tele-existence and Tele-control can not only be used for 1:1 real time control of a single robot or intelligent construction machine by one assigned operator. With rising degree of autonomy of the robot systems used the tele-operator becomes a sort of supervisor able to control multiple construction machines at once. Already in the 80s the vision of multiple cooperating construction robots are operated by a single human supervisor from a central existed (Figure 03). Today indeed more and more researchers succeed in developing fully functioning and highly autonomous construction machines that can be tele-supervised (Figure 03).

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Fig. 2. Left: Prof. S. Tachi, Tele-existence Mechanical Engineering Laboratory (MEL) and MITI, 1986; Middle and Right: Contol of Honda ASIMO Humanoid; Tokyu Construction, Kawasaki Heavy Industries,and AIST

Society of Civil Engineers, Construction Robotics Commission, Prof. Shigeyuki Obayashi, 1985

Fig. 3. Multiple cooperating construction robots are operated by a single human supervisor from a central box, Vision Sketch Japanese Research Institute, 1980

Kajima, Pictures taken form website:
http://www.kajima.co.jp/gallery/civil_kajima/bousai/bousai01.html, last visited 24/07/2011.

Fig. 4. Real world applications for tele-operated construction machinery as e.g. excavators and trucks had been developed in Japan since the Mount Unzen incident in 1991. A Vulcan eruption covered a large area with dust which would be health threatening for humans removing it. Thus a number of construction machines with the ability to be remote controlled from a save place had to be developed. Kajima Corporation, Japan, 1991

Copyright T. Bock, Picture taken at Hanyang University, Laboratory of Prof. Han.

Fig. 5. Fully functioning system for tele-operation of robotic excavators, the excavators can operate on a high level of autonomy; the excavation process is monitored by separate laser module (picture right side) providing information to the robotic excavator. Hanyang University, Korea, 2011.

2.4 Actuator and control system technology

Complex systems of actuators, joints and links are controlled based on information sensed and interpreted by internal and external sensor systems. Actuators create the activity and movement within robotic systems. Today following actuation systems are used in a robotic power, motion/sensing and cognition augmentation:

- Electric Motors
- Series Elastic Actuators
- Air Pressure
- Muscle Wire (e.g. Shape Memory Alloy)
- Electroactive Polymers
- Piezoelectric Actuators

Besides the increasing ability to downsize motors it is by now possible to improve precision and speed. Advances in robot kinematics and robot dynamics are important for developing robust and save control system technology for more complex man-robot systems in construction and building technology.

2.5 Energy supply

Energy Supply is a crucial issue in developing exoskeleton and humanoid robotic applications for construction and building technology. Unlike to robotic applications in other industries, many tools and assistive devices need to be independent from connecting cables. However, battery packs necessary to supply energy for the actuators represent heavy load. Thus, on the one hand the battery systems need to be developed so that they support mobility and wear-ability of robotic systems but on the other hand robotic applications and systems have to be designed to be highly energy efficient.

2.6 Development complexity

Only interdisciplinary cooperation can handle the complexity associated with advanced man-robot cooperation systems. Besides knowledge from fields related to robotics (electrical engineering, mechanical engineering, and informatics), knowledge from various anthropological sciences as psychology, ergonomics, neuroscience and psychology is needed to design such systems [10]. Moreover, the blurring of borders between man and machine within a single system gives rise to philosophical and ethical questions. Finally, in order to receive subsidies from investing enterprises and to manage complex system developments, entrepreneurs with the ability to lead highly interdisciplinary teams and complex innovations have to be educated.

2.7 Categorization according to system complexity

In order to be able to design work tasks and application scenarios for exoskeletons and humanoids in construction and building technology we classify robotic systems according to system complexity. With complex systems we mean systems that consist of a number of sub-systems and sub-elements. Accordingly, element technologies are basic technologies. They can be applied as standalone systems or combined as sub-elements to more complex subsystems. Subsystems denote e.g. partial exoskeletons (exoskeleton for lower body part/feet, Exoskeleton for upper body part). A total system consists of several sub-systems; here we mean e.g. total exoskeletons or mobility robots. Autonomous robot systems (humanoid robots, service robots) and distributed robot systems can operate highly autonomous and are able to support robot service on city scale. They stand for highly complex robot systems built up by multitude of element technologies, subsystems and autonomous robot systems.

1. **Element Technology**
- Power Augmentation
- Sensing and Motion Augmentation
- Cognition Augmentation
2. **Subsystems**
- Assistive Devices and Partial Exoskeletons
3. **Total Systems**
- Exoskeletons
- Mobility Robots
4. **Autonomous Robot Systems**
- Android/Humanoid Robots
- Service Robots (Service in Buildings)
5. **Distributed Robot Systems**
- Town Robotics & Space Robotics

3. Examples according to system complexity

In this section we outline several examples of each of the categories introduced above. All examples contain information about the developing institution and about the systems' performance. We also go into the target groups and the development stage of each system. Each category is introduced by a short description of the status quo in the field. Further, we outline applications in construction and building technology for each category.

3.1 Element technology

Element technologies are basic technologies that can be applied as standalone systems or combined as sub-elements to more complex subsystems. We denote technologies for power augmentation, sensing and motion augmentation and cognition augmentation as element technologies.

3.1.1 Power augmentation

"Power Effector" developed by MMSE Project Team is a robot which augments the strength of a part of human body, but its concept is different from others. Most wearable robots must be compact and light in order to be comfortable for the users and be suitable for the surroundings which are designed for the dimensions of the human body. On the other hand, another approach is to be bigger and heavier so that operations can be carried out which a person itself could never accomplish. Mr. Katsuya Kanaoka, Ritsumeikan Univ. has proposed the concept "Man-Machine Synergy Effector" (MMSE), which combines flexible human skills with precision and high power of machines [11]. "Power Effector" can amplify human power 1 to several thousand times. This Technology is expected to be introduced to heavy physical work that is not programmable and requires not only powerfulness but also intelligence, facility, and experience.

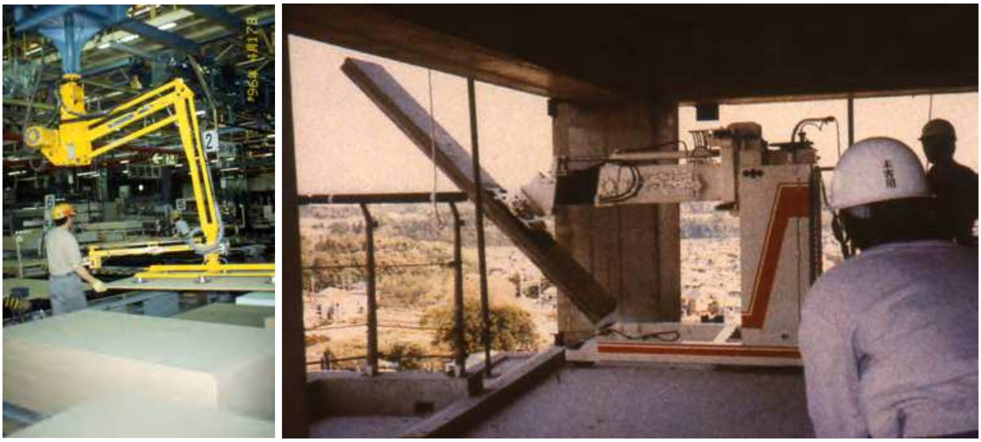
Power Effector	
Developer	MMSE Project Team
Leading Researcher	Katsuya Kanaoka, Ritsumeikan University
Purpose	Augmentation of the strength in upper limbs
Output	Arm: 50 kgf, Grip: 500 kgf
Height	1550 mm
Width	1200 mm
Length	3360 mm
Weight	120 kg
Driving System	AC Servo Motor, Ball Screw
Power Supply	AC Power Supply
Sensor	6-Axis Force Sensor

Power Effector: Scanned from Takashi, Y. (2005) Collected Data on Partner Robot Technologies, NTS. INC.

Power Pedal	
Developer	MMSE Project Team
Leading Researcher	Katsuya Kanaoka, Ritsumeikan University
Purpose	Augmentation of the strength in upper legs
Output	7 times of human power
Commercial Launch	2015
Price	20 million yen
Degree of Freedom	Leg: 3 DOF x 2 Sole: 3 DOF x 2
Sensor	6-Axis Force Sensor

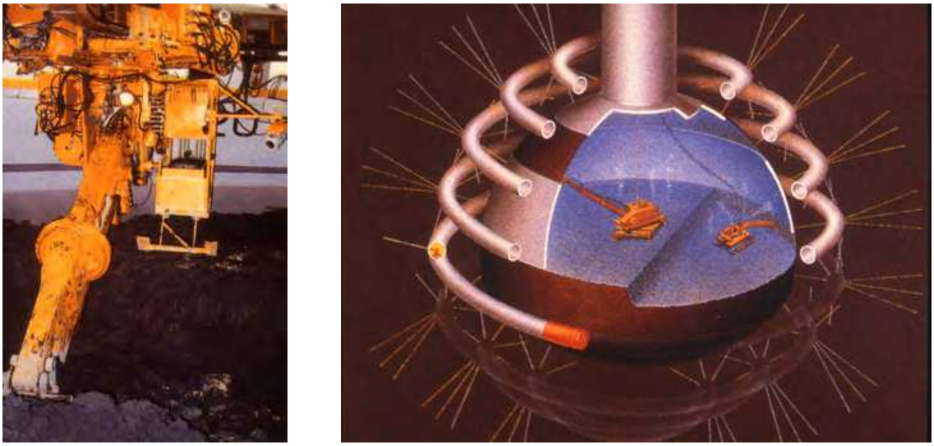
Power Pedal: http://robonable.typepad.jp/trendwatch/2008/07/post-483b.html

Application in Construction: Pre-fabrication, handling and assembly of heavy building components in factory and on-site installation of heavy panels to walls and facades.



Left: Copyright T. Bock, Right: Copyright T. Bock Komatsu Construction Machinery Division, applied at Kajima Construction

Fig. 6. Left: handling robot used in building prefabrication, Germany. Right: Power Effector used in high-rise construction for façade element installation, Japan.



Left: Copyright T. Bock, Telerobotic Caisson Construction Project, Right: Copyright T. Bock, MITI Chikakukan Project, 1985

Fig. 7. Tele-operated Power Effectors used in mining, Japan

3.1.2 Sensing and motion augmentation

This category represents robotic devices which are equipped with a part of human body and support its movements. These systems should be designed accurately not to interfering complex movements on joints. An exoskeleton developed by University of Tsukuba works only when the wearer needs its help so that it doesn't disturb wearer's delicate works [12]. Researchers in Okayama University developed some wearable robots called "Power Assist Wear" [13]. Their actuator is a pneumatic rubber artificial muscle which is light, soft and fitted for users. "Power Assist Glove" is made from a curved type of artificial muscle which is a combination of materials with different stretch, e.g. rubbers and cloths. Although they are mainly used as rehabilitation tools at the moment because of their limited effectiveness, some products aim at being adapted to construction works and enabling elderly or female workers to work with less physical efforts.

Exoskeleton hand and wrist support system	
Developer	University of Tsukuba
Leading Researcher	Yasuhisa Hasegawa
Technology Readiness	Prototype, Research and Development Project
Target user	People with weakened holding force
Purpose	Assist for motions of hand and wrist without decreasing DOF
Weight	1850 g
Sensor	Bio-electric potential measurement
Actuator	DC Motor x 12

Exoskeleton Hand and Wrist Support System: http://www.edu.esys.tsukuba.ac.jp/~hase/ForearmSupport.html

Power Assist Glove	
Developer	Okayama University
Leading Researcher	Noritsugu Toshiro
Technology Readiness	Prototype, Research and Development Project
Target User	Elderly and female workers, Heavy workers
Purpose	Assist for bending motion, Augment of the grasping force
Weight	120 g
Actuator	Two-Joint Curved Pneumatic Rubber Artificial Muscle

Power Assist Glove: http://www.smrj.go.jp/incubation/od-plus/labolist/055057.html

Application in Construction: Support of workers simple and continuous movements such as grasping control sticks or lifting heavy building materials up. Enabling weakened workers because of aging or injuries continue to work.

3.1.3 Cognition augmentation

Wearable computing systems are systems which are attached to a person’s body during use. A main goal of researchers and developers is that this systems work seamlessly in the background. They shall assist a person in various situations but not distracting him or the environment - at the best they are invisible. Wearable Computing technologies have initially been developed for monitoring astronauts: Life Guard [14] by NASA and Stanford University, USA, Health Gear [15] by Microsoft Research, E-Watch [16] by Technical University of Munich, Germany and Carnegie Melon University, USA, V-Mote [17] by Virginia Commonwealth University. Today, wearable computing systems are increasingly applied in the industry and service scenarios. A multitude of applications are envisioned in the military, too. This category “Wearable Computing” mainly represents technologies that support or augment human sight, hearing and cognition but not human’s physical motion power. Compared to mobile robots and humanoids, these wearable computing devices generally have a lower degree of autonomy as they are directly connected to the human activity.

Application in Construction: Augmented and Mixed Reality applications can support workers off-site and on-site to perform assembly operations. Wearable sensors devices attached to workers can be used to monitor their construction acidity as well as their health. Various AR and MR application have been developed at the laboratory of the authors in a project called MARY [18].

Liteye LE-700	
Developer	Liteye Systems, Inc.
Product Type	Head Mounted Display
Size	80mm x 24mm x 31mm
Weight	80 g
Display Technology	OLED
Resolution	800 x 600 and 640 x 480
Luminance	Color:>70cd/m2 White:>270cd/m2 Yellow:>650cd/m2 Green:>600cd/m2
Power	5 – 6 v DC input 400 mW Typical

Liteye LE-700: http://www.inition.co.uk/inition/dispatcher.php?URL_=product_hmd_liteye_700&SubCatID_=15&model=products&action=get&tab=summary

Anti-RSI Garment	
Project	the Con Text project: Contactless sensors for body monitoring incorporated in textiles
Developer	Philips Research Technische Universität Berlin Katholieke Universiteit Leuven Textile Research Institute Thüringia-Vogtlandia Netherlands Organization for Applied Scientific Research Clothing Plus Oy
Product Type	Wearable Computing
Purpose	Prevention against repetitive strain injuries
Sensor	Contactless EMG Sensors

Anti-RSI Garment: http://www.gizmag.com/smart-fabrics-medical-applications/10242/picture/56113/

3.2 Subsystems (assistive devices and partial exoskeletons)

This category represents wearable robots which assist wearers during laborious and continuous work. Their output is not very strong, but these devices are effective in preventing workers from getting injuries such as backaches. Honda has developed several walking assist devices based on the technology utilized in ASIMO, their famous Humanoid robot. "Walking Assist Device with Bodyweight Support System" supports a part of the wearer's weight while walking, going upstairs and downstairs and keeping in a hard position. The supposed users are not disabled but need support for certain works. Smart Support is a business company from Hokkaido University, which is aimed to popularize their product called "Smart Suit". It's a light and comfortably wearable power assist system motivated "Semi-Active Assist Mechanism". This product has been already used for restoration works after the big earthquake in Tohoku Japan.

Walking Assist Device with Bodyweight Support System	
Developer	Honda
Target User	Walker, Factory Workers
Technology Readiness	Prototype, Tested in own Factories
Weight	6.5 kg
Drive System	Motor x 2
Power Supply	Rechargeable Lithium-ion Battery
Operating time	2 hours
Support Motions	Walking, going up and down stairs, in a semi-crouching position
Sensor	Shoes: Foot force sensors
Based Technology	Honda Humanoid Robot ASIMO

Walking Assist Device Honda: http://world.honda.com/news/2008/c081107Walking-Assist-Device/

KAS: Knee-assistive System	
Developer	Hanyang Univ. Korea
Leading Researcher	Chang Soo Han
Target User	Construction Workers
Purpose	Prevention against impairment on knees
Support Motions	Level walking and Step walking while carrying heavy materials
Technology Readiness	Prototype, Research and Development Project
Strength of Assistance	45 kg
Sensor	Muscle Stiffness Sensor
Actuator	Flat motor, Harmonic drive

KAS: Prof. Thomas Bock

Smart Suit	
Developer	Smart Support
Leading Researcher	Takayuki Tanaka, Hokkaido University
Target User	Agricultural workers, Care workers
Technology Readiness	Prototype, Used for Restoration Works
Model	Smart Suit / Smart Suit Light
Weight	1 kg (goal) / 400g
Power Supply	Dry battery
Reduction of Fatigue	14%
Sensor	Back: Bending sensor
Actuator	Elastic Material, small motor / Elastic Material

Smart Suit: http://smartsuit.org/

Application in Construction: Support of workers physical abilities in light construction and restoration tasks. Support of workers in prefabrication factories for industrialized building construction (Sekisui House, Sekisui Heim and Toyota Home)

Smart Suit, Figure taken form Website: http://smartsuit.org/, last visited 24/07/2011

Fig. 8. Smart Suit developed by Hokkaido University and Smart Support Company is used for restoration works after the big earthquake in Tohoku, Japan.

Left: Walking Assist Device Honda, Figure taken form Website:
http://world.honda.com/news/2008/c081107Walking-Assist-Device/, last visited 24/07/2011,
Right: Copyright T. Bock, T. Linner

Fig. 9. Left: Honda is now testing the usability of its Body Weight Assist Device in its own factories. Right: Devices like the Body Weight Assist Device can support existing industrialized and production line based prefabrication of buildings, Sekisui Heim, Japan.

3.3 Total systems

Element technologies as described above can be combined with sub-elements and subsystems (e.g. partial exoskeletons, exoskeleton for lower body part/feet, and exoskeleton for upper body part) to more complex total systems as full body exoskeletons or mobility robots.

3.3.1 Exoskeletons

"Robot Suit HAL" is a well-known Japanese Exoskeleton which is specialized on detecting very weak corporal signals on the surface of the skin which are generated when a person attempts to move. In 2008, Daiwa House Industry started the renting of "HAL for Welfare-being". The product is now used in several nursing homes and welfare facilities in Japan to assist elderly or disabled people in walking. There are also some other prototypes of exoskeleton in Japan, and each of them uses different actuators, e.g. ultrasonic motors, pneumatic rubber artificial muscles, and air bag actuators[19][20][21]. They are tackling some common challenges such as down-sizing, long-time operations, and low-cost manufacturing in order to bring their product to market. These exoskeletons will get further usability when they are combined with some other element technologies. Prof. Shigeki Toyama, who made "Wearable Agri Robot", plans to develop Augmented Reality goggles which show information of vegetables and fruits, the health condition of workers, and the working hours and inform workers when to have a break. Although each project team expects to introduce own products into a specific working area, it's relatively easy to apply one them to other fields, especially construction works, because they support mainly same movements such as bending down or lifting heavy things up and have a common purpose; preventing workers from repetitive strain injuries.

HAL: Hybrid Assistive Limb	
Developer	CYBERDYNE
Leading Researcher	Yoshiyuki Sankai
Type	Full Body / Lower body
Target User	Physically weakened people, Disabled people
Technology Readiness	Lease Rental in nursing home and welfare facility
Price	4 - 5 million yen
Height	1600mm
Weight	23 kg/ 15 kg
Power Supply	AC100V Charged battery
Operating time	2 hours 40 minutes
Sensor	Corporal Signal Sensors Angle Sensor of joints Floor Reaction Force Sensor
Drive System	Power Units

HAL: Prof. Thomas Bock

Wearable Agri Robot	
Developer	Tokyo Agriculture and Technology University
Leading Researcher	Shigeki Toyama
Target User	Agricultural Workers
Technology Readiness	Prototype, Tested in Farmland
Commercial Launch	2012
Price	1 million yen
Type	Heavy/ Light
Support Motions	ex. Harvesting vegetables / Picking fruits
Weight	23 kg/ 30 kg
Strength of Assistance	62 % (average)
Interface	Voice Recognition
Sensor	4 types of sensors (Angle, Pressure)
Actuator	Ultrasonic Motor x 8

Wearable Agri Robot: http://www.tuat.ac.jp/~toyama/research_assistancesuit.html

Muscle Suits	
Developer	Tokyo University of Science, Hitachi Medical Corporation
Leading Researcher	Hiroshi Kobayashi
Target User	Heavy Workers
Technology Readiness	in the phase of Commercialization
Type	Arm & Back/ Back
Weight	7.5 kg/ 3.5 kg
Total DOF	6 DOF/ 1 DOF
Support Torque	Elbow: 45 Nm/ - Shoulder: 45 Nm/ - Back: 90Nm/ 90 - 360 Nm
Interface	Motion Playback by Switch / Switch
Actuator	Pneumatic Rubber Artificial Muscle

Muscle Suit: Prof. Thomas Bock

Power Assist Suit for nursing care	
Developer	Kanagawa Institute of Technology
Leading Researcher	Keijirou Yamamoto
Target User	Nurses, Care-workers
Support Motion	Lifting up a care-gaver
Technology Readiness	Prototype
Weight	30 kg
Power Supply	Ni-MH batteries
Operating time	20 minutes
Strength of Assistance	50 % (for safety measure)
Sensor	Muscle Hardness Sensor
Actuator	Air Bag Actuators driven by micro air pump

Power Assist Suit:
Prof. Thomas Bock

Wearable Robot Suit Version 2	
Developer	Univ. Korea
Leading Researcher	
Target User	
Technology Readiness	
Weight	
Power Supply	
Operating Time	
Strength of Assistance	
Sensor	
Actuator	

Wearable Robot Suit:
Prof. Thomas Bock

Application in Construction: Support of workers physical abilities in prefabrication factories or on the construction site. Support in lifting and assembly of heavy and bulky construction components [22].

Copyright Prof. Han, Hanyang University

Fig. 10. Wearable robotic exoskeleton system for construction workers. The system can e.g. support workers to carry and assemble heavy steel bars. Hanyang University, Korea

3.3.2 Mobility robots

Robots for lifting people are applied at the homely environment to support people with immobility (elderly, patients or disabled) and their caregivers. Lifting is a basic activity of daily life, meaning it is an event that is indispensable for bathing, dressing, going onto the toilet and feeding. Patient transfer robots were in the focus of researchers and commercial developers since the beginnings of the research upon nursing in the 70s. Several types of transfer can be identified and various types of robots have been developed. Robots for lifting people from the bed, robotic wheelchairs and robotic walking frames are just a few basic examples to be named among a series of robotic patient transfer systems, which have been developed up to now. However, recently robotic technology is also applied to personal mobility following a "design for all" strategy. Toyota calls its next generation of downsized, personal, and electrical mobility devices like iREAL and i-Swing explicitly "Mobility Robots" and for that closely cooperates with top robotic researchers making these devices as intuitively controllable as possible. Further, also mobile suits as Toyota's i-foot and KAIST's HUBO-FX1 [23] belong to the category of mobility robots. Mobility Robots can be considered as a special type of mobile suits. They not only augment or multiply human power but they equip human beings with a completely new capability. Mobility robots can communicate with each other and the environment (car-to-x communication) and have a high potential for autonomous or autopilot control. Therefore, in our categorization we place mobility robots between Exoskelettons and fully autonomous Humanoids.

i-REAL	
Developer	Toyota
Driving Mode	Low/ High
Height	1430 mm/ 1125 mm
Width	700 mm
Length	995 mm/ 1510 mm
Maximum cruising speed	6 km/ 60 km
Power Supply	Lithium-ion Rechargeable Battery
Charging Time	2 hours
Cruising range	30 km
Interface	Drive Controller
Other Technology	Communication Display


i-REAL: Prof. Thomas Bock

Personal Mobility for Indoor Use	
Developer	The University of Tokyo IRT, Toyota
Height	1300 mm
Width	600 mm
Length	640 mm
Weight	45 kg
Sensor	Seat: 6-Axis F/T Sensor Seat and Footrest: Pressure Sensor
Other Technology	Perception of pattern on the floor containing information about position


Mobility for Indoor Use: Prof. Thomas Bock

CHRIS: Cybernetic Human-Robot Interface System	
Developer	Hiroshima University
Height	1400 mm
Width	1000 mm
Length	750 mm
Weight	70 kg
Maximum Moving Speed	Forward: 2.5 km / h Backward: 1.8 km / h
Power Supply	Lead Storage Battery x 3
Driving System	DC Brushless Motors x 2
Interface	Cybanetic Interface


CHRIS: Prof. Thomas Bock

Walking Assist Device	
Developer	HITACHI
Height	
Width	
Length	
Weight	
Power Supply	
Driving System	
Interface	

HITACHI: Prof. Thomas Bock

i-foot	
Developer	Toyota
Height	2360 mm
Weight	200 kg
Total DOF	12 DOF
Load Capacity	60 kg
Cruising speed	1.35 km/h
Interface	Joystick Controller
Other Ability	Navigating Staircase

i-foot: Prof. Thomas Bock

HUBO FX-1	
Developer	KAIST
Height	1750 mm
Weight	150 kg
Total DOF	12 DOF
Load Capacity	100 kg
Driving System	400 / 800W AC Servo Motor with Driver
Sensor	3-Axis F/T Sensor at feet Inertial Sensor at Torso 2-Axis Accelerometers on Soles
Interface	Joystick

HUBO FX-1: KAIST Humanoid Robot Series, Public Demonstration

Application in Construction: Support of material and element delivery and installation. Support of factory logistics and construction site logistics. Adaptability of technologies like a recognition system of floor surface which some personal mobility robots already have into logistics on construction site or prefabrication factories.

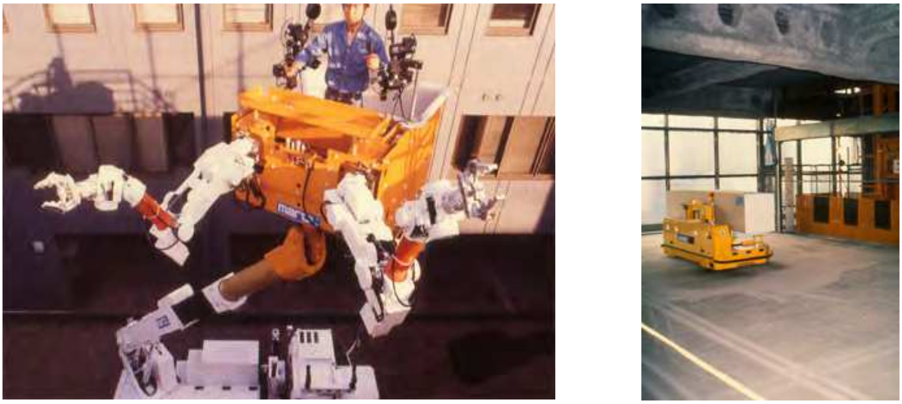


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Fig. 11. Left: Mobile Construction and Maintenance Robot, TEPCO, Japan; Mobile and Remote Controlled Transportation Robot for Construction Sites, Obayashi, Japan

Copyright Dr. S. Lee, Prof. Han, Hanyang University

Fig. 12. Mobile Robotic System for Human-Robot cooperative work tasks (Ceiling Panel Installation), Samsung Construction and Hanyang University, Korea.

3.4 Autonomous robots

Autonomous robots stand for highly complex and autonomous robot systems built up by multitude of element technologies and subsystems. In our categorization we consider android/humanoid robot system and service robots as autonomous robot systems.

3.4.1 Android/Humanoid robots

Humanoid robots are complex autonomous systems that can adapt to changes in the environment. Their appearance, function and motion capability are entirely depending on the equivalent in the human body. Androids not only interpret the human body's function but are designed to imitate human appearance and behavior. For both humanoids and androids service scenarios can easily be envisioned, yet, due to their technical complexity, real world applications are still rare. Exoskeletons come from a contrary approach, combining the flexibility and intelligence of human beings with the speed and power of robotic systems. Today, Wearable Robots and Assistance Suits provide more flexibility, however, in the future, considering advancements in robot control and artificial intelligence, autonomous humanoids, androids and inhuman service robots are likely to increase in flexibility and the ability to adapt to various unstructured tasks and environments.

HRP-2 Promet	
Developer	Kawada Industries
Height	1540 mm
Width	620 mm
Weight	58 kg (including batteries)
Walking speed	0~2 km/h
Holding Force	2kgf (one hand)
Total DOF	30 DOF
Drive System	48V 20A(lmax), 2axes/driver x 16
Power Supply	NiMH Battery DC 48V, 18Ah
Sensor	Joint: Incremental Encoder Visual Input: Trinocular Stereo Camera Body: 3-axis Vibrating Structure Gyro, 3DOF Acceleration Sensor Arm: 6-axis F/T Sensor Leg: 6-axis F/T Sensor

HRP-2: Prof. Thomas Bock

HRP-1S	
Developer	Honda
Height	1600 mm
Width	600 mm
Weight	99 kg (excluding batteries)
Walking speed	0 ~ 6 km/h
Total DOF	30 DOF
Drive System	Brushless DC servo motor
Power Supply	Ni-Zn Battery
Sensor	Body: Inclination Sensor (Gyro-scopes and G-force sensors) Foot and wrist: F/T Sensor Head: 2 Video Cameras

HRP-1S: Prof. Thomas Bock

KHR-3 (HUBO)	
Developer	KAIST
Height	1250 mm
Width	417mm
Depth	210mm
Weight	56 kg
Walking Speed	0 ~ 1.25 km/h
Grasping Force	0.5 kg / finger
Total DOF	41 DOF
Power Supply	300W NiMH Battery
Operation Time	90 min.
Sensor	3-axis F/T Sensor Tilt Sensor CCD Camera Pressure Sensor

KHR-3: http://hubolab.kaist.ac.kr/KHR-3.php

Application in Construction: Control of existing standard construction machinery by tele-operated humanoids (Figure 13). Humanoid Robots (as e.g. HRP-2) can assist workers in construction environments by carrying and installing building parts and building modules (Figure 01).

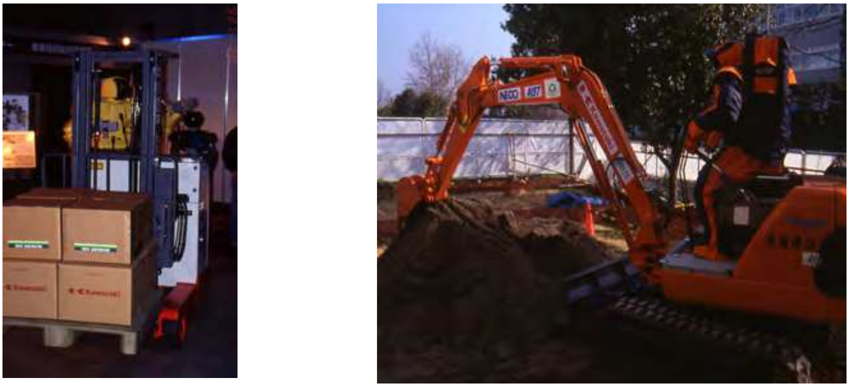

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Fig. 13. Left: HARP Humanoid Robot driving forklift delivering construction material. Right: Honda’s Asimo controlling an excavator.

3.4.2 Service robots (service in buildings)

Especially in Japan, a multitude of so called Entertainment Robots and Service Robots are developed and sold. Entertainment robots are designed to amuse, communicate, and perform simple tasks in the household. Mitsubishi’s Wakamaru and Sony’s Aibo for example had primarily been designed to communicate with household members and play music, not for providing care or household services. Yet, as the upkeep of social interaction increasingly becomes an integral part of care strategies, the taking over of entertainment and communication tasks by robots is envisioned by researchers and developers. Furthermore, homemaking robots are robots which take over simple tasks as cleaning, transport of objects or informing about intruders or the pet's well-being. Often, the robot's performing tasks in the household contain elements of both entertainment and homemaking.

Wakamaru

Developer	MITSUBISHI HEAVY INDUSTRIES
Business Model	Home Service Robot
Height	1000 mm
Width	450 mm
Length	470 mm
Weight	30 kg
Maximum Moving speed	1 km/h
Total DOF	13 DOF
Drive System	DC Servo Motor
Power Supply	Lithium-ion Battery
Operation Time	2 hours
Communication	Human detection, Individual recognition, Voice Recognition, Speech synthesis

Wakamaru: Prof. Thomas Bock

RIDC-01

Developer	Tmsuk
Business Model	Guidance & Cleaning Robot
Height	1300 mm
Width	700 mm
Length	960 mm
Weight	100 kg
Maximum Moving speed	3.0 km/h
Total DOF	10 DOF
Power Supply	DC-24V Lithium-ion Battery
Operation time	2 hours

RIDC-01: Prof. Thomas Bock

PBDR: Partner Ballroom Dance Robot	
Developer	Tohoku University NOMURA UNISON TroisO
Business Model	Dance Partner Robot
Height	1650 mm
Width	1000 mm
Length	1000 mm
Weight	100 kg
Degree of Freedom	15 DOF
Drive System	Servo Motor
Power Supply	Battery

PBDR: Prof. Thomas Bock

Application in Construction/Building: Service Robots can assist to carry out or can (partly) autonomously carry out household tasks and care tasks in an ageing society. Transfer of technologies (which some entertainment robots already have) towards humanoid robots thus gaining communication and cooperation ability. Further service robots can be used to maintain buildings, inspect nuclear power plants [24] and assist in homes for the elderly.

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Fig. 14. *Left:* Wakamaru acting as edutainment and communication robot in a home environment. *Right:* Robot for guiding and helping blinded and disabled people at home

3.5 Distributed robot systems

Urban robotics is a research field situated between smart/sensible city research and robotics research. Its goal is to develop cutting-edge technologies as well as application scenarios for urban life supported by robotic devices. The research field is pioneered by T. Hasegawa and his Town Management System enabling robots to outsource complexity to sensors and vision systems distributed in the city environment [4]. Other interesting impulses in this research field are coming from research on smart cars and e-government. Furthermore, NASA accounts controlled traffic systems and smart grid energy systems as so called "Immobile Robots" [25].

Application in Construction/Building: Distributed robot systems enable robots to execute various tasks for ordinary human life on building and city scale. Further, they can be used to operate highly automated construction sites (this application of robotics we describe in detail in [26]). Tele-operated robot and construction system consisting of multiple subsystems can be used for automated construction on moon, mars or deep sea and underwater mining operations.

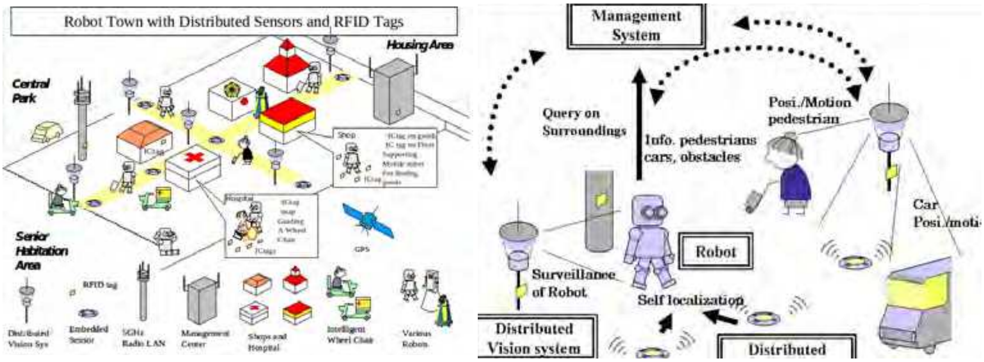

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Fig. 15. The Robot Town enables robots to execute various tasks for ordinary human life by creating an urban environment well structured in informative way for robots and service systems. T. Hasegawa, Kyushu University [4].

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Fig. 16. Control Center of Shimizu's automated construction system for highly automatic erection of high-rise buildings, Japan, Shimizu Corporation

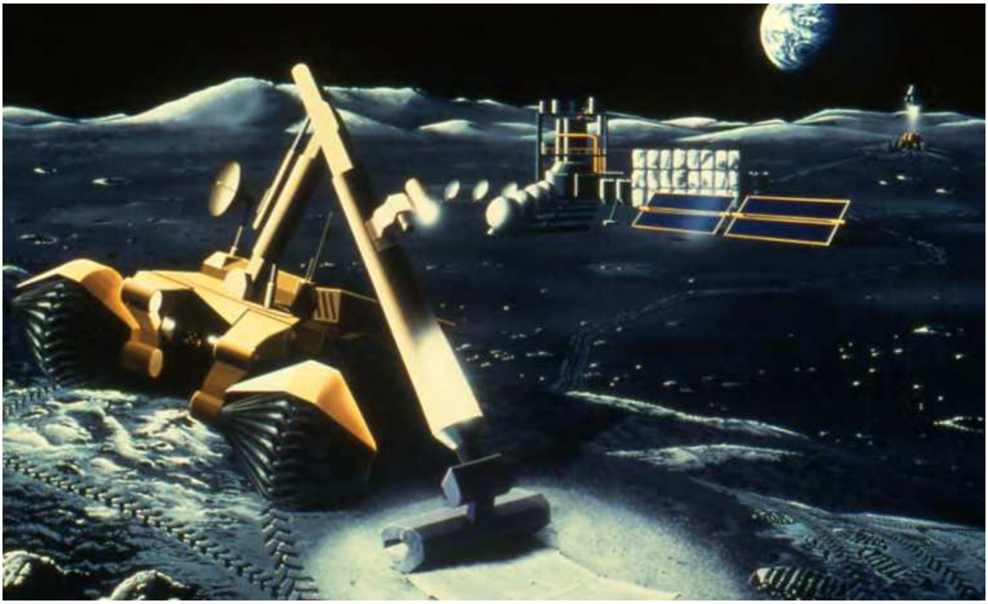

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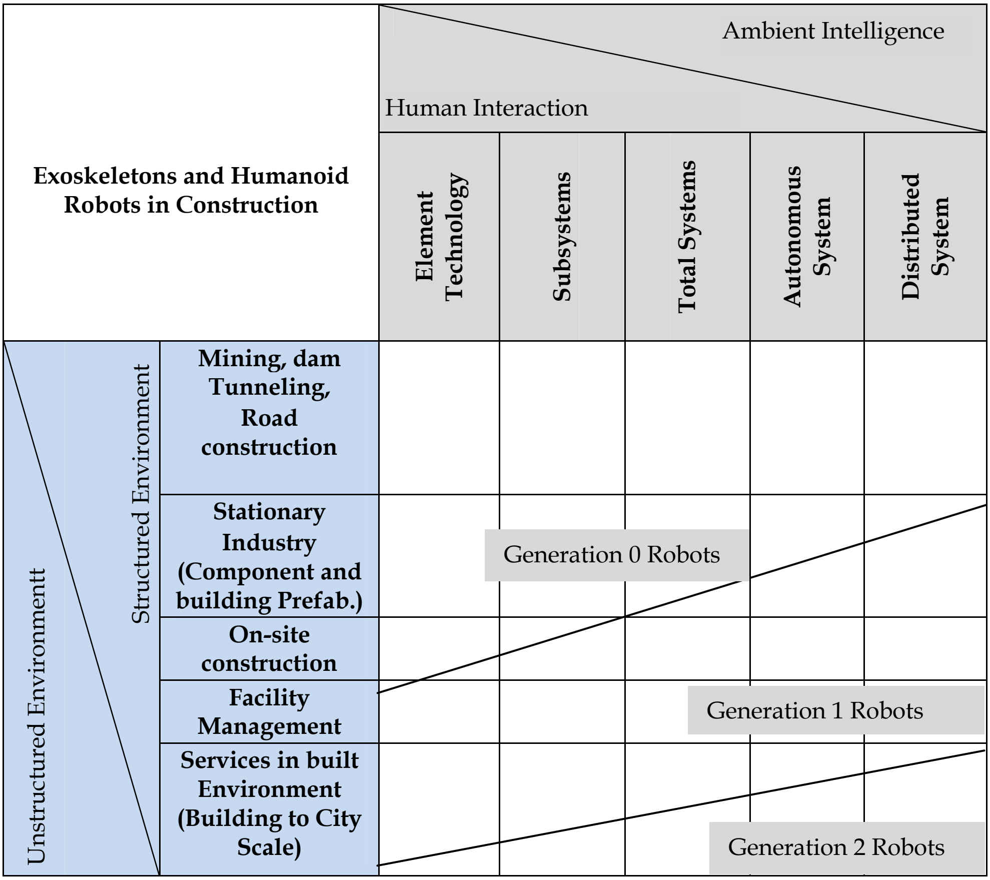
Fig. 17. Tele-operated robot and construction system consisting of multiple subsystems for automated construction on moon or mars, Japan, Shimizu Corporation.

4. Relation of system complexity and work task complexity

By implementing robotic technology in construction and building technology, the degree of autonomy of the robotic system has to be considered. In general, the degree of autonomy of a robotic system is closely correlated to its work tasks it can perform. Work tasks can be classified into work tasks which are structured and standardized on the one hand and unstructured and not standardized work tasks on the other hand. For example, on the lowest level, resources and materials are processed using robots in standardized conditions. However, the assembly of building kits is done in a less structured environment and thus needs robotic systems which are more flexible. Up to today, it was difficult to apply humanoids to other autonomous complex robot technology in work tasks as building kit assembly and service. Yet, advancements in structuring environments and information about the environment for robotic systems on the one hand, and robot control technology and artificial intelligence on the other hand, lead to the fact that all highly autonomous systems can increasingly be applied in service environments.



Exoskeletons and Humanoid Robots in Construction			Human Interaction				Ambient Intelligence
			Element Technology	**Subsystems**	**Total Systems**	**Autonomous System**	**Distributed System**
Unstructured Environmentt	Structured Environment	**Mining, dam Tunneling, Road construction**					
		Stationary Industry (Component and building Prefab.)		Generation 0 Robots			
		On-site construction					
		Facility Management				Generation 1 Robots	
		Services in built Environment (Building to City Scale)				Generation 2 Robots	

Table 1. Up to today, it was difficult to apply humanoids to other autonomous service robots in work tasks as building kit assembly and service. Yet, advancements in structuring environments and information about the environment for robotic systems on the one hand, and robot control technology and artificial intelligence on the other hand, lead to the fact that all highly autonomous systems can increasingly be applied in well planned service environments.

The notion of Generation Robots was introduced by Professor H. Moravec, Carnegie Mellon University, in order to describe the evolution of robot technology in near future. First Generation Robots refer to robot systems have an autonomy and intellectual capacity that is compare able to that of a lizard (available: 2010). Second Generation Robots are capable of learning and their intelligence is comparable to that of a mouse (available: 2020). Further, intellectual abilities of Third Generation Robots shall be comparable to that of a monkey (available 2030) and that of Fourth Generation Robot's intelligence finally shall be comparable to that of human beings (available: 2040). In order to be able to describe earlier developments in robot technology we introduce generation zero in our graphic.

5. Modularity and compatibility of element technology

The authors are currently working on applying and seamlessly integrating distributed robotic technology and mechatronic systems into home, care and city environments [27] [28] [29]. When people are assisted in close correlation by a robotic system, it is necessary to acquire as much data as possible about the person in real-time (e.g. activity, movement, vital signs) in order to understand and be able to predict mental and physical stat at any time. The authors currently develop a chair which is in real-time monitoring and interpreting vital data and is beyond that able to serve as a control station for games and home automation. The chair is developed within GEWOS, a University-Industry collaborative project financed by the German ministry (Runtime: 2010-2013) [30]. Its objective is to upgrade furniture components with sensors and other mechatronic components in order to support a healthy, save and active life at home. Among the partners are the Fraunhofer Institute for integrated circuits (section medical sensors) and EnOcean GmbH, a forerunner in energy harvesting and sensor applications. The first target of the consortium is to develop a "Fitness Chair" which is measuring people's vital signs, then makes those vital signs transparent to the user and finally try to activate the user to become more active (Figure 15), do sports and meet friends.

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Fig. 18. Sensor Chair developed within the authors' R&D (Research & Development) Project GEWOS. The "Fitness Chair" is measuring people's vital signs, makes those vital signs then transparent to the user and finally try's to activate the user to become more active, do sports and meet friends.

Fig. 19. Similarity and interchangeability of underlying basic technologies between robots of different categories. From left to right: Kaist's Humaniod Robot HUBO, Kaist's Mobile HUBO FX-1 suit built upon the HUBO platform, TUM's GEWOS sensor chair serving as control interface, IRT'S and Toyota's r intuitively controllable robotic wheelchair.

Above, the chair provides an open server platform which allows doctors, physical therapists and other health professionals to develop service applications for customers. Beyond that, the chair with its variety of integrated sensors serves as a controller for virtual reality games and home automation. Companies as well as researchers are interested in bringing this solution to the market. In March 2011 it has even been covered by the German issue of Technology Review. The chair contains following systems:

EKG-Module: Measuring heart rate variability

SPO2-Module: Measuring blood pressure and oxygen saturation of the blood by infrared and special signal processing algorithms

Activity-Module: Sensor system for analyzing the user's activity in the proximity of the chair

Weight-Module: Measuring weight and weight distribution on the chair

Data Platform with GUI: Allows third parties (doctors, physical therapists and other health professionals) to develop service applications for customers

Gaming Aspect: Chair itself can be used as controller and training application to enhance the user's activity at home.

The technology applied to the GEWOS Sensor chair has the potential to be applied to Mobility Robots (e.g. IRT'S and Toyota's r intuitively controllable robotic wheelchair) and mobile suits (e.g. Toyota's i-foot, Kaist's Mobile HUBO FX-1 suit built upon the HUBO platform) for more users being accumulated and indirectly controlled. Further, HUBO FX-1 is good example that it is possible to apply technological platforms to robots of various categories. The HUBO leg platform has been applied to the Humanoid robot HUBO as well as to the Mobility Robot HUBO FX-1. It can be assumed that in the future this interchangeability of technologies will increase. So that, for example wearable computers (e.g. head up displays) and Single Joint Assistance Devices can support users to control Mobility Robots and Humanoids.

6. Conclusion

We have argued that human beings are steadily using and advancing tools. Exoskeletons and especially humanoid robotic technology in ill defined construction and built service environment as a whole or its subsystems/elements can be seen as a highly advanced tool or cooperating set of tools. Exoskeletons and humanoid robotic technology not only allows augmenting human abilities but creates tools that are capable of autonomous decision-making and performance in order to achieve certain goals as agent of a human being especially in dangerous, dirty and tedious construction activities. Most major industries have already extensively made use of robotic technology, which transforms production system technology in automotive industry, aircraft industry, the electrical appliance's sector, the medical field, farming and even recently construction. For the near future, we see a huge potential for robotics – wearable cooperative systems as well as fully autonomous systems- to permeate the field of construction and building technology. We have presented a categorization distinguishing between mechatronic, robotic, microsystemic element technology (power augmentation, sensing and motion augmentation, and cognition augmentation), subsystems (assistive devices and partial exoskeletons), total systems (exoskeletons, mobility robots), autonomous robots (humanoids, service robots) and highly complex distributed robot systems. Further, we have shown that with each new generation of robots, the applicability of robots in rather unstructured environments as on the construction sites or in building service environment advances. Finally, new sensing and interface technologies allow that robotic systems can be fully integrated in complex human-machine interaction systems and tasks. Based on the findings presented in this article, we assume that more and more flexible and autonomous exoskeletons and humanoid robotic technology will continue to permeate our in terms of complexity and work tasks rather unstructured domain of construction and building environment. Ultimately those exoskeletons and humanoid robotic technologies even will open up completely new possibilities for mankind in extreme and highly unstructured environments such as deep sea under water mining/habitat and construction and mining in space.

7. Appendix

Appendix should be put at the end of the chapter before Reference. You do not need to include any number before Appendix.

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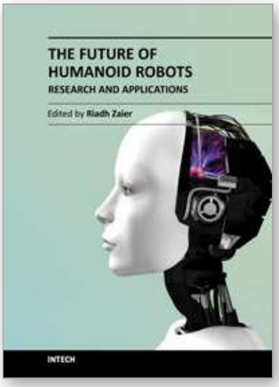

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This book provides state of the art scientific and engineering research findings and developments in the field of humanoid robotics and its applications. It is expected that humanoids will change the way we interact with machines, and will have the ability to blend perfectly into an environment already designed for humans. The book contains chapters that aim to discover the future abilities of humanoid robots by presenting a variety of integrated research in various scientific and engineering fields, such as locomotion, perception, adaptive behavior, human-robot interaction, neuroscience and machine learning. The book is designed to be accessible and practical, with an emphasis on useful information to those working in the fields of robotics, cognitive science, artificial intelligence, computational methods and other fields of science directly or indirectly related to the development and usage of future humanoid robots. The editor of the book has extensive R&D experience, patents, and publications in the area of humanoid robotics, and his experience is reflected in editing the content of the book.

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