# Assistive Mobile Robot Systems helping the Disabled Workers in a Factory Environment

Jung Won Kang*, Hyun Seok Hong**, Bong Sung Kim***, and Myung Jin Chung****

*,**,***,****Department of Electrical Engineering , KAIST, Daejeon, Republic of Korea
(Tel : 82-42-869-8029; E-mail: {kctown, wiser, kbs99446}@cheonji.kaist.ac.kr, mjchung@ee.kaist.ac.kr)

***Abstract-*** This paper presents assistive mobile robots that help the disabled to work in a factory environment. The target users as well as the functions of the robot were determined based on varied survey results. After the specific mission was derived, the robots were developed through a repetitive process of designing, development and evaluation. As a result, three mobile robots were developed. The first version of the mobile robot focused on the various functions of the robot. The robot arm and a forklift part of the robot support various tasks for the disabled. The second version is focused on the mobility. A Mecanum wheel-based omni-directional driving mechanism is adopted to improve the mobility of the robot in small spaces. Furthermore, a foldable forklift is used to reduce the size of the robot. The omni-directional driving mechanism was also utilized on the third version. A unique structure for the body frame of the robot is introduced to reduce the vibration caused by the Mecanum wheel rollers. To improve user convenience while using the lift, the third version is equipped with a multiple pillar-based foldable forklift. These robots are expected to provide assistance to disabled workers in a factory environment.

***Index Terms*** – Assistive robot, Mecanum wheels, Omni-directional mobile robot, Rehabilitation robot

## 1. Introduction

Assistive robots are a means of improving the welfare for the disabled. Previous research on the subject of the assistive robots for disabled individuals has focused mainly on assisting them with their routine tasks. An intelligent bed-robot system [1] and a care robot system [2] have been designed to help the disabled complete their daily activities in an indoor environment. Several human-robot interface devices, including an eye gaze estimation system [3], have been developed for easy control of a robot system. The systems known as FRIEND [4] and KARES II [5] are wheelchair-based rehabilitation robotic systems equipped with a robot arm. They are designed to help the handicapped manipulate small objects such as food, a cup and a book. On the other hand, assistive robots can give the disabled vocational opportunities. Vocational assistive robots can help the disabled live productive lives through their own vocations. That is, development of vocational robot systems that help the disabled in their vocations has significant meaning considering the true meaning of the welfare. The RAID system [6], developed at the Rehabilitation Engineering Research Center in Sweden, assists in removing books from a bookshelf, carrying documents, and serving drinks in an office environment. The WALKY system [7] is able to avoid obstacles while it maneuvers to deliver objects in a laboratory environment. The ProVAR system [8] receives orders using a speech recognition system and helps with office tasks, including serving drinks and delivering documents, diskettes, and video tapes. Although these vocational assistive robots have been developed, their use is limited to an office environment. However, the types of tasks that the disabled perform differ from country to country due to regional differences in industrial structures. As an example, in South Korea, most employers prefer the disabled to work in a manufacturing environment. However, there has been little research dealing with the development of vocational robotic systems that can help the disabled in a factory environment. Therefore, in this research, mobile robot systems that assist the disabled when they work in a factory environment were designed and developed. Fig. 1 describes the development of the proposed robot systems. After a specific mission is derived based on specific target users and tasks, the robots are developed through an iterative process of designing, development, evaluation, and modification.

The criteria for this process are 'assisting the disabled as much as possible,' 'considering an actual employment situation for the disabled' and 'assisting with the most common tasks of the disabled'. To derive a specific mission, the demographics of the disabled, their actual employment situations, and their required tasks were surveyed. Based on the survey results, the target types of disabled individuals along with the functions of the robot were determined. The goal was determined as the development of an assistive mobile robot system that helps an individual with a limb disability perform tasks such as the assembly and carrying of boxes.

As an initial version, the mobile robot termed Type 1 was designed [13][14][15]. This design focused on a range of functions. The Type 1 design was evaluated in existing manufacturing companies. Through these evaluations, it was possible to identify problems with the system and acquire feedback that would lead to improvements. The Type 1 evaluation results led to the development of the system termed here as Type 2 [13][14][15]. This system is operated using an omni-directional driving mechanism and is equipped with a foldable forklift that reduces the size of the robot. The Type 2 design was also evaluated in actual

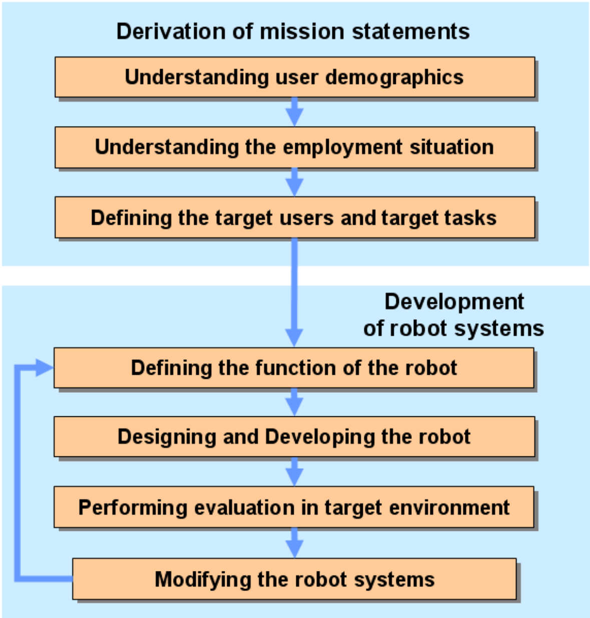



Fig. 1. Development procedure of the robot systems

companies. Due to the small size of the robot and its improved mobility in small and narrow spaces, the workers generally gave positive feedback regarding this system. Based on the feedback from the evaluation, a third version of the robot was developed [16][17][18]. This version is equipped with improved Mecanum wheels. In addition, it has an improved robot body frame and forklift system. Through the aforementioned process of repetitive development and evaluation, assistive mobile robots capable of helping the disabled in actual factory environments were developed.

This paper is organized as follows. Section 2 describes the mission derivation and the target environment modeling procedure. This section also describes the manner in which the target user and the specific functions of the robot are determined. Section 3 describes the Type 1, 2, and 3 mobile robots, including each design concept and evaluation result. This work is concluded in Section 4. In addition, videos of these robots have been posted to the website http://rr.kaist.ac.kr/project_workrobot.htm

## 2. Mission Derivation

### 2.1. Mission Derivation

A survey was conducted to determine the target user and to understand their actual employment situations and most common tasks.

In order to determine the target user, several reports [9], [10], [11] by a government agency were investigated as they pertained to the disabled in South Korea. As shown in Fig. 2, among the total disabled, 55.1% of the disabled can be categorized as severely disabled in terms of physical ability, 8.7% as sufferers of cerebral paralysis, 10.5% have a visual disorder, 8.8% a hearing disorder, and 0.8% a speech disorder. Among those who are severely physically disabled or who suffer from cerebral paralysis, the percentage of those with impaired use of their legs is high, as shown in Fig. 3. Moreover, most of participating workers have crippled disorder regardless of the scale of the workshop, as shown in Table 1. Based on these data, it was confirmed that workers who had crippled disorder were the majority. Therefore, those participants were determined as the target user in order to assist the disabled as much as possible.

In order to determine the type and functions of the robot, the actual employment situations and the most common tasks of the disabled were surveyed. To grasp the actual situation of employment of the disabled, vocational education facilities[1] and companies[2] that hire the disabled were visited. The results of the survey show that the disabled typically prefer computer-oriented jobs and mechanical jobs, as shown in Fig. 4. However, the vocational fields in which employers utilize the skills of the disabled are mainly simple labor jobs [12], as shown in Fig. 5. According to these investigations, there are considerable gaps between the occupations that the disabled desire and those for which companies have a need that the company feels the disabled can fill. As a result,

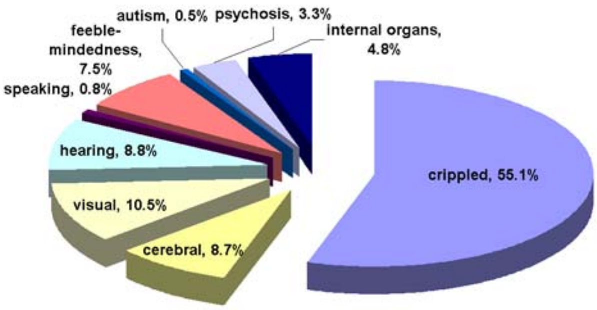



Fig. 2. Types of disabled individuals

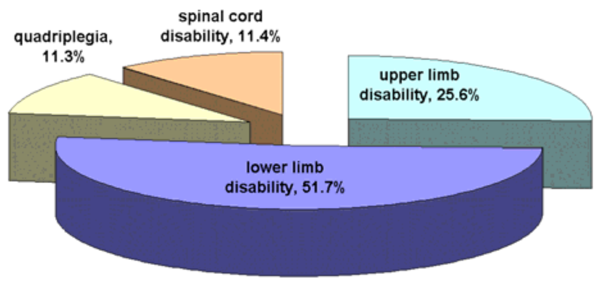



Fig. 3. Distribution of the severely physically disabled(crippled disorder) and those with cerebral paralysis

Table 1
Distribution of Actual Employment for the Disabled[3]

| Types of disorder | Large workshop | Small workshop |
|---|---|---|
| Limb impairment | 82.0% | 81.0% |
| Cerebral paralysis | 0.2% | 0.2% |
| Visual disorder | 4.4% | 3.1% |
| Hearing disorder | 9.8% | 6.2% |
| Speech disorder | 1.2% | 1.1% |
| Other | 2.4% | 8.4% |

[1] Bundang branch of the Korea Employment Promotion Agency for the Disabled and vocational schools in Daejeon and Ilsan, Republic of Korea

[2] Eleven factories including Mugunghwa Electronics and Immanuel Electronics, which primarily create electronics, and Boram-Dongsan, which mainly assembles mechanical parts.

[3] Companies with more than 300 employees are classified as a large workshop.

although many social organizations provide vocational education to the disabled, the actual employment situations typically see the disabled perform only simple labor. Therefore, considering the actual employment situation, it is desirable to develop a system to help the disabled to perform simple labor tasks such as the assembling and classifying of circuit parts, the transport of objects, or those that involve packing or delivering.

Details of the most commonly performed task for the disabled at a workplace was sourced from the literature [11]. According to the referenced report, handicapped workers have difficulty when they are carrying heavy materials, as shown in Table 2. The report also showed that those with upper limb impediments want a robot system to serve as an arm while performing tasks that include fixing and loading, as well as those involving precise motions. Those with leg impediments want a system to substitute for the function of the leg as much as it contributes in movement, loading, and other tasks. Therefore, it was found to be necessary to design the robot to transfer objects and perform dexterous tasks while moving around freely.

In summary, the goal of this study is to develop

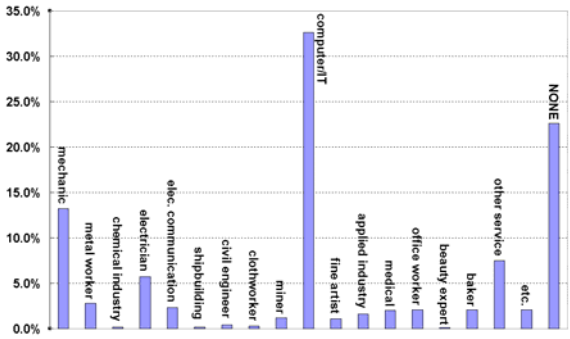



Fig. 4. Vocational fields in which the disabled want to be trained

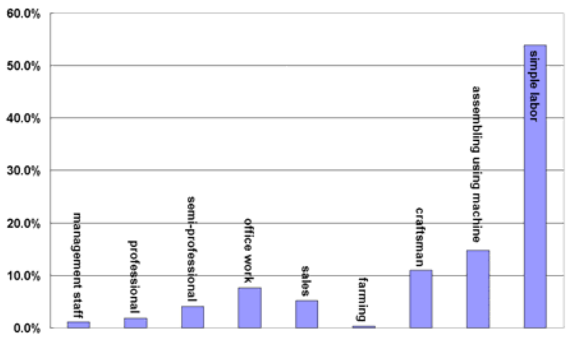



Fig. 5. Vocational fields in which the employers use the disabled

Table 2
Situations where the Disabled Workers Require Help

| Situations | Large workshop | Small workshop |
|---|---|---|
| Transferring stuff | 55.4% | 33.8% |
| Moving around the workshop | 14.5% | 31.5% |
| Operating machines | 27.9% | 20.0% |
| Difficulty to understand instructions | 24.4% | 22.3% |
| Operating speed | 20.0% | 31.5% |

assistive mobile robots that help individuals with lower- or upper-limb disabilities or both lower- and upper-limb disabilities to perform tasks such as assembling, classifying circuit parts, inspecting circuits and moving boxes.

### 2.2. Target Environment Modeling

To define and model the target environment, one of the companies visited as part of this study was selected as a target environment. Fig. 9 shows the overall view of the target environment. According to the survey result, most factories involved in this study produce electronic products such as battery chargers, vacuum cleaners and circuits that require soldering and assembling. Most manufacturing factories consist of long tables equipped with a conveyor, a warehouse containing parts in boxes on pallets, safety lines around them, and aisles, as shown in Fig. 6. At the table space of each worker, boxes that contain parts are stacked on their left and right sides, as shown in Fig. 7. At each space, a worker performs dexterous tasks such as soldering and assembling at the worktable. When a worker does not have enough parts, he moves to the warehouse, and picks up boxes that contain the necessary parts. After returning to the worktable, he resumes working.

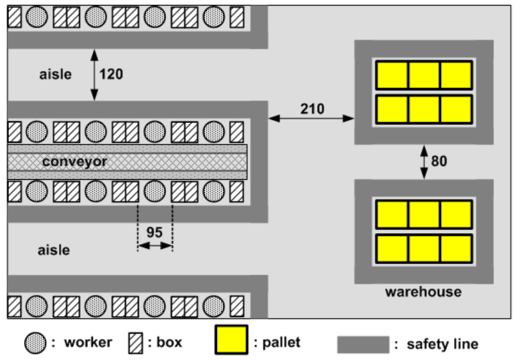



Fig. 6. Top view of the target environment (dimension: [cm])

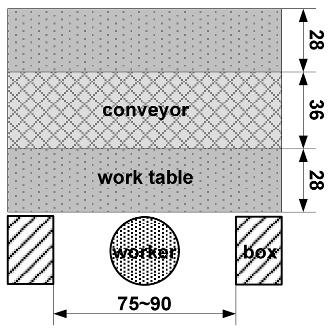



Fig. 7. Top view of space allocated for a worker working at a worktable (dimension: [cm])

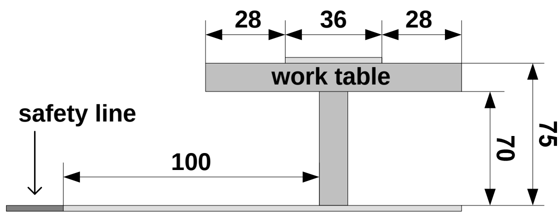



Fig. 8. Side view of space allocated for a worker working at a worktable (dimension: [cm])

Fig. 9. Overall view of the target environment

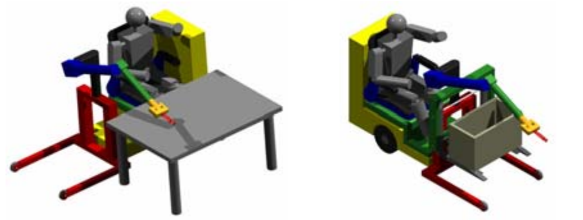
## 3. Development of Assistive Mobile Robot Systems

### 3.1. Assistive Mobile Robot System Type 1

#### 3.1.1. Designing & Development

When parts to be assembled are needed or when it is necessary to transfer materials, the worker moves the robot and picks up the materials. Therefore, a forklift system was adopted in the robot system. The forklift is mounted on the front of the robot. The driving mechanism of the robot is an important issue in that the forklift should move heavy boxes. To satisfy the necessity of convenience when using the forklift and to ensure the stability of the forklift, a forward wheel driving/backward wheel steering mechanism was adopted. This mechanism is very stable, and many commercial forklift trucks use this mechanism. It is assumed that the disabled worker works while sitting on the chair of the robot. Therefore, the height of the chair of the robot should be lower than that of the worktable. Furthermore, it should be possible to rotate the chair up to a right angle to support tasks at the worktable. Fig. 10 depicts a scenario in which a disabled worker at the worktable uses the robot arm and moves boxes using the forklift. To support task at the table, the robot is parked parallel to the table and the chair is rotated toward the table. This setting makes it easy for the worker to work with robot arm.

The first version of the developed robot is shown in Fig. 11. Its system configuration is shown in Fig. 12. The mobile robot has two motors, one for driving and the other for steering. The TMS320LF2407A DSP board is used to control the motors. The forklift system also has two actuators to place and lift objects. A MANUS arm is installed onto the front of the robot. Each component of the robot, including the robot arm, the mobile platform, and the forklift, is controlled by a 2-axis joystick with several operation modes for that allow control of each component. To control the system in real time, a PC running Linux/RTAI is used as the main system. For a table task, the robot has a revolving chair that is rotated manually. To ensure user safety, it also has four limit switches for emergency stopping and ten ultrasonic sensors to detect obstacles in the rear as a type of collision warning system. In addition, a camera is installed in the rear of the robot and a monitor connected to it displays the scene as it appears behind the robot.



(a) (b)

Fig. 10. Operation scenario of Type 1 robot
(a) A disabled worker performs dexterous tasks at the table using the robot arm
(b) A disabled worker carries boxes using the forklift.

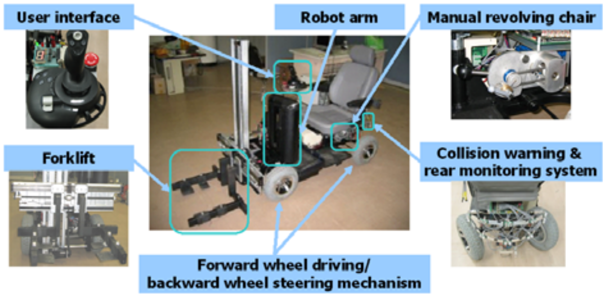



Fig. 11. Assistive mobile robot system Type 1

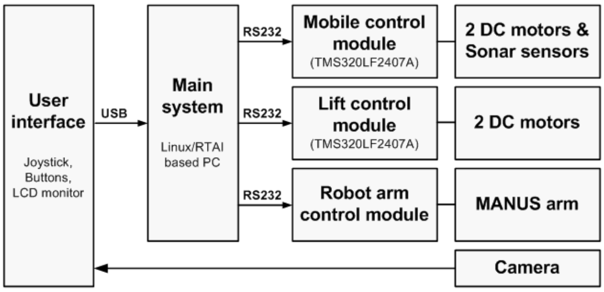



Fig. 12. System configuration of the Type 1 robot

Table 3
Specifications of Assistive Mobile Robot Type 1

| | |
|---|---|
| Size | 650×1400×550 [mm] (Width×Length×Height) |
| Max. Speed(Mobile) | 12 km/h |
| Max. Load(Mobile) | 200 kg |
| Max. Load(Lift) | 60 kg |

#### 3.1.2. Evaluation

The proposed robot was tested in the existing manufacturing factories of Boram-Dongsan and Mugungwha Electronics, both of which are located in South Korea. Two participants were randomly selected among workers with lower- or upper-limb impairments or both lower- and upper-limb impairments. Fig. 13 shows the user trials with this robot. After the user trials of the robot, the users were interviewed regarding the ease of controlling the robot, the forklift and the arm as well as the use of the user interface and the device as it pertains to user safety. Furthermore, comments from another fifty workers were gathered through a written survey.

The respondents said that the driving mechanism was appropriate when using the forklift mounted on the front. Moreover, they reported that it was easy to control the mobile robot using the joystick. They also

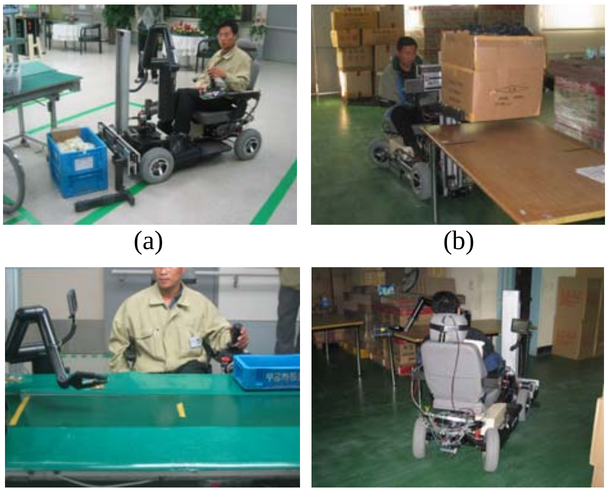

(a) (b) (c) (d)

Fig. 13. User trials of assistive mobile robot Type 1
(a) Moving material - lifting up
(b) Moving material - lifting down
(c) Working at worktable
(d) Moving around

reported that they felt safe while moving around due to the collision warning system. On the other hand, several shortcomings were identified. First, the size of the mobile robot and the turning radius of the robot need to be smaller, as the actual environment is small and has narrow spaces. The forklift system should be also smaller or capable of being folded electrically. Second, the chair needs to be rotated electrically. Third, it was reported to be difficult to control the robot arm, and this arm needs to be installed on a worktable. Finally, controlling each component using the joystick with several modes can confuse a worker. Therefore, a more intuitive and simpler user interface is required.

### 3.2. Assistive Mobile Robot System Type 2

#### 3.2.1. Designing & Development

Based on the evaluation result of the first version, the second version of the robot was developed. As the robot arm is used primarily when performing tasks at the table and not as much when moving the robot around, the robot arm was installed on the table and an electrically foldable forklift is used and mounted on the back to reduce the size of the robot. To improve the mobility of the robot in small and narrow spaces, an omni-directional driving mechanism was adopted. Among many types of omni-directional wheels, 'Mecanum' wheels were used, as the use of four wheels guarantees the stability of the system.

Fig. 14 shows the process of a task involving the moving of boxes from a warehouse to a worktable. Fig. 15 shows the second version of the developed mobile robot. Fig. 18 shows its system configuration. As Mecanum wheels are used, the robot can move in any direction by simply controlling the rotation of each wheel without steering them. When a user picks up objects using the forklift or when he works at the worktable, the chair can be rotated electrically to support lifting task or to face the worktable. Fig. 16

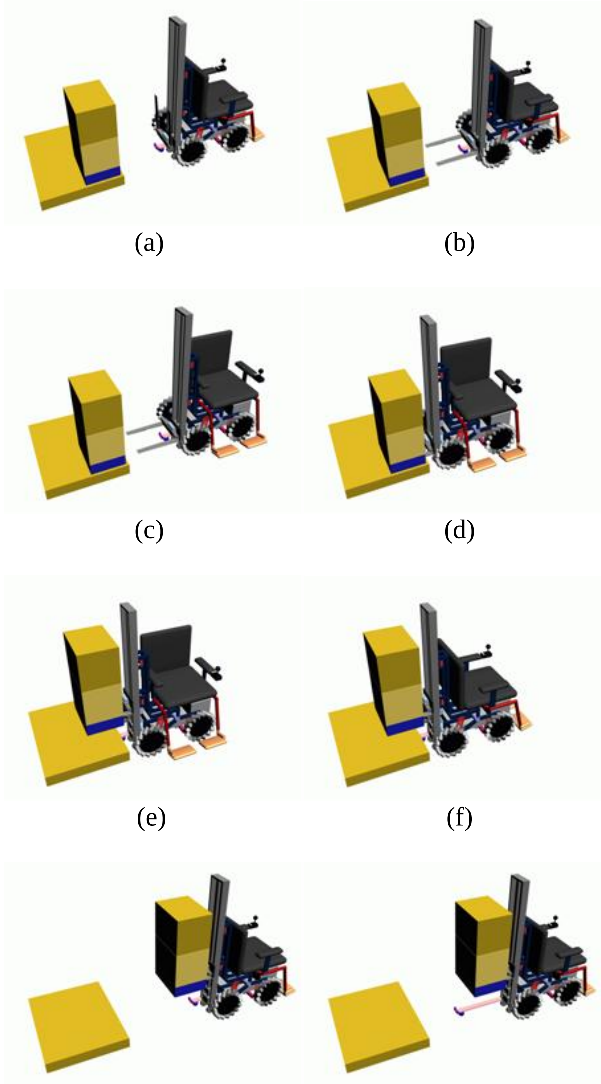

(a) (b) (c) (d) (e) (f) (g) (h)

Fig. 14. The process of moving boxes of Type 2 robot
(a) The robot moves to the warehouse and backs up to box on a pallet in the warehouse, (b) the user unfolds the fork, (c) the user rotates the chair, (d) the robot moves toward the box and picks up the pallet, (e) the user makes the robot lift up the fork, (f) the user rotates the chair in the forward direction, (g) the robot moves toward the table, and (h) when moving boxes, two sonar sensors are stretched so that they do not interface with the fork-lift.

shows the design of the electric revolving chair. A worm gear rotated by the dc motor is attached to the chair axis. For user safety, a sonar sensor-based collision warning system that detects obstacles in the rear is used. As objects on the forks can be recognized as obstacles, a sonar sensor transferring device that is manually operated by the user was added. The design of the sonar sensor transferring device is shown in Fig. 17. The driving of the mobile robot is controlled by a three-axis joystick, and the other components are operated and controlled using simple switches and buttons.

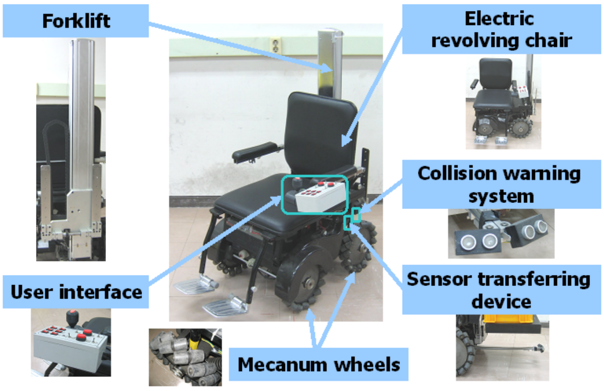


Fig. 15. Assistive mobile robot system Type 2

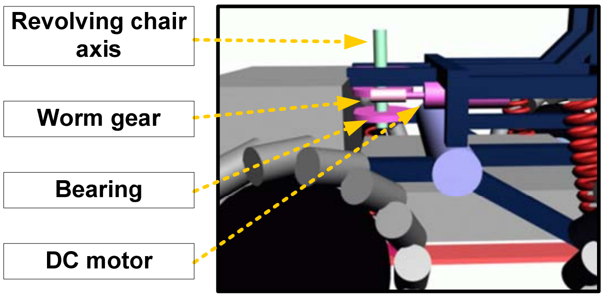


Fig. 16. Electric revolving chair

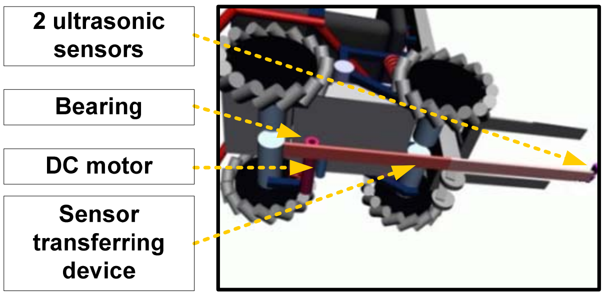


Fig. 17. Sonar sensor transferring device

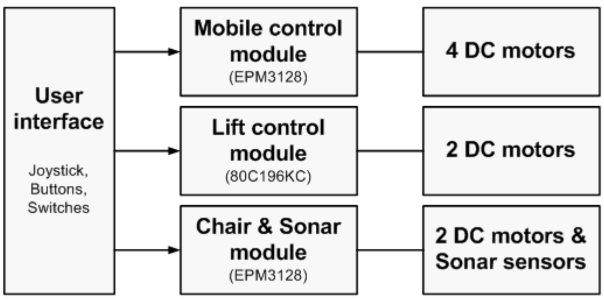


Fig. 18. System configuration of the Type 2 robot

Table 4
Specifications of Assistive Mobile Robot Type 2

| | | |
|---|---|---|
| Size | 760 × 1180 × 510 [mm] (W×L×H) | |
| Max. Speed (Mobile) | Translation | 5 km/h |
| | Rotation | 45 deg/s |
| Max. Load (Mobile) | 120 kg | |
| Max. Load (Lift) | 30 kg | |

Fig. 19. User trials involving the assistive mobile robot Type 2
(a) Transferring to the robot
(b) Moving around
(c) Working at the worktable
(d) Moving materials - lifting up

#### 3.2.2. Evaluation

User trials of the second version were also conducted. The method of these user trials is essentially identical to that of the first version. Fig. 19 shows the user trials of the second version. The participants reported that it was a very good idea to adopt the omni-directional driving mechanism. They also reported that the size of the robot was sufficiently small. Although the test environment was small and had narrow spaces, users could move easily in any direction. They also commented that it was very easy to use the user interface, as it was simple and intuitive. However, a number of problems were identified. As this robot did not have a suspension system, a user could experience vibration caused by the rollers of the Mecanum wheels. Moreover, noise was made by the rollers of these wheels. A problem with the user interface was also identified. As the joystick itself could also be rotated while the chair was rotating, it was not intuitive to control the robot using the joystick when the chair was rotated to one side. One issue with the forklift system was that it was inconvenient for a user when he tried to pick up parts from a box at the worktable, as the pillar of the forklift blocked his arm movement as well as his sight. Furthermore, it was difficult to check the height of the forks when the user attempted to place pallet onto the forks. Finally, as the sensor transferring device was considered as a cumbersome device, participants tended not to use the device.

### 3.3. Assistive Mobile Robot System Type 3

#### 3.3.1. Designing & Development

The third version of the robot was developed based on the evaluation of the second version. A Mecanum-wheel-based driving mechanism was used with this version as well, as the usefulness of this mechanism was verified through the evaluation of the second version. To reduce noise from the rollers of the wheels, bearings were inserted into each roller. Fig. 21 shows the designed body frame of this robot. To reduce the vibration caused by the Mecanum wheels, a suspension system was adopted. To apply the suspension system to this version of the robot, a Y-shaped body frame was designed. To satisfy the condition in which each Mecanum wheel should make contact with and be parallel to the ground, a four-link suspension structure was designed for each wheel.

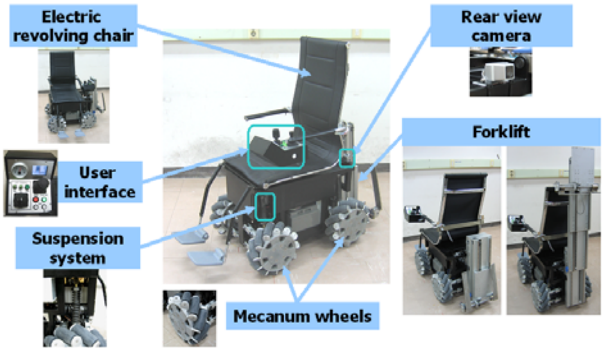
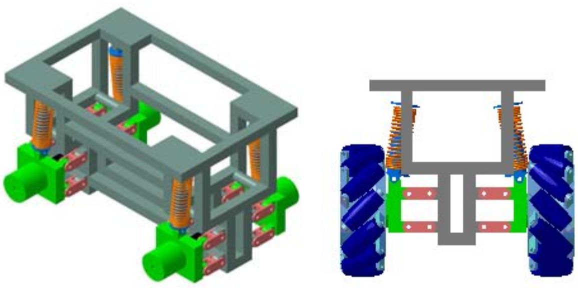



Fig. 20. Assistive mobile robot Type 3



(a) (b)

Fig. 21. The body frame of the Type 3 robot.
(a) Body frame with the suspension system
(b) Body frame with wheels

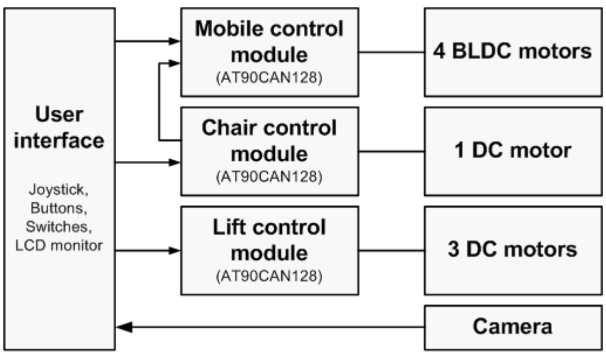



Fig. 22. System configuration of the Type 3 robot

Table 5
Specifications of Assistive Mobile Robot Type 3

| | | |
|---|---|---|
| Size | 680 × 1280 × 570 [mm] (W×L×H) | |
| Max. Speed (Mobile) | Translation | 5 km/h |
| | Rotation | 45 deg/s |
| Max. Load (Mobile) | 250 kg | |
| Max. Load (Lift) | 30 kg | |

(a) (b) (c) (d)

Fig. 23. User trials of assistive mobile robot Type 3
(a) Moving around
(b) Moving objects - lifting up
(c) Moving objects - after tilting
(d) Working at a worktable

The developed robot is shown in Fig. 20. For user convenience while controlling the robot, a simpler and more intuitive user interface compared to that of the second version was designed. As the rotation state of the chair is inputted to the mobile control module, as shown in Fig. 22, the user can easily control the robot using a joystick regardless of the rotation state of the chair. To solve the problem in which the pillar of the forklift blocks the arm movement and sight of the user, a multiple pillar-based forklift system with an adjustable height was designed. As the height of the pillar depends on the height of the fork, the forklift system can provide more convenience, which mitigates the drawbacks of the second version. The height and speed of the fork are controlled by a one-axis joystick. When a material is loaded onto the forks, the lift system can tilt depending on the weight of the material. This, however, has safety implications. Thus, a lift tilting system in which the user could tilt the lift was designed. This system offsets the tilting caused by the weight of the material on the forks. To provide a convenient means of checking the height of forks, a laser pointer was attached to the bottom of the forks. For user safety, a camera that monitors the rear area was added. The sonar sensor-based collision warning system and the sensor transferring device were removed as they could not be use conveniently.

### 3.3.2. Evaluation

A self-evaluation of the third version was conducted. Fig. 23 shows the user trials with the third version. As the bearings were inserted into each roller, the rollers revolved smoothly without noise. Moreover, vibration was reduced significantly due to the suspension system. Control of each component becomes easier due to the simple and intuitive user interface. The user can control the mobile platform using a three-axis joystick, the height of the fork using a one-axis joystick, and all other components, including the revolving chair, the tilting system, and the folding/unfolding of the forks are controlled by simple buttons and switches. The user can also check the remaining charge of the batteries and can observe what is behind the robot via the small LCD monitor. The operation of the forklift system was also optimized. As the height of the lift system depends on that of the fork, the pillar does not block the arm movement and sight of a user when the user picks parts from the box at the worktable. The laser pointer at the bottom of the forks helps the user to check where the fork is positioned, although this actually depended on the illumination condition of the test environment.

## 4. Conclusion

This paper introduced assistive mobile robots that are able to help the disabled to work in a factory environment. The criteria of this research were 'assisting the disabled as much as possible,' 'considering the actual employment situation of the disabled' and 'assisting with the most commonly performed task of the disabled'. To derive the specific mission based on these criteria, the demographics of the disabled, their actual employment situations, and their required tasks were surveyed. From the survey results, the target user and the functions of the robot were determined.

The proposed robots were developed and improved through an iterative process of designing, development, and evaluation. As a first version of the robot, the Type 1 mobile robot used a robot arm and a forklift system on the front. For simple use of the forklift system, a forward wheel driving/backward wheel steering mechanism was adopted. However, its bulky size and low mobility in small and narrow spaces were pointed out during evaluations in actual factories. The Type 2 mobile robot was developed based on these evaluation results. To reduce the size of the robot, the robot arm was installed onto a worktable and a foldable forklift was adopted and mounted on the back of the mobile robot. For improved mobility in small and narrow spaces, an omni-directional driving mechanism using Mecanum wheels was utilized. As this omni-directional driving mechanism is appropriate for movement in small and narrow spaces, this mechanism was also used for the Type 3 robot. The Type 3 mobile robot was also developed based on the evaluation results of the Type 2 robot. Low-noise Mecanum wheels were developed for the Type 3 system. A body frame of the robot that ensured low vibration and simple operation of the Mecanum wheels was proposed. A multiple pillar-based foldable forklift system was also utilized to overcome the problems associated with the lift of the second version, in which the pillar blocks the arm movement and the sight of the user. These robot systems are expected to provide practical assistance to disabled workers in a factory environment.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