Sensor-based navigating mobile robots for people with disabilities

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Preface

Rehabilitation robotics is a research field where human needs meet the possibilities of high technology. I have found it very stimulating to work on technological advances that may make life easier for people with disabilities

The work upon which this thesis is based was carried out over a long period, first in the robotics section of the Department of Production Engineering and at Certec from October 1, 1990 to October 15, 1997 and thereafter at Certec exclusively.

I would like to thank my supervisors, professors Bodil Jönsson and Gunnar Bolmsjö for their creative guidance. I would also like to express my gratitude to Håkan Eftring, MSc, with whom I have had daily discussions over the course of the Walky project, as well as to all the engineers and technicians at Certec who have assisted me in my work: Jonas Falkvall, Kirsten Rassmus-Gröhn, Fredrik Ljungbeck, Anders Wahlström, Ingvar Jönsson, Mikael Lindström and Christer Månsson. Moreover, I would like to thank Gunilla Knall for valuable explanations regarding disabilities, Anna-Karin Batcheller for English translation and revision, Anna Josefsson for proofreading the Swedish text, and Anu Uus and Calle Sjöström for layout. I would like to express my personal gratitude to my wife Helena and my daughters Anna and Malin for their encouragement and support and for being there when I needed them.

The Swedish Council for Work Life Research and the foundation ”Stiftelsen för bistånd åt vanföra i Skåne” have provided financial support for the Walky project, for which I am very grateful.

Summary

People with severe physical disabilities need help with everyday tasks, such as getting dressed, eating, brushing their teeth, scratching themselves, drinking, etc. They also need support to be able to work. They are usually helped by one or more personal assistants. Various technical devices, such as a mobile personal robot, offer an alternative or a complement to personal assistance.

Personal robots can be divided into three groups, each providing a different basic solution:

- Stationary personal robots
- Wheelchair-mounted personal robots
- Mobile personal robots

The technical work described in this licentiate thesis consists of the design and construction of Walky, a mobile personal robot for people with disabilities, as well as tests and trials of various sensor system configurations for it. The thesis also outlines relevant projects in the field of rehabilitation robotics and gives an introduction to navigation methods that can be used in the field of mobile personal robots. The work was carried out over a period of four years and was finished about three years ago. There has been considerable technological progress since then. I would probably have chosen other robot and computer solutions today.

During the course of the construction work, there were continuous consultations with people with physical disabilities. Interviews have shown that many would prefer a personal robot to a personal assistant wherever possible. Several reasons were given: increased personal independence, less unwanted interaction with others, a technical device (unlike a person) does the same thing every time, etc. All interviewees believe that Walky's successors may become an assistive device used by people with disabilities. Most also believe that a mobile personal robot would be of great assistance in various vocational situations.

My thesis makes the following contribution to the field of rehabilitation robotics:

- A working Walky, whose main use will be as a demonstration object and stimulus to further study at the Lund-Orup Rehab Center. This may also encourage people with disabilities as a group to make more vigorous demands for robotic aids. In my experience (cf. also interviews) there is great interest in robots as an alternative to personal assistance in many situations.

- Detection of tables, chairs, bookshelves, etc, with the aid of ultrasonic sensors on a mobile robot system.
- Control of a mobile robot system on the basis of a CAD drawing, as well as how the user can choose between automatic and manual control, or a combination of automatic and manual control.
- The insight that it is possible to make an experimental product such as Walky, which is not intended for serial production, and that such a product can provide interesting results despite the fact that research projects of this kind necessarily operate on a limited budget.

I also hope that chapter 2 (a survey of four major projects in the field of rehabilitation robotics) will prove useful, for instance, in educational programs for engineers and occupational therapists and that it will serve as an introduction to the subject for professionals in the disability field. The section on Walky (ch. 5) will hopefully help the reader envisage how a future assistive device might function.

To people with disabilities

When I began this work many years ago, there were great hopes for the field of rehabilitation robotics. As the years went by, it became increasingly obvious that the pace of development would not be as rapid as had been hoped. In fact, functioning robots and manipulators capable of working close to people, such as the Manus arm, the PHANToM, and the small Electrolux vacuum, are only now becoming available. It is safe to say that it will be quite some time before personal robots are as common as personal computers.

Swedish research in the field of rehabilitation robotics is no exception to the general international trend of dashed hopes compared to our expectations of ten years ago. Still, it should be pointed out that Sweden is at the forefront in the field. Christer Evaldsson of Helsingborg has used a robot as an assistive device at work longer than anyone else in the world. Through the years, Certec has been very much a part of the work involving Christer.

Personally, I have tried to contribute to the field of rehabilitation robotics in various ways, mainly by developing Walky. It was created as an experimental product, that is, a product intended for user trials only. As an experimental product, it was decided from the outset that it would not be mass-produced as is, but that it would be used for finding out how it works in practice. This means that assumptions made about user interests, needs and dreams are subjected to rigorous scrutiny.

Picture no 1. My ugly but cherished Walky.

That may sound irresponsible: one could just as well have asked the user in the first place! This is true, and at Certec we *do* ask, continually. But the fact is that not even users can know beforehand: it is not easy to wish for something before you have experienced what is possible [1, 2]. In our experience, for a concrete discussion with users to be possible without talking at cross-purposes, it is necessary to develop preliminary technology. Walky, my ugly and incomplete robot, should be seen as an example of something that must exist (it will be placed at the Lund-Orup Rehab Center) if we are to be able to make possibilities visible and as a result make it easier for dreams, wishes and criticism to come to light.

I have devoted many days, weeks, months, and years to this device. In this thesis, I will try to present the new knowledge I believe I have contributed through my work on Walky. Was it worth the huge effort? I leave that judgment up to you.

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1 Introduction

Personal robots can be divided into three groups, each providing a different basic solution:

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- Wheelchair mounted personal robots
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People with severe physical disabilities need help with everyday tasks, such as getting dressed, eating, brushing their teeth, scratching themselves, drinking, etc. They also need support to be able to work. They are usually helped by one or more personal assistants. Various technical devices, such as a mobile personal robot, offer an alternative or a complement to personal assistance.

Stationary personal robots

Stationary personal robots are placed in a location where they can provide assistance to the user by carrying out certain tasks. From a technical point of view, it is preferable to use a wholly known environment, where all tasks performed by the robot are preprogrammed. This increases its reliability; i.e. the robot performs the given tasks with a low percentage of error. However, if something unforeseen happens, the problem cannot be solved without somebody restoring the physical environment. The user may be able to solve the problem, but only if he has full manual control of the robot. The stationary personal robot can be made intelligent with sensors, whose signals can be used to enable the robot to work in a changing environment. The use of sensors complicates the device and reduces its reliability because the number of possible sources of error rises.

Wheelchair-mounted personal robots

A wheelchair-mounted personal robot accompanies the user as she moves around in, for example, her home or work environment. Its main and obvious advantage is that it is always next to the user wherever she is. The robot arm is mounted on the right or the left side of the wheelchair. This means that the center of gravity of the wheelchair is displaced, which may result in major or minor instability affecting its handling. The robot works in a changing environment, which means that the need for preprogrammed tasks is limited. Examples of such tasks are drinking from a glass, grasping a control lever located on the wheelchair and placing it in a predefined location, etc. Tasks that are not preprogrammed require a considerable amount of skill on the part of the user in controlling the robot. Making a wheelchair-mounted robot intelligent with the aid of sensors is more complicated than in the case of a stationary personal robot. Each time the robot arm is to perform a manipulation task, the wheelchair starts from a different position since it is impossible for the user to stop it in exactly the same spot each time, unless some type of docking station is provided. Tests have been carried out on the RAID workstation,

using direct control and automatic gripping [50] respectively: see chapter 2.3. In the tests, the user carried out gripping with the aid of direct control and placed the gripping means close to the object to be gripped. Subsequently, the robot gripped the object closest to the gripping means with the aid of sensor feedback. The tests showed that the test subjects preferred automatic gripping because it requires less concentration and is much quicker. I believe that this type of sensor support has a future in the field of personal robots.

Mobile personal robots

The third basic solution is a mobile personal robot. Just like a wheelchair-mounted robot, such a robot is intended to work in a more or less changing environment. It has the advantage that it can be kept out of sight when not in use. A mobile personal robot consists of two robots: a mobile robot base and a robot arm. The mobile base can be controlled by the user in several ways. For instance, the user can issue a command to the base: ”go to a certain target!” The intelligence built into the base will then determine which route to take to reach that target. Even if there is an obstacle along the route, the robot base will find its way around it and be able to reach the target. Another alternative is that the user himself chooses the route and guides, via direct control, the mobile base to the target. These two alternatives can also be combined into a semi-automatic guiding method.

When the mobile personal robot has reached its target, the base must assume a predefined position; otherwise the robot arm will be operating in an unknown environment. The mobile base can assume its position either by means of docking or by means of sensors. If the base finds the predefined position, the robot arm can operate in a known and well-defined environment. If the mobile base is unable to find the predefined position, the environment will be unknown to the robot arm, which will then require powerful sensor support to be able to carry out its manipulation tasks.

In October 1991, there were existing projects and test stations with personal robots as well as ready and almost ready commercial stationary and wheelchair-mounted personal robots. I decided to try to build a mobile robot system for people with severe physical disabilities. In doing so, I wanted to demonstrate that:

- it was technically possible
- it can offer people with severe physical disabilities an alternative to personal assistance.

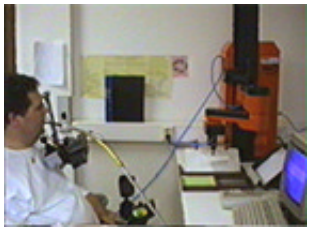
2 Robotic Devices for People with Disabilities — a Survey

A national perspective

Three robot installations for people with severe physical disabilities were set up in Sweden during 1990 and 1991. They were located at

- Skanska, Helsingborg
- The Swedish Handicap Institute, Stockholm
- Volvo, Skövde

The purpose of the installations was to investigate the need for robots as an assistive device for people with severe disabilities in various vocational situations and to gather new experience and knowledge.



Picture no. 2. Digitized video images from VHS of Christer Evaldsson at his robotic work station.

Skanska, Helsingborg

As a result of a fall at the construction site where he was working as a carpenter, Christer Evaldsson suffered a spinal cord injury that left him quadriplegic. After his injury, Christer continued to work for the same company, doing office work, such as invoicing.

Invoicing involves producing an invoice based on reference documents. In the office where Christer was working, there was a sheet conveyor which, although designed and redesigned several times to send one document at a time, would sometimes send two or more sheets (reference documents) at the same time by mistake. The only solution was for Christer's personal assistant to put out two or three documents in front of him. In less than two minutes, Christer would produce the invoices and the assistant had to remove the documents and put out new ones.

After the robotization of the workstation (see Picture No. 2) the robot handled the coming and going previously done by the assistant [3]. The robot's standard gripping claw was replaced by an end-effector with suction cups that was specially designed to handle sheets of paper.

To make it possible to replace the end-effector, the robot was modified to include an end-effector replacement system. The robot was installed in October 1990 and is used for about four hours each day. As a result of experience gained from the RAID

project (see chapter 2.3.), certain modifications were made to the workstation in 1994.

The Swedish Handicap Institute, Vällingby

Åse Rambrink is systems manager and head of training in the computer department at the Swedish Handicap Institute in Vällingby. Åse has cerebral palsy as well as a speech impairment and a slight hearing impairment. Her cerebral palsy forces her to carry out all her work using her feet while sitting in a wheelchair.

In her daily work, Åse uses manuals, educational materials, etc. Before the robotization of her workstation, Åse had all her educational materials spread out on the floor along the walls of her office.

After the robotization, her educational materials were put into some 30 magazine holders on a bookshelf. Åse issues a command to the robot via a keyboard located on the floor. The robot can fetch a specific magazine holder containing a binder, a book, etc. The magazine holder is always delivered by the robot to the same location, where it is easy for Åse to manipulate using her feet.

The robot was installed in January 1991 and is still in use, although not to the same daily extent as the robot at Skanska.

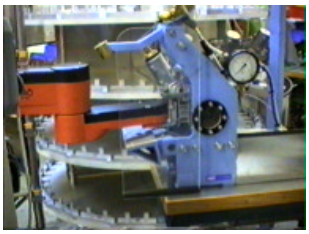
Picture no. 3. Digitized video images from VHS of Åse Rambrink at her robotized work station.

Volvo, Skövde

The Volvo plant in Skövde has an assembly shop, which employs people with work-related injuries or slight cognitive and physical disabilities. It was decided that the functional inspection of by-pass valves used in Volvo diesel engines should be robotized. Previously, the valves had been inspected manually. After the robotization, an automatic valve inspection device was created with semi-automatic material handling. The operator controls the material handling by pressing one of the buttons ”get new valve”, ”release approved valve”, or ”release rejected valve”. The valve inspection involves three automatic functional tests with the results displayed on the operator’s screen in the form of three horizontal columns with parallel number scales. The number scales are divided into green and red areas. If a valve is accepted, i.e. if all the columns are within the green areas, the operator presses the button ”release approved valve”.

Erik Larsson, who has cerebral palsy, uses a wheelchair, has a speech impairment and limited movement, as well as spasms in both arms and hands, was chosen to operate the device. Before the start of the project, Erik had experience only of office-type work.

The installation was finished in the spring of 1991, but because Erik did not enjoy the switch from office work to factory work, the project was terminated after approximately two years.



Picture 4. Digitized video images from VHS of Erik Larsson at his robotic work station

The lessons learned from the evaluation of the three Swedish pilot projects [4] were as follows:

- Divide the task into modules and then try to solve the subtasks one by one. When a subtask has been solved, it can be integrated into the system.
- The user should preferably have worked at the workstation before the robotization; i.e. the user should feel comfortable with his existing tasks.
- The robotic workstation should be programmed with a user-friendly programming language to enable, for example, an occupational therapist to easily make changes to the program.
- The extent of the need for robotic assistance should be investigated before any robotization takes place.
- Satisfactory safety measures must be provided for the user and his/her fellow-workers.
- The choice of robot, which is based on, among other things, the tasks that it is to perform, must be made with the aid of a requirement specification.
- The robot must not make the work less meaningful, i.e. the robot should only carry out the assisting tasks.

At present, in 1998, Swedish activities in the field of rehabilitation robotics are centered around the National Robotics Center for People with Disabilities. Active project participants are Certec and the Lund-Orup Rehab Center. In addition to Walky, which is described extensively in chapter 5, a RAID station (see chapter 2.3) and a Manus arm (see chapter 2.4) are used for research and development. The Robotics Department at Lund University is working on two projects involving personal robots, headed by Professor Gunnar Bolmsjö, in close collaboration with the National Robotics Center. The first project is aimed at improving the technical performance of Handy 1 (see chapter 2.1) and at expanding its field of application. The goal of the second project is to create a completely new wheelchair-mounted personal robot.

An international perspective

Elsewhere in the world, over the last 20 years there have been several research and development projects in the field of rehabilitation robotics. Some of the projects and some initiatives from small companies have resulted in commercial products. Table 1 contains a list of these products as well as information on their country of origin, cost, etc.

I have chosen to provide a more detailed presentation of four of these products: Handy 1, DeVar, RAID, and Manus (see chapter

2.1-2.4). These offer an insight into available commercial personal robots. I have personally tested six of the nine products.

Product name	Country	Company	R&D Support/ financing	Robot type	Cost Swedish Kronor (000s)	Units sold	sold to
Prab Command	USA	PRAB Robotics	Boeing Company	Stationary work station	?	?	Companies, Research Bodies
DeVar	USA	Independence Works, Inc	VA Palo Alto, Rehab R&D Center, Stanford University	Stationary work station	800	3	Evaluation
Manus	Holland	Exact Dynamics	IRV,TPD	Wheelchair mounted	250	50	Dutch users
Handy 1	Britain	Rehab Robotics	Degree project, undergrad. level.	Manual Movable work station	48	140	Users
Helping Hand	USA	Kinetic Rehabilitation Instruments	”Start-up company”	Wheelchair mounted	76	10	Clinical evaluation and research evaluation
Papworth Arm	England	Papworth Group	Inventaid	Wheelchair mounted	64	5	?
RAID	England France Sweden	Oxford Intelligence Machines	EU TIDE-project	Stationary work station	440	9	Clinical evaluation
Arlyn Arm Workstation	USA	Arlyn Works	U.S. Education Department	Stationary education station	240	0	-
Robotic Assistive Appliance	Canada	Regenesis	Neil Squire Foundation	Stationary work station	184	7	Clinical and industrial applications
TOTAL						224	

Table 1. A survey of commercially available personal robots [5].

2.1 Handy 1

Handy 1 [6,7,8,9] is a robotic assistive device designed to enable people who would otherwise need help from a personal assistant to eat and drink independently. The user has complete control of the choice of food (meat, potatoes, etc.) and of the pace at which the meal is eaten. Handy 1 is controlled through a single switch, which is activated by only a slight physical movement.

A scanning system, consisting of 7 LEDs in Handy 1's tray section allows the user to select food from a specific area of the dish and to drink at any point during the meal. When Handy 1 has been powered up and the food has been placed in columns on the dish, the LEDs start scanning from left to right behind the dish. The user waits for the LED to scan behind the column of food he/she wants to eat from before activating the switch to set Handy 1 in motion. The robot proceeds to the selected column and scoops up a spoonful of the chosen food. It then delivers the food in a comfortable position just in front of the user's mouth. The user can now eat at any speed he/she wishes. Next, the user presses the switch again. The procedure can be repeated until the plate is empty. By using an eighth LED. the user can drink at any point during the meal.

Picture No. 5. Outline of Handy 1.

Background

Mike Topping got the idea for the Handy 1 project when he was an adult student at Keele University , studying mathematics, computer science, and education. While on a work placement at a special school, he observed a young student, Peter Higginbottom, who was being fed by an assistant. The assistant paid no attention to the type of food Peter wanted to be fed or how fast he wanted to chew. Mike thought this was degrading and insisted that it must be possible to construct some kind of device that would enable Peter to eat without assistance.

Evaluation

Handy 1 has been evaluated on two occasions. On the first occasion [10], in the early 1990s, the evaluation was carried out by the Department of Psychology at Keele University. The test subjects were 20 individuals with severe physical disabilities, all of whom had been using Handy 1 for at least three months.

The results showed that Handy 1's main advantage was that the user was able to choose for him/herself what he/she wanted to eat. One child's status was even elevated among his peers because they believed he must be extremely smart to be using a computerized robot. His assistant believed that this new higher status inspired him to try harder.

One side effect of the testing of the device was that 25% of the test subjects stated that it revealed that they had problems with their position in the wheelchair. This became clear because the robot, unlike a person, is unable to deliver the food to different positions, and the test subjects noticed that the wheelchair did not support them sufficiently to enable them to eat from the same place every time. Most of the assistants believed that the test subjects were generally more alert and more interested in things.

During a meal, a user might need to activate the robot switch up to 42 times and to move his head a similar number of times to the position of the spoon. In doing so, several users improved their co-ordination. The assistants also believed that the test subjects were now less in the habit of biting the spoon. When an assistant feeds a user, the assistant takes the spoon out of his mouth. But when using Handy 1, the user must move his mouth away from the spoon. To do this, he must let go of the spoon with his teeth. Several users also experienced improved head control, lip control, and swallowing.

On the second occasion the evaluation [11], carried out by the Psychology Department at Staffordshire University, was done in the form of interviews with 22 individuals who were using Handy 1 regularly. Nineteen of the test subjects were satisfied with the appearance of the robot, while three were dissatisfied. Fourteen

test subjects stated that the robot was easy to use, seven said that it was very easy, and one that it was very difficult to use.

When asked if Handy 1 had increased their independence, twelve stated that they were very satisfied, five that they were satisfied and four that they were dissatisfied. Two thirds of the test subjects answered that in their opinion, Handy 1 was very reliable and the rest said that it was reliable.

Picture No. 6. Applying make-up with the aid of Handy 1.

Handy 1 is now a commercial product [12] with an established sales organization in Great Britain. Moreover, the Handy 1 system is being developed further to improve its technical performance and to make it capable of carrying out more tasks, such as tooth brushing, make-up application, shaving, and washing.

2.2 DeVar

A robotic work station [16] for desktop publishing has been designed and built at the Palo Alto VA Rehabilitation R&D Center in collaboration with the Spinal Cord Injury Center with the aim of enabling people with quadriplegia to return to work after their injury. One goal was for the robot to carry out assistive tasks in place of a personal assistant. The other goals were increased independence and productivity, as well as a higher quality of life for the employee. It was considered that it if these goals were reached, a high tech solution would be justified.

There are approximately 70,000 individuals with quadriplegia in the United State. It is estimated that, every year, between 2,400 and 6,000 individuals suffer injuries resulting in quadriplegia. Most of the recently injured are young adults with ordinary lifestyles.

System Design

The robot is of the PUMA 260 type with a VAL-II controller mounted on a 120-mm long travel, having a repeating accuracy of 0,3 mm. The end effector is an Otto-Bock Greifer prosthetic hand which measures the hand opening with an accuracy of 0,6 mm. The controller of the PUMA robot is monitored by an IBM PC with a VOLTAN board with built-in functions for voice recognition and digitized speech. A simple user-friendly program written in TurboPascal has been developed for controlling the robot with simple commands.

This design [17,18] was preceded by simpler versions of the robotic station. The difference in the construction is the travel. Tests were carried out with 19 individuals with quadriplegia, C3 to C5, as well as one individual with Gullian Barrés syndrome [19,20,21]. The following preprogrammed tasks were performed:

- Meal preparation (using a refrigerator and a microwave oven)
- Eating using cutlery (fork and spoon)
- Brushing teeth using an electric toothbrush and rinsing mouth
- Drinking water or juice through a straw
- Washing and drying face
- Shaving face and neck with an electric razor
- Receiving a mouthstick from the robot. The mouthstick is used for keyboarding and turning pages
- Environmental control tasks (lighting, radio and telephone)

The results of these tests showed that the test subjects gave the robot a positive rating as an assistant in the following areas:

- Safety
- Ease of learning
- Sturdy construction
- Reliability
- Voice recognition
- Aesthetics
- Space utilization
- Noise level
- Task completion time
- Overall impression

The test subjects were satisfied with the robot's performance when washing their face, brushing their teeth, shaving, making soup, and eating. For these tasks, the test subjects preferred being assisted by a robot rather than a person. 16 out of 20 test subjects

stated that their personal assistants and families would react positively to a robot as an assistive device. 18 answered that they would use the robot regardless of the reaction of their personal assistants and families.

A study has been carried out on the latest version [22] of the DeVar robotic workstation with a test subject with quadriplegia, C3, at his worksite. Initial trials have also been performed at a school for students with severe disabilities, in which routines for selecting, handling, and inserting diskettes were tested. The test results led to changes to the design of the DeVar workstation. The changes facilitated its subsequent installation at the test subject's worksite.

Picture No. 7. The DeVar workstation installed at Pacific Gas & Electric with test subject.

Before his accident, the test subject was working as chief programmer at Pacific Gas & Electric, and he has been able to continue in his old job after his injury. After the accident, his employer installed the Kurzweil voice recognition system to replace the keypad. Prior to the installation of the robot, the test subject worked four 10-hour days per week. He was assisted in the usual way by a personal assistant in handling papers, eating, etc.

Prior to the installation, an occupational therapist filled out an activity analysis form to document the test subject's daily work habits over the course of a week.

The test subject used the DeVar system for up to 10 hours/day four days a week for three months. The robot was able to perform the following tasks:

- Provide a glass of water
- Provide throat lozenges
- Dispense medication

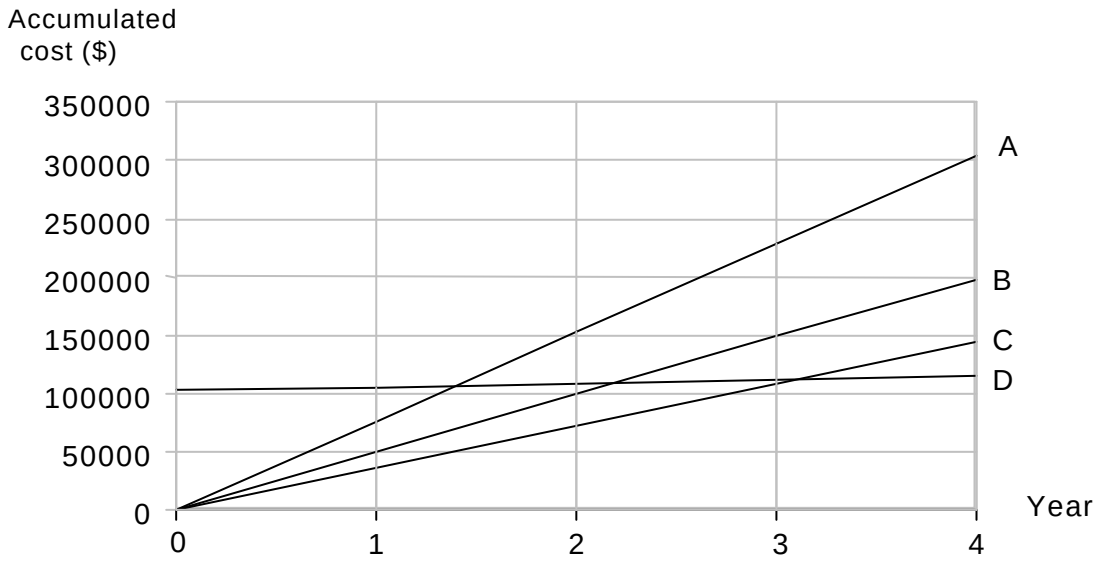
- Serve food
- Deliver a mouth stick (and a new one if the test subject happened to drop it)
- Get print-outs from the printer
- Display the print-outs
- Store the print-outs
- Operate the phone

Analyses showed that the test subject used the robot an average of six times per hour and that it took the robot a total of 12 minutes to complete these tasks. The robot requires approximately twice as a much time as a personal assistant to complete the tasks provided that the assistant is present in the test subject's office. The robotic workstation needs weekly maintenance for reprogramming the various tasks. To reduce the need for technical maintenance, a journal file was installed for recording all commands used. By studying the journal file, errors in the system could be found.

The conclusion was that the test installation [23] had been successful, but that the process of identifying robot tasks and of modifying the environment had been difficult. Regular maintenance of task programming is required, which is not satisfactory in a fixed installation. In that case, automatic calibration and a search method has to be introduced for finding the various objects.

Is a robot installation such as DeVar cost-effective?

The total cost of the robot has been compared to the cost of a personal attendant, and it has been found that the cost of the robotic system is recouped in about 1.5 years if it is used 8 hours per day [24]. The total cost of the robot includes a $100 000 investment cost, a $2400 installation expense, and $3000 annually for maintenance. This should be compared with the hourly rate of $30 paid by American insurance firms for a personal attendant (in 1991).

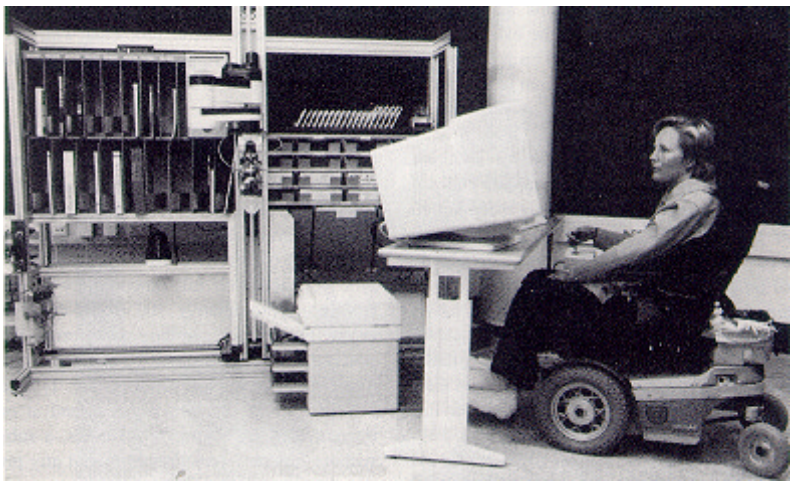


Graph 1. Cost comparison between the DeVar robotic station (D) and a personal assistant for an 8 (A), 6 (B), or 4-hour workday (C).

2.3 RAID

RAID was a project carried out under the TIDE program set up by the European Union. The project was based on a number of existing prototypes [20,25,26,27,28,29,30].

The RAID workstation was developed by companies and universities in Britain, France, and Sweden. It was designed for users with two degrees of freedom: the ability to control an input device such as a joystick or a trackball fitted to a standard electric wheelchair. The input device is used to control a computer application, for instance CAD, desktop publishing, bookkeeping, spreadsheet programs, etc. The input procedure was made more efficient by the use of a WiVik keyboard emulator. When the user wants to perform tasks such as handling papers and documents, reading a manual, printing and filing a report, photocopying, or sending a fax, he/she issues a command to the robot who carries out the task. The robotic station is based on a lengthened and improved RTX robot mounted on a travel. The RAID workstation is shaped like a bookshelf and is 1.7 m tall and 2.1 m wide.



Picture No. 8. The RAID1 robotic workstation.
Photo: Helena Alvesalo.

The robot is able to bring books and sheets of paper from the bookshelf and the document racks to the reader board, as well as turn pages as instructed. It is also able to manage peripherals such as a printer, scanner, stapler, etc. Moreover, it can move diskettes and CD-ROMs to and from storage shelves. It can also serve beverages.

The workstation described above is the RAID1 station, which was developed in the period from 1991 to 1993. EPI-RAID, phase two of the project, lasted from 1993 to 1996 and consisted of:

- Developing RAID1 on the basis of user feedback, into a version called RAID1A;
- Conducting enhanced user trials and market research on RAID1A;
- Specifying a commercializable version, RAID2, based on the above-mentioned feedback;
- Conducting user trials and market research on RAID2.

The results of the user trials involving RAID2 [31] showed that both users and attendants believe that RAID is a usable assistive device. There was marked improvement in the users' assessment of RAID2 in comparison with RAID1A, and a number of technical improvements were made to the final version of RAID2.

Some of the test subjects found the workstation too large. This criticism had also been advanced in connection with the evaluation of RAID1, with the result that RAID was constructed as a modular system. This means that the user can choose between a couple of different sizes of the workstation. There are 9 RAID stations at present in France, Sweden, and the UK.

Picture No. 9. Photo showing the RAID2 robotic workstation.

2.4 Manus

The Manus project was initiated by the Muscular Dystrophy Association of the Netherlands. The goal of the Manus project was to develop a reasonably priced wheelchair-mounted manipulator with a modular computer-assisted control structure, adapted to people with severe physical disabilties affecting their arms and legs.

The Manus system consists of:

An articulated manipulator arm [32,33,34,35,36,37] on a telescoping column, mounted on one side of the wheelchair. The arm has 8 degrees of freedom including gripping, a maximum range of 80 cm, and can lift objects weighing up to 1.5 kg. Its maximum gripping force is 20 N. The arm weighs 20 kg and has a maximum speed of 10 cm/s.

Picture No. 10. The Manus arm mounted on a wheelchair.

Brief functional description

The manipulator gives the user direct control of the gripper end point by providing user-friendly translation of commands for displacing this end point. The Manus arm is controlled through a keyboard or an analogue joystick. When the arm is not in use, it can be folded away at the side of the wheelchair. It can also be detached from the wheelchair.

The Manus arm has been evaluated in several countries by work groups [38,39,40] consisting of occupational therapists, engineers, and users. Two major studies [41,42] have been undertaken in Canada in a collaboration between Bloorview Children's Hospital and the Hugh MacMillan Rehabilitation

Centre. The results of these studies have produced suggested criteria for prospective users. He/she should:

- have minimal or no hand function;
- be unable to lift his or her arm against gravity;
- have no compensatory arm function;
- be electric wheelchair dependent;
- have limited coordination of arm, hand, or fingers;
- have fair to good spatial coordination and insight;
- be unable to feed him/herself and be unable to drink independently;
- be unable to manipulate objects;
- be able to control a suitable input device.

Picture No. 11. A user drinking with the help of the Manus arm.

The main prospective users of the Manus arm were identified as people with progressive dystrophy, specifically Duchenne muscular dystrophy, and severe spasticity, as well as users with spinal cord injury, multiple sclerosis, and rheumatoid arthritis.

The potential user should:

- engage in activities in different locations, indoors and out;
- be able to manage alone without supervision for significant parts of the day;
- live in either supported or independent living environments or at home where the absence of a technology such as Manus would constitute an unacceptable burden for other family members;
- be able to commence or resume work or studies with help from Manus;
- be motivated to use the Manus arm as much as possible;
- be able to understand and remember technical information;
- be creative and persistent in the area of computer technology;
- have access to persons in their environment to attach/detach the Manus from their wheelchair.

A three-month training period is recommended. Subsequently, the effectiveness of the technology should be reviewed to determine whether it meets the following three criteria:

- the Manus was used in the home in carrying out the tasks it is intended for;
- the Manus-user's independence and quality of life have increased;
- the load on assistants and/or family members has lightened noticeably.

3 Sensors

A mobile robot requires a sensing system to enable it to control its path of movement and its environment. There are a number of possible solutions available. For example, the robot can use a camera and an image processing system (machine vision) to detect if a nearby object is stored in its database, meaning that it will know how to manipulate it. The robot can also be equipped with sensors for detecting distances and obstacles. There are optical, mechanical (based on e.g. gyroscopes or tactility, i.e. touch), electric (inductive, capacitive), magnetic, and acoustic transducers. I chose the latter category, equipping Walky with ultrasonic sensors.

The reason I opted for an ultrasonic system was that it was readily commercially available, integrated in the robot base, and had a cost, which complied with the requirement specification for Walky. With the aid of its ultrasonic sensors, Walky is able to keep track of the distance between itself and obstacles such as walls.

Most distance-measuring ultrasonic systems are based on the time-of-flight method. This method comprises.

1. Transmitting an ultrasonic pulse, consisting of one or several discrete frequencies, from a suitable ultrasonic transmitter.
2. Radiating ultrasonic pulses over a certain range.
3. A receiver receiving the ultrasonic pulses.
4. Calculating the time between the transmission and the reception of the ultrasonic pulse, where the distance (d) to the object having reflected the ultrasonic pulse can be calculated as:

   $$d = \frac{v * t}{2}$$

   where v = velocity of sound and t = time between the transmission and the reception of ultrasonic pulse.

The time measured can easily be transformed into distance, provided that the velocity of sound is known. It varies somewhat depending on the temperature and humidity of the air, and for optimal accuracy it is important to be able to calibrate the sensor system on the basis of current conditions.

Two methods are generally used for this type of linear measurement. The first, the pulse-echo method, utilizes the same unit as a transmitter and a receiver. The distance measured by this method is from the transmitter to the reflected object and back to the transmitter, see Fig. 1a. In the second method, separate transmitters and receivers are used. In this configuration, the

linear measurement is either a measurement of the distance between the transmitter and the receivers, see Fig. 1c, or of the distance from the transmitter to the reflected object and onwards to the receiver, see Fig. 1b.

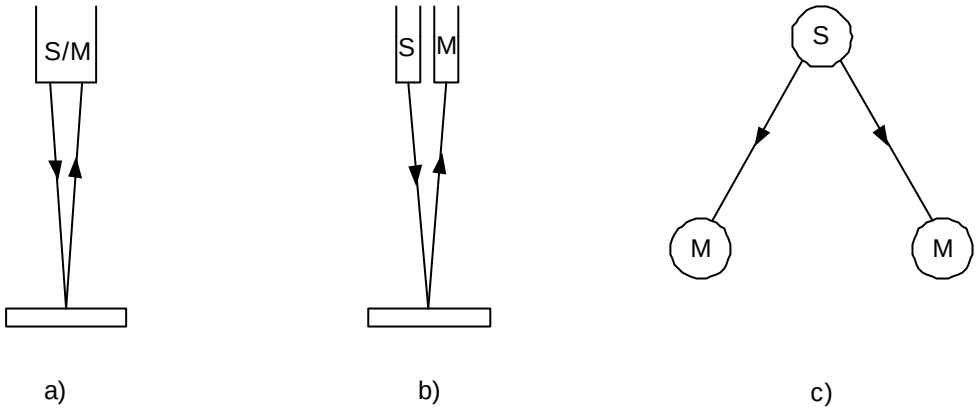


Fig. 1. Different fundamental configuration options for distance measurement using ultrasonic sensors
a) Same transmitter (S) and receiver (M),
b) Different transmitter and receiver,
c) Two-dimensional detecting of transmitter with two fixed receivers.

Possible sources of errors

In the following examples, Figs 2-6, the receiver and transmitter are located in the same unit, in the same way as Walky's ultrasonic sensors.

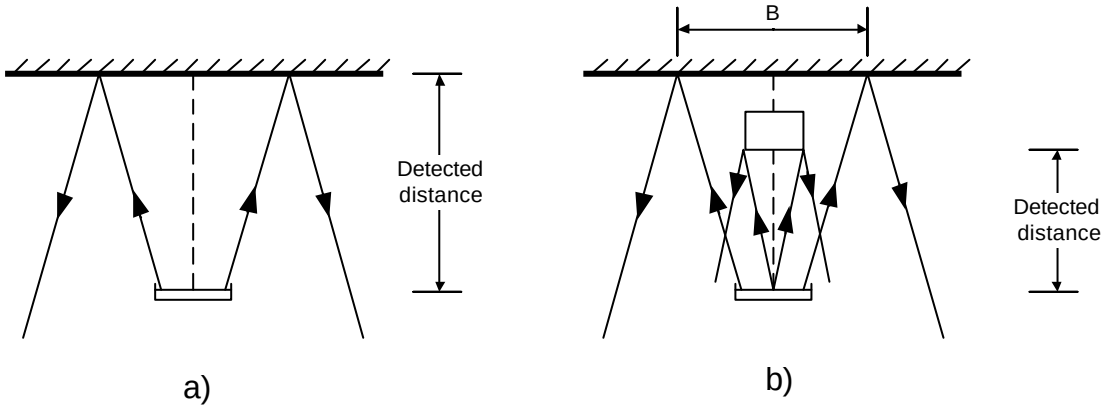


Fig. 2. a) Accurate distance measurement, b) A small object is placed in front of the sensor.

When the centerline of the sound wave is perpendicular to a wall, the distance measured is accurate (Fig. 2a). If a small object is

placed in front of the wall, the distance to the object is measured correctly, but the lateral position of the object is not determined within the range B (Fig. 2b). From a practical point of view it is advantageous if two or more sensors have common and individual detection areas, since this makes it possible to determine the lateral position of an object with higher accuracy.

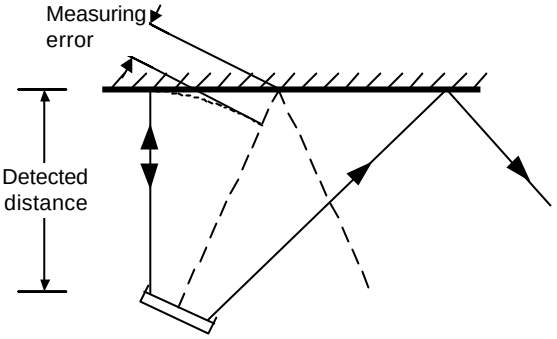


Fig. 3. Detecting a wall when the centerline is not perpendicular to the wall.

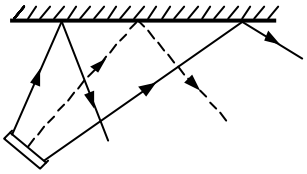


Fig. 4. Wall which cannot be detected.

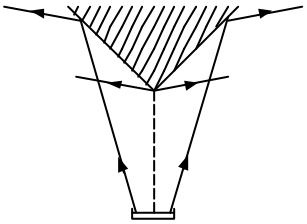


Fig. 5. Detecting a sharp corner.

The distance detected by the ultrasonic sensor is a function of the angle of the sound wave relative to the surface reflected. If the sensor is rotated so that the centerline of the sound wave is angled towards the wall (Fig. 3), the measured distance to the wall follows the edge of the sound wave rather than the centerline of the sound wave. The apparent distance is thus shorter than the axial distance, which results in a distance measuring error. The seriousness of the measuring error depends on the rotation of the sensor and the beam angle of the sound wave.

The above-mentioned errors can be reduced by the use of sensors with a smaller sound wave beam angle. However, with a reduction of the beam angle, the risk of other errors increases, see Figs 4, 5, and 6. These errors result from a mirror reflection of the sound wave on smooth surfaces. The errors can be reduced by making the surfaces rougher, which increases the radius of the reflected sound wave.

If the rotation of the sensor is increased, at a limit value for the rotation, the sound wave is reflected away from the wall and the wall becomes invisible, see Fig. 4. The limit value for whether the soundwave is reflected or not depends on the size of the rotation and the roughness of the wall surface.

Serious detection errors occur when a corner becomes invisible, see Fig. 5. Fortunately, only a slight curvature of the corner is required for it to be visible. Another source of errors is false reflection, see Fig. 6. The sound wave is reflected from one object to another and back to the receiver. These multiple reflections make the object appear farther away than it really is.

4 Navigation

The navigation of mobile robots can be divided into the following sub-operations:

- mapping and modelling the environment
- path planning
- driving along a path and collision avoidance

4.1 AGV

Navigation based on guidance systems is common in Automated Guided Vehicles, AGVs, in the manufacturing industry as is navigation correction of measuring errors when driving along predefined paths with the aid of landmark detection.

Guidance systems

The maps used in these systems consist of predefined paths. They may, for example, comprise conducting wires built into the factory floor. The conducting wires are detected by induction and the AGV is controlled by an on board computer via a wireless connection. AGVs also have a collision detection system, which shuts them down before a collision.

AGVs are unable to deviate from their predefined paths. If an obstacle blocks its path, the AGV cannot continue on its way until the object has been moved. This type of navigation is sufficient for spaces which do not change. Guidance systems are expensive to install as well as being completely inflexible. Another drawback is that failures of the guidance system may be both difficult to detect and expensive to correct, and may cause severe production disturbances.

Alternative guidance systems are painted lines, rows of magnets, or fluorescent lines.

During the mapping stage, measurement data is gathered from both the external and internal (dead reckoning, see below) sensors. The map of the environment in question, stored in a structured data file, is either a digitization of an existing map or else learned by the computer as it moves through the environment. Measurment data is used to create a map or to modify an existing map.

In the path-planning phase, the map is searched for suitable alternative routes. A suitable path is selected from the various alternatives based on the conditions imposed.

When the route has been determined, the driving phase starts. As the robot advances, its movements are monitored according to given dynamic and static conditions. Sensor data is continuously examined and the information obtained is compared with the existing map to avoid collisions. In case of a potential collision, a collision avoidance motion starts automatically.

Dead reckoning

Some mobile robots use dead reckoning to follow predefined paths, and landmark or beacon detection to correct their position. Dead reckoning is a calculation method for determining the position and orientation of the robot by measuring the movements of its wheels. A number of sources of errors are associated with dead reckoning as a guidance method:

- Poor mechanic alignment of the wheels;
- Wheels spinning
- Sensor signal distortion
- Driving mechanism play
- Sensor signal error
- Route variations due to surface roughness

Imagine a mobile robot with two parallel driving wheels driven at the same angular speed and consequently the same circumferential speed. If only one wheel drives over an obstacle the robot will turn slightly towards the obstacle.

Beacons

A way to reduce the problems connected with dead reckoning is for mobile robots to detect beacons along their path. The robot calculates the position of the beacon with the aid of sensors [43] and corrects its motion accordingly. Beacons are very similar to remote controls for television sets and operate close to the infrared range (880-950 mm wavelength). Infrared signals in this range are only slightly weakened by smoke and airborne dust. Each beacon emits a pulse train with, among other things, an identification number until it enters into communication with the robot. Subsequently, the beacon is activated as an infrared transmitter and transmits its position to the robot.

4.2 Various mapping methods

Maps of the environment can be divided into four main categories:

- Path maps
- Free-space maps
- Object-oriented maps
- Composite space maps

The basic principles of *path maps* are introduced in the section on AGVs. Maps created from sensor information can be designed in such a way that they can be said to be included in one of the other three categories.

Free-space maps

A mobile robot can move in an unknown environment without a detailed map by using sensor information. The robot drives along various paths in the environment and stops along the way to detect. The result is then schematically shown in some type of diagram.

An example of this is Hans Moravec's [44] use of a vision system for detecting points with characteristic contrast difference relative to the environment. These points were unequivocally located from various directions and their positions were determined. If a sufficient number of points were localized to define an object, the model proved adequate for planning a collision-free path, if one existed. All objects were modeled as circles, see Fig. 7. Subsequently, possible paths could be selected, see section 4.3.

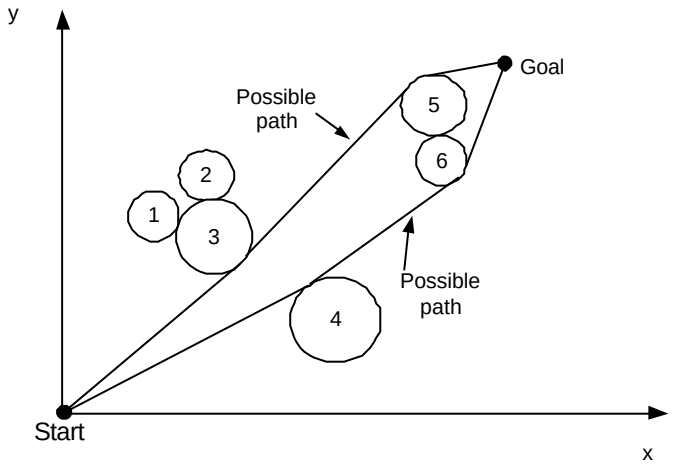


Fig. 7. Map based on the detection of objects by means of a vision system.

Object-oriented map

In situations where the environment is well known, objects are often mapped out in an object-oriented map [45] that clearly indicates the position of objects in the environment, which means that surfaces that are not occupied by objects constitute free space.

Composite-space maps

Free-space maps and object-oriented maps are limited in that they only partly describe the environment. Either the "free spaces" are roughly mapped out while the rest is neglected or else the objects are mapped out and the "free spaces" are inferred. Many problems associated with mobile robots stem from the fact that both free spaces and objects have to be known. When a robot is driven in an

open space, it must be able to avoid colliding with objects which form part of its tasks, such as a docking station.

The most common method of creating maps for composite areas is the area-grid method. This method consists of applying a grid to the map of the robot's work area in which the status (empty or occupied) of each square of the grid is described. A difficulty of this method involves making the squares the right size. If the grid is too coarse, it may seem like all squares are filled with an object, and the robot will not find any free space for getting to its target. On the other hand, if the grid is too fine, considerable computer capacity is required to handle the ensuing large amount of information.

One way of minimizing this problem is the so-called quadtree. [46]. A quadtree recursively divides the map of the robot work area into squares of equal size, see Fig. 8. The recursion ceases when either the quadrant is homogeneous or the minimum square size has been reached. A quadrant is homogeneous when the whole surface of the quadrant has the same status (empty or containing part of an object).

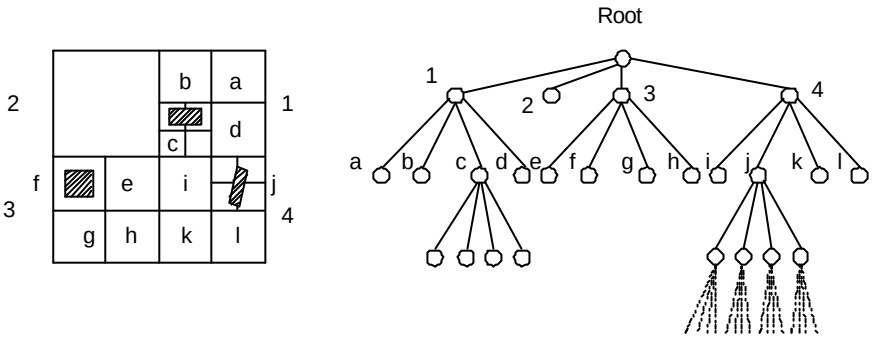


Fig. 8. Examples of
a) geometric representation;
b) associated tree structure according to the quadtree method.

A quadtree is stored in a tree structure, in which the status of the quadrant is stored in the node. If the quadrant is covered by a uniform surface, further division of it stops. Thus, large surfaces with the same status are described by a small number of quadrants. This works well as long as the sides of the object are parallel to the quadrants. Objects whose sides are not parallel (see quadrant j in Fig. 8) to the quadrants require increasingly smaller quadrants in order to minimize the uncertainty of the status of a particular quadrant, The smallest quadrant size determines the depth of the tree structure and the accuracy of the mapping.

4.3 Path planning

Maps for mobile robots have two main purposes: registering where the robot has been and planning the onward route. This involves:

1. finding a path through the mapped environment for the robot to drive along while avoiding collisions;
2. managing uncertainties of the sensor-detected model as well as errors in the planned path;
3. minimizing the impact of objects entering the field of vision of the sensors by keeping the robot away from these objects.
4. Finding an optimal path, if that path is regularly used.

Path planning for AGV

Paths for AGV systems are usually planned by humans. When the paths have been constructed with a guidance system in the floor, the choice of path to be made by the robot is carefully planned in order to achieve an efficient transportation system.

Automatic path planning

If there is a limited number of known subpaths [47], it is suitable to create a search tree, see Fig. 9. The robot's start point is the root of the tree structure and the subpaths are the branches of the tree. The path from the start to the target according to Fig. 9 can be solved in many different ways. A search algorithm can be used, which searches the tree primarily to find out if there is a path leading to the target and also to minimize the total length of the search path.

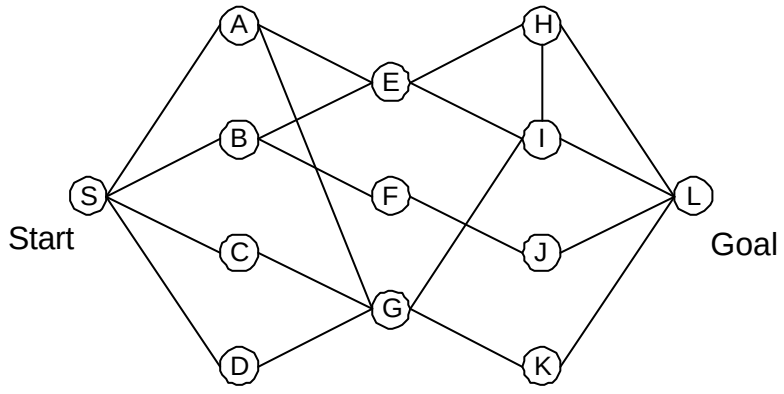


Fig. 9. An example of a search tree showing how the path from the start point S to the target T can be broken down into subpaths.

Free-space planners

As the name indicates, this type of path planner is intended for free-space maps. In a narrow corridor it is desirable for the robot to move in the center between the walls as this minimizes the risk of collision in case of a minor sensor error. On the other hand, in a wide corridor it is more suitable for the robot to follow one wall at a certain safe distance. In a large open area there may be a problem of the robot driving a longer distance than required.

Planners for object-oriented maps

In object oriented maps the path is planned as a series of vectors connected by the intermediary of the outer edges of the objects. When the objects are modeled as circles, see Fig. 7, the robot is reduced to a point and the diameter of the circles is increased by the diameter of the robot. The path is either a straight line from the start to the target or a sequence of the tangential segments between the circles and part of the arc around the circle.

In this path planning method, the optimization problem consists of finding the shortest path between the objects and around the same. This is more complex that it may at first seem. There are four possible paths tangentially between each pair of circles. The point on the arc where a tangent is connected and the point where the next tangent leaves are not the same. The length of the arc between these points must be added to the length of the tangent.

A complete path search requires every tangential path between each pair of circles to be generated and added to a search tree of all possible paths. Next, search algorithms are used just as in automatic path planning.

Planners for composite area maps

Planners using the area grid method plan subpaths from the center of an empty square in the grid to another empty square in the grid. This planning tool suffers from the same weakness as free-space planners but the problem is not as significant. When many squares in the grid together form a polygon having an empty status, the planned subpath tends to be closer to objects in the environment than in an optimal solution. The area of the robot is taken into consideration by reducing the robot to a point and expanding the diameter of the objects by the diameter of the robot.

5 Walky

The purpose of designing and building Walky, an experimental mobile personal robot, was to give people with disabilities ideas and thoughts about how a flexible high technological device might assist them in a work and/or home environment.

Individuals with physical disabilities are often excluded from the workforce. Even if they have the requisite skills and an interest in the job, their disability often prevents them from working unless they can receive assistance. A robot fetching and moving things can provide this assistance.

Earlier projects (see chapter 2) for developing personal robots for people with disabilities have focused on office-type work. However, people with disabilities are neither more nor less interested or competent in administrative work than other people, and consequently an alternative to office work is needed. I have found that a laboratory may be a good environment for robotization.

In this context, "good" means that the work content should still be meaningful after the robotization. The work should not be of a therapeutic nature only, which is the case if the remaining work task could easily be automated once the workstation has been robotized. In laboratories, a robot can carry out the mechanical tasks (moving test tubes, etc.) while the truly qualitative tasks still remain.

Another advantage of the laboratory sector in this connection is that the objects to be handled are relatively light, which means that a small robot can be utilized. A mobile personal robot could also help several disabled individuals working in adjacent locations. This will result in more efficient use of the device and spreading of costs.

Being able to use the same mobile personal robot in the home and at work is the vision of the optimal solution. When the disabled person is picked up by the transportation service at his/her home and driven to work, the personal robot is also brought along. The mobile personal robot then accompanies him /her throughout the day.

Previous robotizations of worksites for people with disabilities have involved stationary solutions. The advantages of a mobile personal robot in comparison with a stationary one include:

- considerable flexibility for the user;
- little interference in the physical environment;
- the possibility of several users utilizing the same equipment;
- ease of storate when not in use

The drawback is that the technical solution becomes much more complex, the number of sources of errors increases and, consequently, the risk of functional disturbances rises as well.

The main requirements for the robotic system were:

- optimal safety
- high user-friendliness

The main requirement for the worksite was the work should still be meaningful after robotization.

5.1 System design

On the basis of documented experience (my own and that of others) from projects with stationary personal robots, I decided that all constituent components should be of a standard type. With the cost of a stationary workstation such as RAID and a wheelchair-mounted personal robot such as Manus as a guideline, I decided that the cost of the prototype should not exceed 500,000 Swedish kronor (ca $64,000). The safety of the user and other individuals who come into contact with the robot as well as the user interface were other important factors determining the basic requirements for the system.

I chose a 5-axis robot, SCORBOT ER VII, despite the limitations on the movement of the robot imposed by a robot arm with fewer than 6 axes. The robot arm was to be mounted on a LabMate, a mobile robot base with three axes of movement. This meant that the system as whole had 8 degrees of freedom, which solved the problem of the limited movement of the robot arm.

AGVs (Automated Guided Vehicles) are used by the manufacturing industry in flexible production systems for transporting objects to and from production units. The guidance methods used for AGV navigation entail major intervention in the physical environment, e.g. installing a wire a few centimeters blow the floor level. Intervention of this kind is unusual in home or office environments.

I decided that the navigation should be carried out with the aid of a sensor system. The sensor system I selected was a combination of ultrasonic sensors and infrared sensors. The sensor system was adapted to work with the above-mentioned mobile robot base. The mobile personal robot system was named Walky.

The system integration meant that, through his computer and a wireless connection, the user was able to communicate with a communication computer on board Walky. The purpose of the communication computer is to communicate with the control unit of the robot arm, the wireless connection, and a local area network for the mobile robot base and the sensor system.

The robot arm was modified from 220V AC voltage to operate on a 24 V battery. The sensor system was tested, and successively expanded, for navigation in a home and office environment with the ability to detect, for example, table edges, thresholds and doorways. The sensor system was also adjusted for wall-following and collision avoidance.

A map of the surroundings was created in AutoCad and was transformed for the Windows environment. Manual subtargets were created in each room on the map. The number of subtargets depended on the size of the room. Walky was then able to navigate between these pre-defined subtargets with pre-calculated subpaths, point-to-point navigation. Information about the surroundings was obtained from the sensors. The sensor signals were interpreted and a subpath was created between the non-pre-defined position and the subtarget. The route was the sum of all the pre-calculated subpaths plus the subpaths that had been calculated using visual navigation.

The locations of the sensors were chosen to detect obstacles as well as to create safety zones in Walky's driving direction. The closer a detected obstacle is to Walky, the slower is the speed at which Walky moves forward.

When point-to-point navigation is used, the route taken is determined exclusively by the intelligence built into Walky, and the user has no way of influencing this route. I supplemented point-to-point navigation with two other guidance methods: complete manual control and a combination of the other guidance methods. The combined guidance method means that the collision avoidance algorithms from the visual navigation are used while the user manually selects the path Walky will take. The user should be able to chose which guidance system he/she wants Walky to be guided by.

A map created in AutoCad is displayed on the user's computer enabling him/her easily to guide and locate Walky.

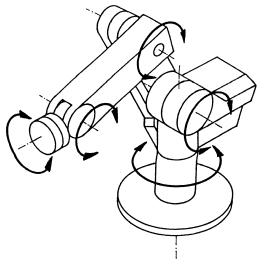


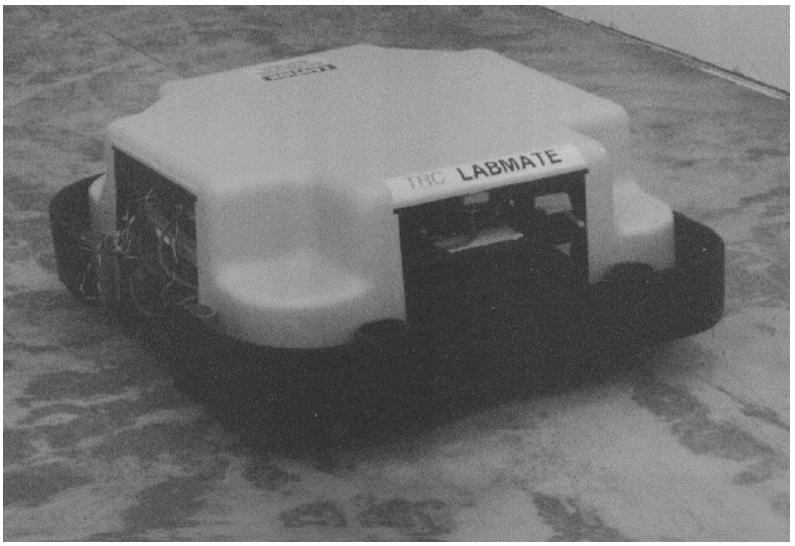
Fig. 10. SCORBOT ERVII.

The Robot

In this project, I chose to work with a SCORBOT VII robot with the following technical features:

Structure:	spherically articulated 5-axis robot
Driving system:	
drive	DC booster
transmission	harmonic drives
Operating range:	
base	250 degrees
shoulder	170 degrees
elbow	225 degrees
handled pitch	180 degrees
handled roll	360 degrees
Max. operating radius	190 mm at the wrist 850 mm with end-effector
Max. speed	1 m/s
Max. load	2 kg
Repeating accuracy	0,2 mm

Mobile base



Picture No. 12. LabMate with body.

LabMate is a mobile base designed and manufactured in the USA by Transitions Research Corporation. The base comprises a tubular frame made of steel with a plastic body. It has two drives made of hard rubber mounted on a central shaft. The shaft is resiliently mounted on the frame. The springs are adjustable to offset various loads. The base is guided by varying the individual speed of the wheels. If, for example, the speed of the left wheel decreases, the base turns to the left. Four smaller, non-resilient

castors are located in the corners, resulting in a very stable base. The base is 700 mm long, 750 mm wide, and 280 mm high. It weighs 49 kg without the batteries and is dimensioned to support a maximum load of 90 kg. Its top speed is 1 m/s with no load, but it decreases as the load increases. The base is powered by two 12 V car batteries connected in series.

Sensor system

A contributing factor in choosing the LabMate was that Transitions Research Corporation sells a sensor system comprising a maximum of 24 ultrasonic sensors and 24 infrared sensors, which is integrated into the LabMate. The infrared sensors are of the photo cell type. They enable the detection of an obstacle, but not of the distance to the obstacle. Consequently, I decided to use only the distance-measuring ultrasonic sensors, which are described below.

The special conditions present in a home and laboratory environment formed the basis for the sensor system configuration (see section 5.3).

The Polaroid ultrasonic sensors

Polaroid's ultrasonic sensors were developed for distance measuring in cameras, with the distance indicated by time between the emission and the reflection of the pulse. It is possible to measure distances from 27 cm up to 10.7 m. The sensor diameter is 4 cm and it can detect the distance to objects located within a 30 degree angle, see Fig. 11.

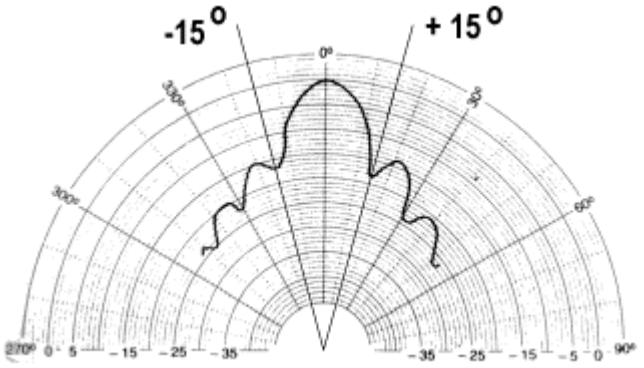


Fig. 11. Typical beam pattern at 50 kHz.

The ultrasonic sensors are so-called low-cost sensors (ca 250 SEK each), which is important in keeping costs at a reasonable level since the system may contain 24 such sensors.

Wireless radio communication

Commands and data are transmitted between the personal computer and the robot base by means of a wireless serial link using two radio modems: ARLAN (Advanced Radio Local Area Network) 130 from Telesystems SLW Inc., USA. The transfer rate of the modems is 9600 bps. Their range is 30 - 45 m in a normal office (divided into rooms with physical walls). In an open-plan office, their range is 45 - 75 m, while up to 300 m in an obstacle-free environment.

Communication computer

Today, we would have chosen a conventional portable computer with three communication ports and the Windows NT operating system as the onboard computer for Walky. This option was not available when Walky was being developed. In the course of the project, I tested various computer solutions, but none was satisfactory with respect to the use of three communication ports. Instead, I used a manual switch for communicating with the robot or the mobile base.

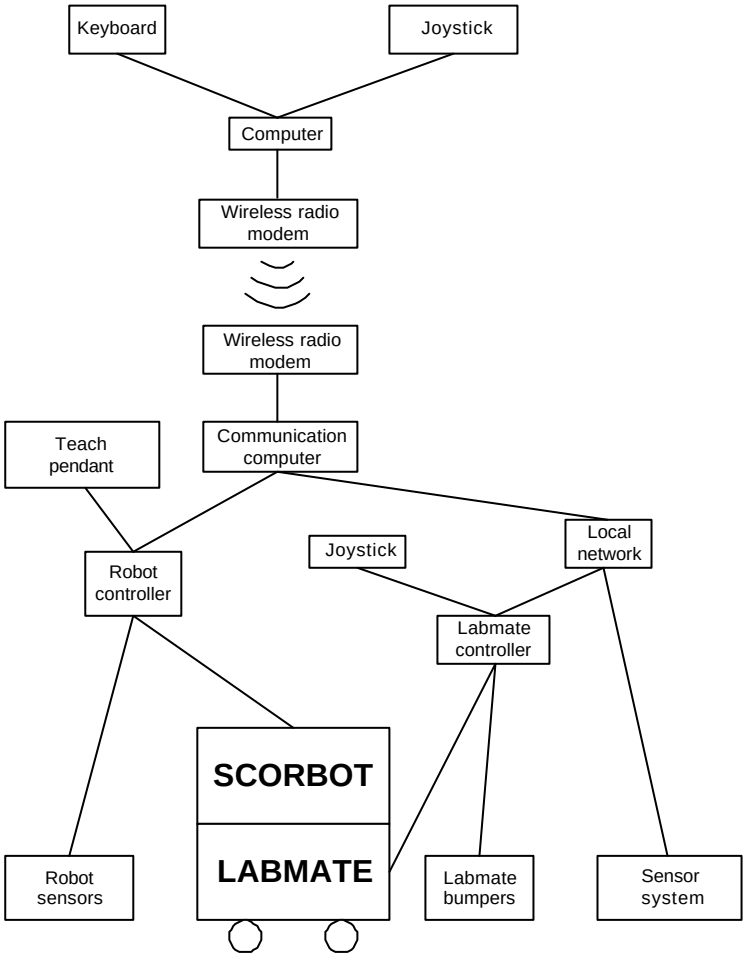


Fig. 12. The structure of the mobile robot system.

5.2 Sensor System Configuration

Version 1

Eight ultrasonic sensors were placed on the LabMate mobile base, according to Fig. 13 and Table 2. The sensor configuration is a modified version of the configuration developed by the German Fraunhofer Institute for its IPAMAR [48] mobile robot. The sensors are read in the following order: 0, 1, 2, 3, 4, 5, 6, 7, 0, 1, etc.

I carried out several tests to determine whether eight sensors were sufficient for detecting the distances to various objects in different situations or whether it would be necessary to increase the number of sensors.

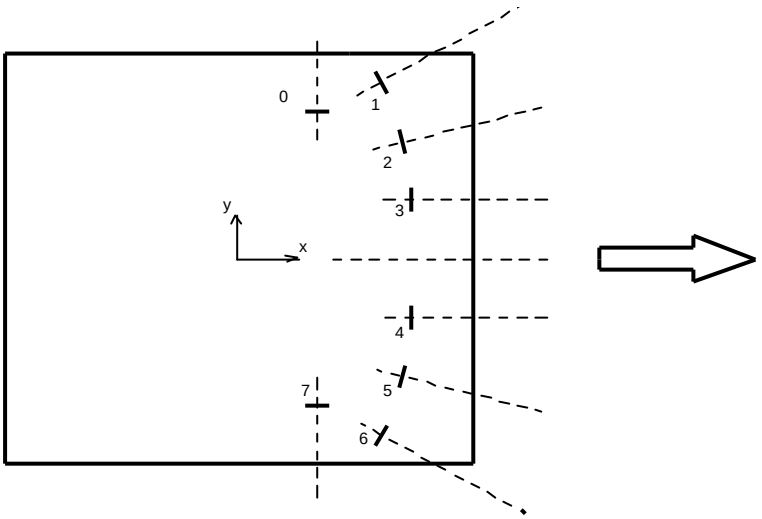


Fig. 13. Walky's sensor configuration, the origin of coordinates is located in the center of rotation of the mobile base.

Sensor no.	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**
x-coordinate/mm	125	227	260	275	275	260	270	125
y-coordinate/mm	250	300	200	100	-100	-200	-300	-250
rotation/degrees	90	30	15	0	0	-15	-30	-90

Table 2. The table shows the x and y coordinates of the sensors as well as their rotation.

In the first test scenario, a chair leg was detected. The result showed that sensor 3 was interfering with sensor 4. Consequently, the order in which the sensors are read was changed to 3, 1, 2, 0, 4, 5, 6, 7, 3, 1, etc.. The other sensors did not interfere with one another.

Tests were performed with chair and table legs of different geometrical dimensions (various standard designs) which indicated that detection is not dependent on distance *(m)*, see Fig.

14, but if the leg is outside a beam angle of 23 (2α, as shown in Fig. 14) it can usually not be detected. This meant that the dispersion cones in front of the sensors had to be reduced and that the first sensor configuration had to be modified, so that there would be no significant areas where the sensors would be unable to see a possible obstacle.

I also tested what the sensor is sensitive to, chair legs or background surface, when the distance (m) varies. The results showed that the distance has no effect on the measurement result. Irrespective of the value of the distance x and the choice of chair leg, the material the chair leg is made of, and the material the background surface is made of, there was a clearly observable difference between the leg and the background.

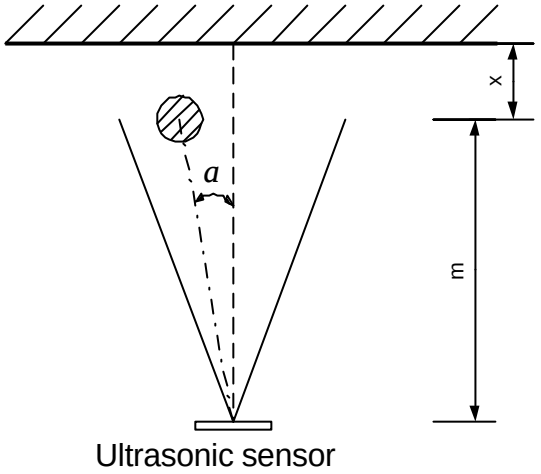


Fig. 14. Chair and table leg detection test.

Moreover, I tested how large the angle to a wall can be, before the wall becomes invisible to the sensor, see Fig. 15. Tests carried out on different materials show the largest angles possible.

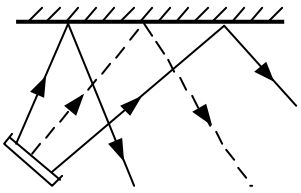


Fig. 6. Detecting an invisible wall.

material	angle
plywood	20
cloth, wallpaper	33
lacquered beech	25
Plexiglas	15

Table 3. The table shows the largest detectable angle for different wall materials.

Can the sensors detect a pen on the floor or perhaps a threshold? If yes, at what distance (m) (see Fig. 16)? How tall, h, must the object be to be detected? The results of this test are important, since the mobile base is unable to drive over objects whose height is greater than 7 mm. It can drive over a firmly

attached electrical cord, but a pen may become wedged under one of its wheels.

It was found that the height of the smallest object that can be detected is 45 mm when it is located 180 cm in front of the mobile base.

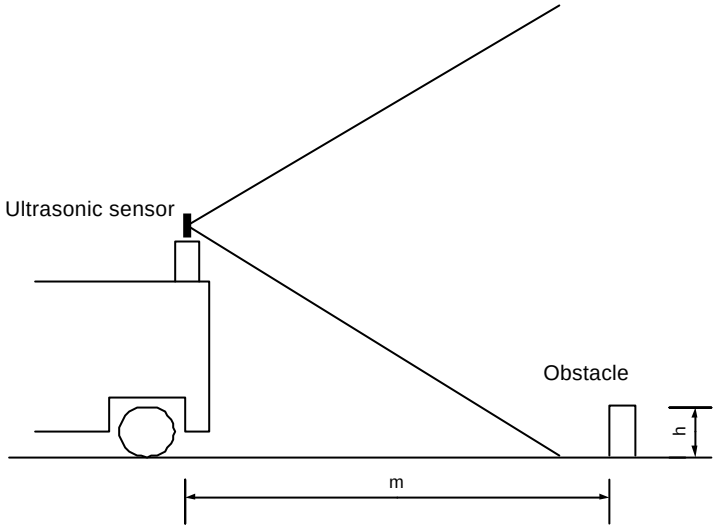


Fig. 16. Testing detection of obstacles located on the floor.

The conclusion drawn from the experiment was that to detect small objects on the floor at least one sensor directed obliquely towards the floor is required.

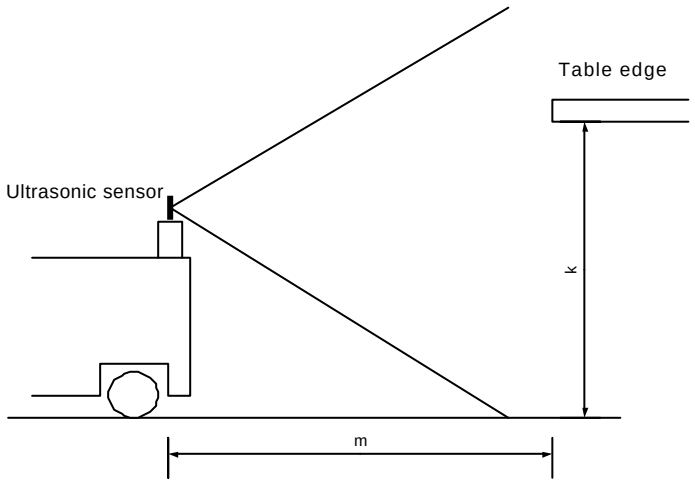


Fig. 17. Detecting a table edge.

I tested whether the ultrasonic sensor was able to detect a table edge and, if so, at what distance (m). The table height chosen was 73 cm.

The tests showed that if the thickness of the tabletop was 25 mm, the edge could not be detected with the existing sensor configuration, but if the thickness of the table top plus the

subjacent support is 50 mm, it could be detected at a distance of 170 cm.

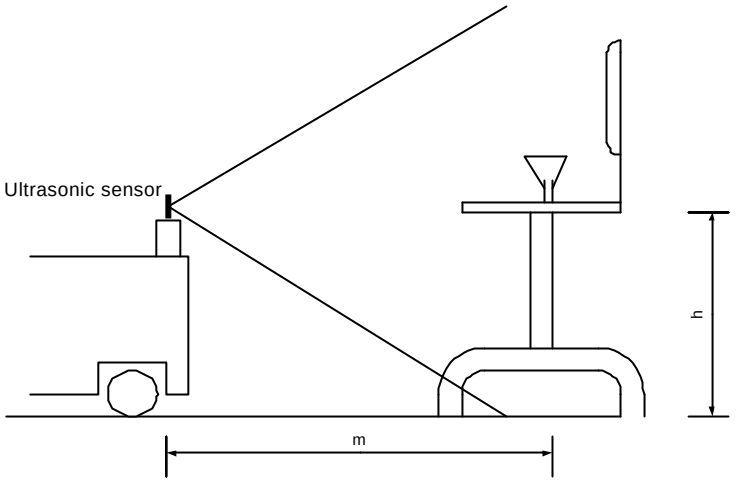


Fig. 18. Detecting a desk chair.

Where on the desk chair will the waves from the ultrasonic sensor be reflected, when the height(h) of the seat of the chair can be adjusted to between 43-48 cm depending on the user. It was found that the seat is the part of the chair that is detected and that the distance measured is correct.

Bookshelves that are full or half-full can be detected, but empty bookshelves or shelves with only a few books can be detected only in certain cases – depending on the angle of detection.

Measuring long distances: no problems were found when measuring was carried out in very large rooms. But problems did occur when measuring was carried out in corridors. Reflections from doorframes sometimes resulted in false detection.

Version 2: An extended sensor system

One sensor on each short side, sensors 8 and 11 in Fig. 19, were added to the extended sensor system to facilitate wall-following. Two sensors were placed on Walky's back to enable the robot to detect objects when it is backing up. A sensor, sensor 15 in Fig. 19, solved the problem of detecting a tabletop located 73 cm above floor height. In addition, it became possible for the sensor system to detect obstacles on the floor which are larger than 3 mm. Sensors 12, 14, and 15 (see Fig. 19 and picture No. 13) were angled towards the floor so that the centerline of the sensor was directed 80 cm in front of Walky.

The influence of changes in ambient temperature and humidity were compensated for by means of a calibration sensor mounted on Walky having a fixed detection distance.

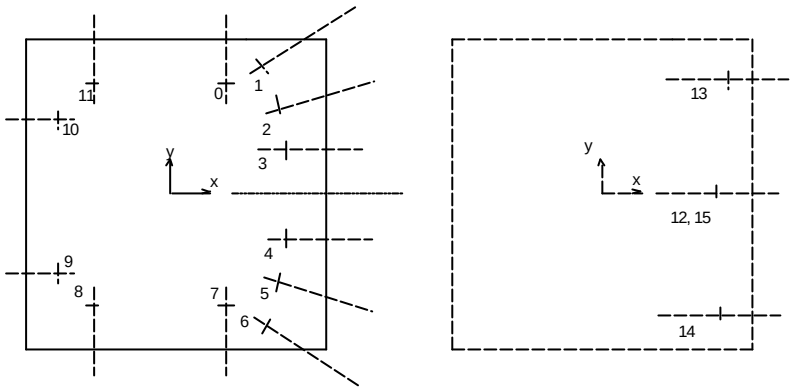
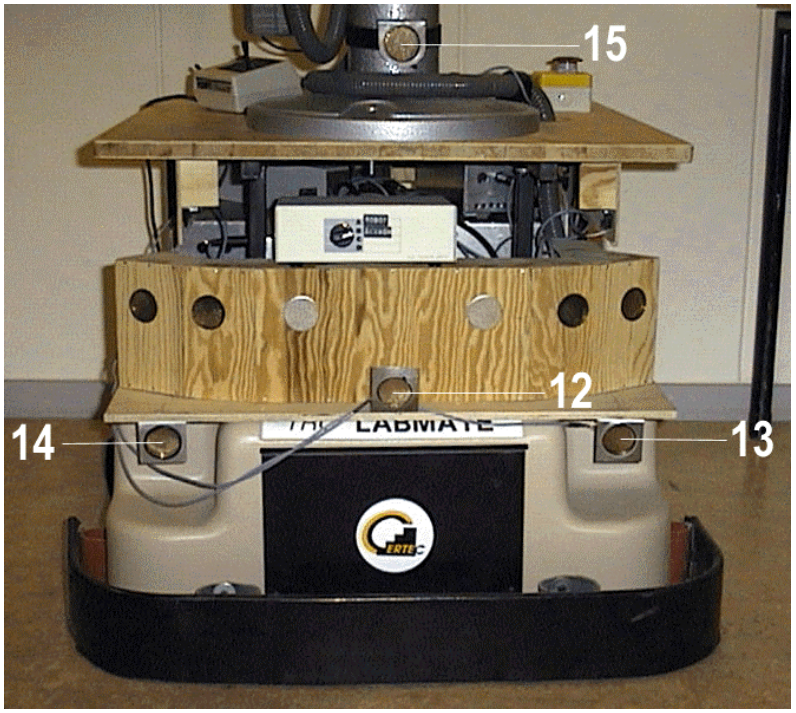


Fig. 19. The extended sensor system.



Picture No. 13. The front of Walky with the extended sensor system.

Safety zones

With the aid of the sensor system I established various safety zones in which obstacles were detected. I used 23 degrees as the maximum detection angle of the sensors. The zones are:

1. 210 cm, nothing happens (the ignore zone).
2. 130-210 cm, Walky's speed is reduced to 70% of the normal speed (the obstacle detection zone).
3. 40-130 cm, Walky's speed is reduced to 50% of the normal speed and the obstacle avoidance algorithm starts (the reflex zone).
4. < 40 cm, Walky stops immediately (the safety zone).

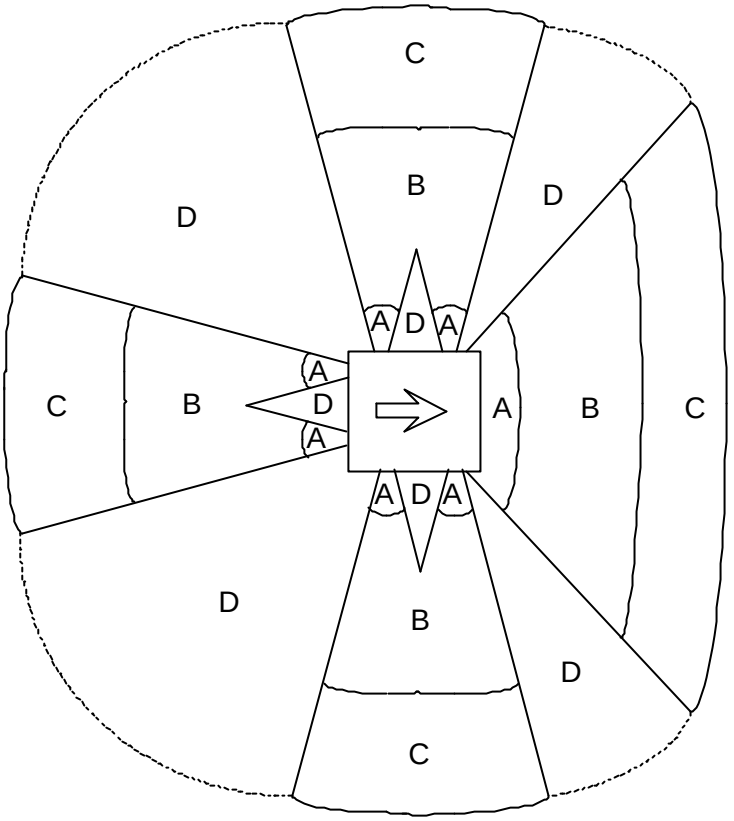


Fig. 20. Detection zones,
A=safety zone, *B*=reflex zone, *C*=obstacle detection zone and *D*=blind zone.

Fig. 20 shows that the sensor system is unable to detect obstacles in zone D. If, for some reason, the sensors have not detected a possible obstacle, Walky's bumpers will sense the obstacle and Walky will stop immediately.

5.3 User Control of Walky

On the users computer is a AutoCad created map transformed to Windows, the user can easy control Walky and on the map see where Walky is.

Automatic navigation

In another project [49], a software program was developed which automatically calculates the path from the start to the target. The starting position must be known. The program used an object-oriented map with no information from external sensors. All the user was required to do was to point to the location on the map where he wanted Walky to go. I developed the program further to enable Walky to determine its starting position with the aid of sensor information.

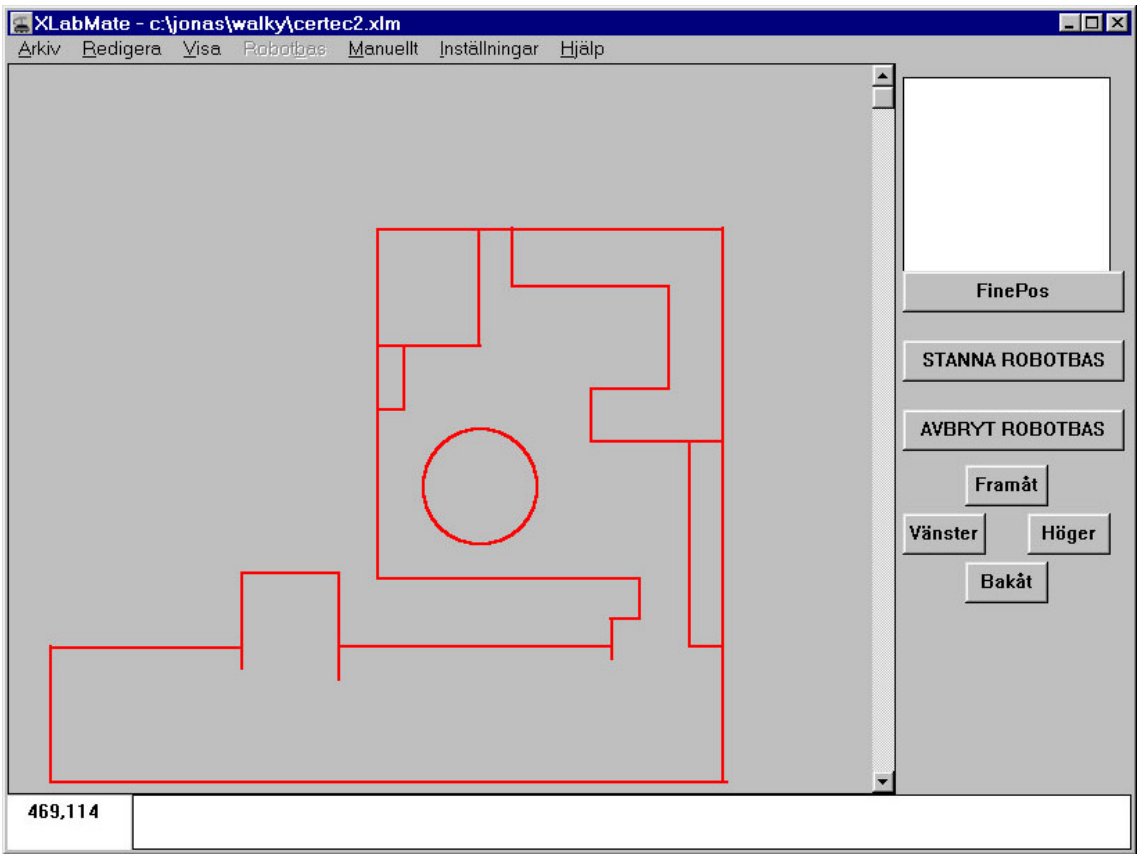


Fig. 21. Walky driver interface.

The latter control method was demonstrated to Christer Evaldsson (see Chapter 2). During the demonstration, Walky was to drive straight ahead a distance of about 6 m through a doorway and then make a 90 degree turn. The software program calculated a number of subpaths, some of which were selected by a search algorithm and were then added together creating a navigation path. The calculation time was approximately 100 s. Christer and I agreed that this was much to long. Christer mentioned that the user did not know if the robot had received the command. He also said that he did not feel certain that the robot was carrying out its task as commanded when it disappeared out of sight through the doorway and around the corner.

To minimize the waiting time, I developed a new method of navigation in which in every room on the user's map a number of points, so-called subtargets, are predefined (see Table 4).

Room	Number of subtargets
> 7 m2	2
7 - 12 m2	3
12 - 20 m2	4
< 20 m2	4 + 1 for each additional 10 m2
Corridor max width 1.5 m	1 every 3 runing meters
Corridor wider than 1.5 m	2 every 3 runing meters

Table 4. The table shows the number of predefined subtargets in rooms of various sizes.

To enable Walky to move more efficiently across the map, additional subtargets are needed. One additional subtarget is placed in the center of every doorway and subtargets are added between 0.5 m and 1.5 m from the first subtarget on each side of the same. This means that Walky is able to pass through a doorway quickly and safely. A subtarget is placed at every location Walky is intended to use, for example for fetching and delivering test tubes or videotapes.

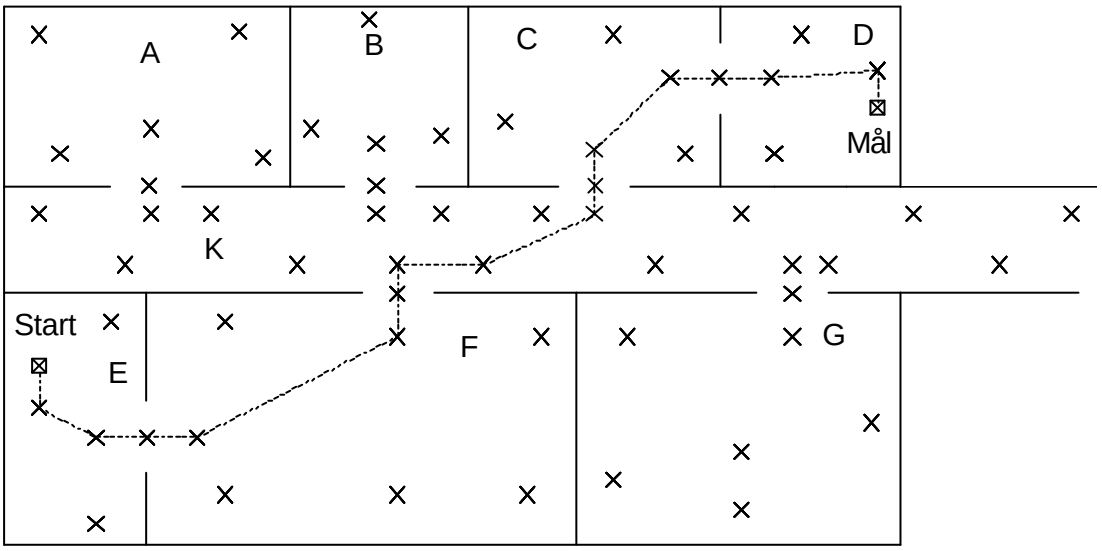


Fig. 22. Walky's path from the starting point to the target.

When all the subtargets have been marked out manually, the path is calculated by means of a search algorithm between all possible combinations of subtargets. These different path options are stored in a database. When the user marks Walky's starting point, the subpath or subpaths from the starting point to the nearest subtarget are calculated in the same manner. A calculation is also performed for the target and the subtarget closest to the target. The calculation time is no more than a few seconds, and then Walky can start driving towards the target.

Avoidance algorithms

What happens if an obstacle appears on the path? I developed obstacle avoidance algorithms based on the use of the subtargets. When Walky has avoided an obstacle and has passed it (point A in Fig. 23), it tries to drive towards the next subtarget. If the subtarget is too close or if Walky has already driven past it, i.e. the robot is required to make a large angle turn towards the object, it goes to the next subtarget. Walky has an internal coordinate system and the map has a global coordinate system. When the two coordinate systems are compared, Walky's position and direction can be determined.

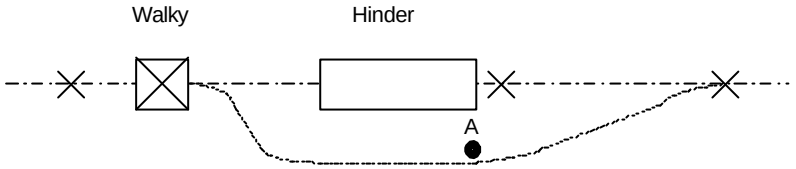


Fig. 23. Walky's path around an obstacle. The pre-calculated path is indicated by a dash-dot line and the path around the obstacle, calculated by the obstacle avoidance algorithm, is indicated by a dotted line. The subtargets are indicated by a cross.

Manual control

The user can decide whether he wants to control Walky by manual control only. In such a case, the user marks out subtargets and targets himself, for example by clicking the mouse on the map to indicate the path Walky should follow.

Semi-automatic control

Semi-automatic control functions in the same way as manual control with the difference that the avoidance algorithm is operating.

Regardless of the type of control employed, the user can see Walky's location on the display. Walky transmits its position to the computer and as a result the Walky symbol moves on the screen.

5.4 Interviews with some disabled persons in Tenerife in March 1998

A, *B*, *C*, *D* and *E* are the interviewees and *IP* is the interviewer.

1. Overall impression

Do you think that Walky can be used as an assistive device in the future? If yes: For whom? If no: Why not?

A: YES. Me. Everything! Perhaps not Walky specifically, but I would like to have two kinds of robots:

a) One that will adapt me in terms of interface. Perhaps, like armor around my legs, so I will be able to walk. A chair/robot that is able to negotiate stairs.
b) One that will do simple tasks. Picking up small things off the floor. Handling switches, turning things on and off. Opening elevator doors.

B: Absolutely!!! It is an excellent alternative to the trained monkeys used in the United States and the trained guide dogs used by people with disabilities in Sweden. I am really into technology. I bought an Apple computer in 1979! Because it is *impersonal*, technology is good if you want to maintain your personal integrity.

C: Certainly. For me in my kitchen! (*D*: "Yes , you are definitely the Walky type, C!")

D: Would it be able to hand me my electric guitar? That's the kind of thing I would like to use it for.

E: Yes. In some way or other. For special tasks. For the mailbox In stores. At indoor worksites. I think that the real problem is whether or not those around you will accept it.

2. Personal independence

Which of the tasks performed by a personal assistant would you rather have a robot do instead?

A: Everything actually, but primarily the really simple tasks. But the robot must not be too bulky. At least not in the home.

B: Preferably everything. I think it is degrading if other people have to lift me, for example. Even if it is my son who does it. It was necessary a little while ago, when I had broken my arm.

C: Everything. We are not very good at even imagining using personal assistants as a tool. It is probably much easier to use technology since it is supposed to be so impersonal.

D: Do I have to choose? I think that it would probably be good to be able to have both. Some days I may not even want to speak to anyone at all – then it would by good to use technology. On other days, I may want to have another individual present.

E: Quite a lot around my desk. Feeding me. Opening the refrigerator to get a drink. Brushing my teeth. I would like to go to bed on my own – but I don't suppose Walky would be able to help me with that?

Could it result in INCREASED personal independence?

A: Absolutely! I know, of course, that technology is not always reliable (the elevators in this place, for instance!). But neither are people.

B: Yes, to me, there is no alternative . I definitely want to be independent.

C: YES

D: Yes, I think so. As you can see, we need a great deal of personal assistance, but so far, we have not even been given that. I have been told that as long as I am able to feed myself, that is bring a spoon to my mouth, home-help service is all I get.

E: I'm not sure. No, I think that I have accepted that I am very dependent on others in some respects. Perhaps because my wife is my personal assistant and we have organized our lives accordingly. But I won't deny that there are some things I would like to be able to by some other means. For example, sometimes I would like to be able to go to bed when she is not at home.

In what situations would you rather not use a personal assistant?

A: All situations. If I have to specify the most important situations, I would have to say that it is actually not about personal integrity (when using the bathroom, etc.) but it's about having someone interfering in your life. For example, my wife doesn't want someone to come to our house late at night to help put me to bed – in that case, she would rather do it herself. But this creates a dependence between us that is not good: if she wants to go to bed before me, I would like to be able to go to bed on my own. Without having anyone come to our house. Robotic assistance or something similar would be great.

B: All

C: All

D: All. In particular, when it comes to personal hygiene and going to the bathroom. It is awful that there are so many assistants and that they all do things differently. Some of them wipe very roughly. I find it hard to say anything when it hurts, instead I just grit my teeth.

IP: "But what about food? You seem to think that soon you will no longer be able to feed yourself."

At this point, an animated discussion began.

IP said that she could not imagine anything worse than being fed by someone you do not like. Going to the bathroom is more the same thing each time. Finished already so to speak. But your

mouth is much more private. Opening your mouth to someone you don't like and swallowing the food he or she puts in your mouth: yuck.

D thought more about it: Yes, maybe. What if they are too rough when they put the spoon in my mouth? And what if they are using snuff and blow on the food to cool it down? Yes, maybe I would prefer to be fed by a robot. But actually I think that I would like to switch between the two.

E: Not being fed by my wife? No, I can't even imagine something like that.

What kind of work do you think you could do with the aid of a mobile robot?

3. Work

A: Anything at all – except for tasks where I deal directly with people. I couldn't work as a policeman, but I could work in a warehouse, for example.

B: I had polio when I was five months old, so I have never really had any other choice than doing administrative work. I have worked extensively in the area of sports for the disabled – dealing with people even if the work is administrative. I was able to walk until six years ago. I actually like administrative work, so perhaps I would like to use a Walky in the office. I like mathematics and statistics – I studied those subjects at university.

But, it's true: I have always wanted to become an actress. Perhaps Walky could be useful on stage? No, I guess not. But if, as before, I modify my wishes to at least being able to do radio plays, perhaps I could use Walky there?

C: I would like to work in a seniors' home. Be the one they come to about their problems. I want to help them and comfort them, to be there when they need me. I am good at that. I could obviously use a Walky in that situation, to do things I am unable to in terms of movements.

D: I would like assistance in all aspects of working in a sound studio. Connecting electrical cords, picking things up from the floor, lifting my guitar, fetching papers...

E: I have a great job, i.e. I run my own business. I haven't been an employee since the accident and I don't think I would like to be one. We have a full life. I am into the stockmarket – I started fairly soon after the accident. I studied business administration. Had a caravan rental business – did all aspects of it: advertising, bookkeeping, etc. We have traveled a lot. Here , I publish a paper "In Tenerife". We live in Tenerife for 8 or 9 months of the year. I use my computer a lot, I control it by means of a stick. It put a strain on my neck. I am testing dictation programs, and they are getting quite good! Soon, I will probably use one of those instead. – A robot in my work? I don't know. Perhaps it could help me with a few things around my desk.

4. Control

A: I would prefer voice and joystick – I want to be able to switch between the two.

B: Joystick. I would like to use touch. And to control it with my own movements.

C: Joystick

D: Joystick

E: Voice

How would you like to control the robot? Voice, eyes, joy-stick, zip and puff, other?

5. A wheelchair-mounted robot or a mobile one, such as Walky?

A: I would prefer a Walky – but probable subsequent version will also be too bulky to bring along with you. And since I want to be mobile, a wheelchair-mounted robot is probably better.

B: I would prefer a Manus arm so that I could control it myself.

C: Walky. It's quite OK with me if it moves around freely and disappears behind a wall so that I can't see it. I would trust it! We already have a self-navigating lawnmower.

D: On my wheelchair. I want to be in control. For example, when I am charging the batteries for my wheelchair, I want to be able to check that the charge indicator light is on.

E: Walky. I don't want any kind of extension of my body close to me and I definitely don't want to look like some kind of monster myself. I might look like an accessory for the robot if I am sitting there with a Manus arm.

Which one do you prefer?
Why?
Do you want them both?

6 Discussion

Does a product like Walky have a future as an assistive device for people with disabilities?

I divided this question into three sub-questions:

1. Do the users want a personal robot as an assistive device?
2. Can the Walky technological concept be improved?
3. Would investing in a personal robot so that a disabled person can have a job be cost-effective in terms of public finances?

Do the users want a personal robot as an assistive device?

The user interviews revealed that all interviewees would like some type of assistance from a robot, but with different types of tasks. Some would prefer a mobile robot and some a wheelchair-mounted one.

Can the Walky technological concept be improved?

Yes, but it will require a considerable amount of work. My Walky concept was based on the premise that all component parts would be standard products. This would also be necessary in the case of a Walky II – otherwise the cost of the robot will be tremendously high. Designing and building a robot arm or a mobile base are projects involving millions of kronor. In my opinion, the base of one of the larger wheelchairs made by Permobil would be suitable as a mobile base. At the moment, my choice for a robot arm would be the arm made by the Canadian company CRS, but I think that in a year or two, the robot arm being developed by the robotics section at Lund University will be the best choice.

Walky II must be designed to work with people. The technology inside the present products must be provided with a new shell. Walky's sensor system should be supplemented with one or more rotating sensors. In addition, beacons should be part of the concept.

Would investing in a personal robot so that a disabled person can have a job be cost-effective in terms of public finances?

Revenues include the value of the work carried out by the user, calculated as 50% and 25% of a fulltime monthly salary of SEK 16,000. While the disabled person is working and has access to the robot he is not considered to need personal assistance. Consequently, the work carried out by the assistant is calculated as revenue (actually: a reduction of expenses). The cost to the municipality of a personal assistant is set at about SEK 165 /h. I have reckoned with a time saving equivalent of the hours of work put in by the disabled person, i.e. 4 or 2 hour workdays, 5 days a week for 40 weeks per year.

In the above calculation, I have not taken into consideration the money flows between different levels of society – who is paying for what – the central government, the county council, the municipality or even the employer in question. That would seem too petty in the circumstances. Moreover, I have not discussed how valuable it is to the individual to have the ability to work. The value of this cannot be expressed in monetary terms. Rather, it is about an invaluable boost to one's self-esteem and sense of belonging. It is this aspect that has been the intangible driving force behind the work presented in my thesis.

Some calculations based on the Manus arm.

Expenses:
Investment = SEK 250,000
Operating costs = SEK 25 000 /year
Installation and training costs = SEK 25 000

Revenue if the disabled person works 4 h/day:
Value of the work done by the user = SEK 137 000 kr/year
Assistant's salary saving = SEK 132 000 /år
In the case of a 2h workday, the revenue will be 50% of the above.

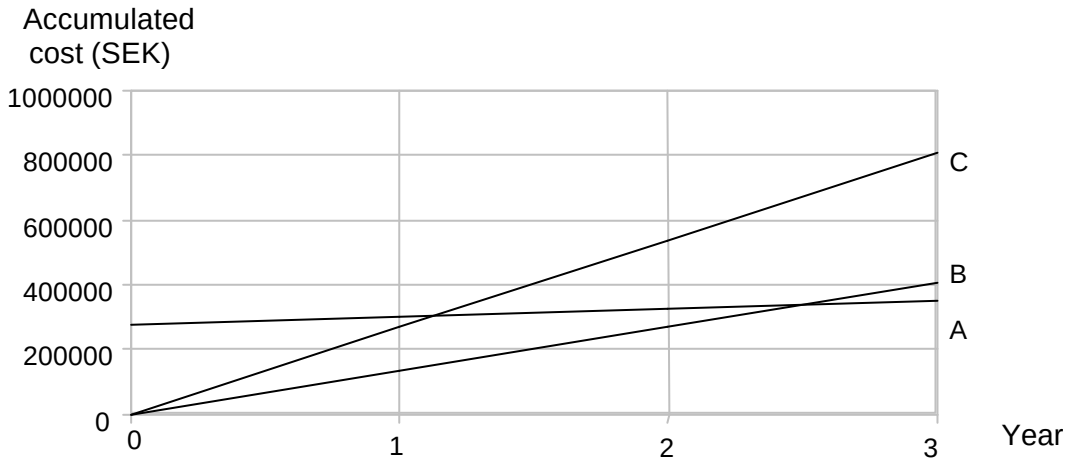


Diagram 2. The diagram shows the time needed for the Manus arm to become profitable. Line A illustrates the investment and operating costs of a Manus arm, lines B and C, respectively, represent the revenue/reduced expenses if the disabled person works 2 and 4 hours per working day. The investment will pay for itself in a little more than a year and in 2.5 years, respectively.

7 Published Reports and Conference Papers

The following is a selection of the published reports and conference papers, etc., that form the basis of this thesis. They have been slightly edited to improve their readability and to avoid duplication of content. (Naturally, when presenting various Walky results, I have been obliged to repeat the same background information on each occasion.)

Article:

Bolmsjö, G, Neveryd, H, Eftring, H, *Robotics in Rehabilitation*, IEEE Transactions on Rehabilitation Engineering, vol. 3, No. 1, pp. 77-83, March 1995.

Conference papers:

Neveryd, H, Bolmsjö, G, *Mobile Robot System for the Disabled,* Proceedings of the 2nd European Conference on the Advancement of Rehabilitation Technology (ECART 2), pp. 24.1, Stockholm, Sweden, May 1993.

Neveryd, H, Bolmsjö, G, *Walky, a mobile robot system for the disabled,* Proceedings of the Fourth International Conference on Rehabilitation Robotics (ICORR 4), pp. 137-141, Wilmington, Delaware, USA, June 1994.

Neveryd, H, Bolmsjö, G, *The ultrasonic navigating robot, Walky,* Proceedings of the 4th International Conference on Computers for Handicapped Persons (ICCHP 4), pp. 129-135, Vienna, Austria, September 1994.

Neveryd, H, Bolmsjö, G, *Walky, an ultrasonic navigating mobile robot for the disabled,* Proceedings of the 2nd TIDE Congress, pp. 366-370, Paris, France, April 1995.

Neveryd, H, Bolmsjö, G, *Path planning methods for the ultrasonic navigating mobile robot Walky,* Proceedings of the 3rd European Conference on the Advancement of Rehabilitation Technology (ECART 3), pp. 185-187, Lisbon, Portugal, October 1995.

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Robotics in Rehabilitation

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Abstract - Robotics in rehabilitation provides considerable opportunities for improving the quality of life of physically disabled people. However, practical results have been limited, mainly because it is necessary to develop different robotics concepts for people working in different fields. This paper explores some of the developments needed and presents two projects currently underway at Lund University. The first concerns end-effector design for a robotic workstation for office-based tasks, while the second relates to a mobile robotic system for use by disabled people in medical and chemical laboratories. Both projects show promising results. There is also a need for further research into developing new robotic systems for use in rehabilitation with new mechanical features, as well as programming and control suitable for every user.

1 Introduction

REHABILITATION is an activity that seeks to enable a disabled person to reach an optimum level of mental, physical, and/or social functioning. Thus, rehabilitation robotics deals with advancing robotics technology to provide physically disabled people with tools to improve their quality of life and work productivity [1].

Examples of applications include vocational tasks, such as manipulative operations in a structured environment (paper handling in office-based work, test procedures in laboratory-based work, etc.) and daily living activities in structured and unstructured environments, such as game playing, educational tasks, eating, and personal hygiene [2]. This implies the use of robots in a way that is quite different from industrial applications where robots normally operate in a structured environment with predefined tasks, independently of human operators. Furthermore, industrial robots are operated by specially trained workers who have a certain amount of interest in the technology. This may not be the case in rehabilitation robotics. Thus, rehabilitation robotics have more in common with service robotics which integrate humans and robots in the same task, requiring certain safety measures and special attention to human-machine interfaces for people with little interest in programming or people with physical problems operating a specific programming device. Therefore, more attention must be paid to the user's requirements, since the

user is a part of the process in the execution of various tasks. Although there is a need for a home-based service robot for general-purpose use, we have selected two application areas which relate mainly to structured environments, such as those normally found in vocational workplaces. This enables us to concentrate on functionalities defined or evaluated by users rather than novel robotics research, which may be difficult to develop to a stage necessary for practical evaluation by disabled users within a limited time frame.

However, there is a need for research and development in robotics to focus on developing more flexible systems for use in unstructured environments. Important areas of rehabilitation robotics needing further development in this regard include:

1. Mechanical design, including mobility and end-effectors.
2. Programming, control, and human- machine interfaces.

These areas will be described in more detail below.

2 Mechanical Design

Robotics for use by the disabled is an application area where, from a home-based perspective, robots integrate robots and humans both in a common work-space and in the execution of the same work task. Therefore, the mechanical design of robots for rehabilitation must take into consideration specifications which are different from those used in industrial applications and which may affect design aspects of the mechanical structure. Examples of differences are:

- payload of the robot will be in the low range (typically less than 5 kg);
- the payload/weight ratio must be much higher than in existing robots, giving priority to maneuverability and quick set-up;
- lower accuracy is allowable if the resolution in the motion control is the same as in existing industrial robots;
- a larger work-space and a more flexible configuration will be needed compared to industrial robots of the same size;
- life cycle will be shorter for assisting robots than industrial robots;
- acceleration and velocity performance may, in general, be much lower than in heavy-duty robots; and
- design criteria must enable high volume production at a low cost.

Nevertheless, most robots used in rehabilitation today have similarities with industrial robots, such as the RT-series robots and SCORBOT, which were developed for educational purposes. An

example of an adaptation of a robot for rehabilitation purposes is HANDY1, which is used to assist in eating [3], and DeVar, which uses a PUMA robot for assisting the disabled in home-based or vocational workplaces [4]. However, new designs are on the way that will include the use of compact and flexible arms, as well as new drives/actuators. Examples of this include the wheelchair-based Manus robot [5], the Tou soft (flexible) assistant arm [6], the pneumatically driven Inventaid arm [7], [8], and the compliant actuator Digit Muscle [9]. Wheelchair-mounted manipulators are becoming more interesting not only because of the manipulators themselves but also because of enhancements to wheelchair control, providing it with sensors and control systems like other mobile robotic bases [10]. The development of flexible arm/link systems will also have a great impact on gripper systems, which need a high degree of flexibility in terms of maneuverability and dexterity. Despite these developments, much work is needed in the area of mechanical design, specifically the introduction of composite materials in the arm structure with inbuilt strain gauges which may be used as flexible links with feedback of the deflection and redundant kinematics for optimal reachability.

3 Programming, Control and MMI

A basic goal in rehabilitation robotics is to design a robot to carry out unique tasks. This is in contrast to most industrial uses of robots, where robots are used in preprogrammed repetitive tasks. Another difficulty is that robots for rehabilitation may be used by "anyone", unlike industrial robots, which are operated by skilled workers who, in most cases, have an interest in robotics technology. Thus, many tasks in rehabilitation robotics can be said to be unique in the sense that a movement required for a certain task, e. g. picking up a newspaper or opening a door, cannot be preprogrammed. This indicates that there is a need for manual or direct control of the robot in the way of a telemanipulator. Also needed are an increased use of sensors to guide the robot and enhance its performance in autonomous tasks as well as interface devices to program and control the robot arm. It should also be noted that direct control of the robot arm puts a high cognitive load on the user and that physically disabled persons may have difficulty operating joysticks or push-buttons in delicate movements. Thus, there is an obvious need for a certain degree of autonomy of the robotic system, such as automatic grasping, which includes recognition of a specified object in front of a sensor. A positive factor in this context is that there is a human operator working with and supervising the robot. Therefore, if a task fails to a limited extent, the user will be able to correct the situation.

To a high degree, programming and manual control of the robot corresponds to MMI (Man Machine Interface) which, for disabled people, not only puts certain demands on programming languages, but also on input devices by which the user can interact with the system. Generally speaking, robot systems should be developed to allow any input device to connect to the standard set of devices, such as keyboard emulation, mouse emulation, and serial communication through RS-232/422 interface. Since more severely disabled people need individual adaptation, this type of work is normally done at rehabilitation centers. However, in the RAID project described in this paper, the joystick used to control the electrical wheelchair is interfaced with the control language of the robot and the mouse control function of the PC. This is a good solution for most users, as it enables them to control their wheelchair with the same control device.

Taking into account both the need for an interactive programming method, as well as different interfacing devices depending on the individual disability, several attempts have been made to provide programming and control methods which resemble the interactive use of modern graphical software for personal computers. As an example, most robot languages for industrial robots are robot-oriented in that they are specially adapted to a specific robot and all operations are carried out on the robot itself, e.g., motion types, poses, I/O. If the task is repetitive, it does not matter very much whether the robot program is defined through poses or frames which are related to the robot or attached to objects in the environment. However, if the task is frequently redefined by moving objects in the workspace of the robot, such as paper and book handling, page turning, etc., it is preferable to adopt an object-oriented approach. This means that the tasks are defined by manipulating objects and that the robot must adapt its motions and logic to fulfil the program description.

Consequently, much work in the area of rehabilitation robotics is directed toward controllers or control languages, such as MASTER [11], which allows the user to interact in the performance of a task, e.g. directing the robot by manual control, as well as advanced sensory interfacing and object or task level description which frees the user from concentrating on how the robot will operate in executing its tasks. An example of an object-oriented language is CURL [12], which provides a flexible programming environment through direct (manual) control, object manipulation, and selection/definition of procedures. An interesting development in this area is RoboGlyph [13], which uses a set of icons which graphically represent different robot actions on the screen like a storyboard. This is in line with new

developments of the CURL language which, by using drag and drop techniques, make use of the possibilities of graphics. A workstation could, for example, be represented by a bookshelf and a reader board. When the user drags a book (document) from the shelf to the reader board, the system will activate appropriate procedures to execute the task. Another direction in the development of languages with high-level characteristics are event-based controller languages and reactive planners which are based on the state of the system and activate a certain action or procedure [14]-[17].

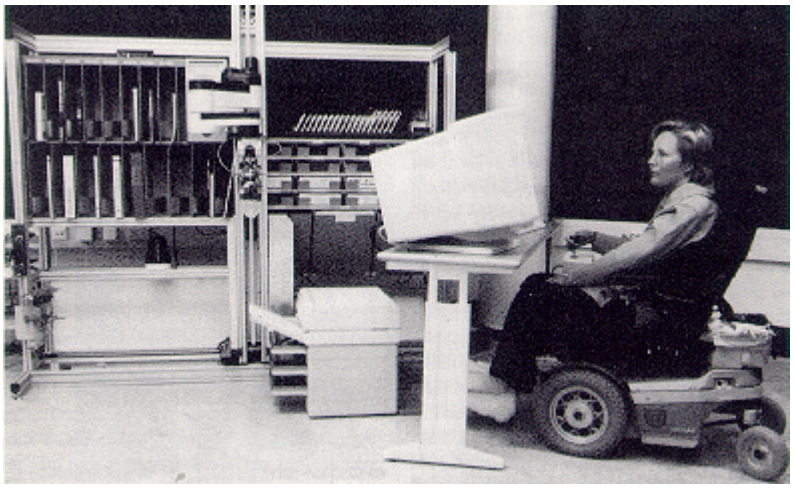

Fig. 1. RAID workstation (prototype) with moving robot, framework with bookshelves, and storage for diskettes, documents, and peripherals, such as a printer, etc.
Photo: Helena Alvesalo.

4 The Raid Workstation and End-Effector Design

The EPI-RAID (Evaluation of Prototype and Improvement to RAID workstation) project is concerned with the development of the RAID (Robot for Assisting the Integration of the Disabled) robotized computerized office workstation, which was developed in an earlier project. The project is part of the European Community TIDE (Technology Initiative for Disabled and Elderly People) program.

The partners in the EPI-RAID project are: Armstrong Projects Ltd, UK, Cambridge University, UK, Oxford Intelligent Machines Ltd., UK, CEA/DTA/UR, France, HADAR, Sweden, and Lund University, Sweden.

The robotized system is intended primarily for vocational use in an office environment (see Fig. 1). The selected application areas include CAD (Computer-Aided Design) and other office computer tasks such as desktop publishing, graphics layout, and

word-processing. These applications involve a large number of handling tasks for the robot and creative work for the user.

During our initial work on the end-effectors, it became evident that they should be designed with the highest degree of flexibility possible in order to minimize tool changing operations. The technical solution is based on two end-effectors, called the "book gripper" and the "page turner".

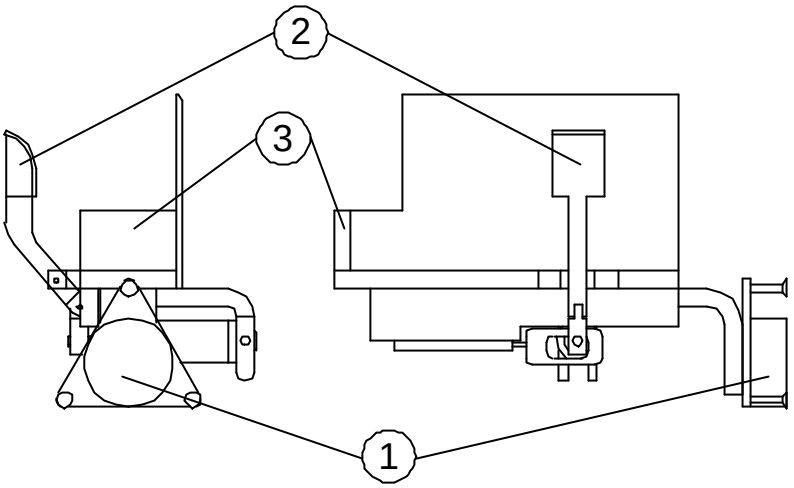

Fig. 2. The book gripper viewed from the top (left) and from the side (right). (1) Tool changer interface, (2) pneumatic "thumb" for book grasping, and (3) book supporting shelf.

End-Effector Design

The two end-effectors are shown in Figs. 2 and 3. The book gripper is designed to handle books, catalogs, and manuals of varying thickness and geometrical size (maximum weight 2 kg, maximum width 75 mm) between the bookshelf and the reader board.

The book gripper is based on a pneumatic clamping device. The movements of the gripper's "thumb" are controlled by a double-acting pneumatic cylinder (diameter 16 mm). The gripper will hold a book with a force of 30 N, if the air pressure is set to 0,6 MPa (6bar). The book grasped is supported by a small shelf to reduce the maximum clamping force needed. The approximate friction coefficient of the surface of the "thumb" is 1 and the weight of the book gripper is 0.8 kg.

The design of the book gripper resulted mainly from the user requirement that the books be stored in a normal upright position and that the bookshelf look as normal as possible. These requirements have been met, with the exception that the books must be stored with space between each object. The width of these spaces must be at least 100 mm, which is the width of the book gripper when it is open. A photoelectric switch detects if a book is in the gripper.

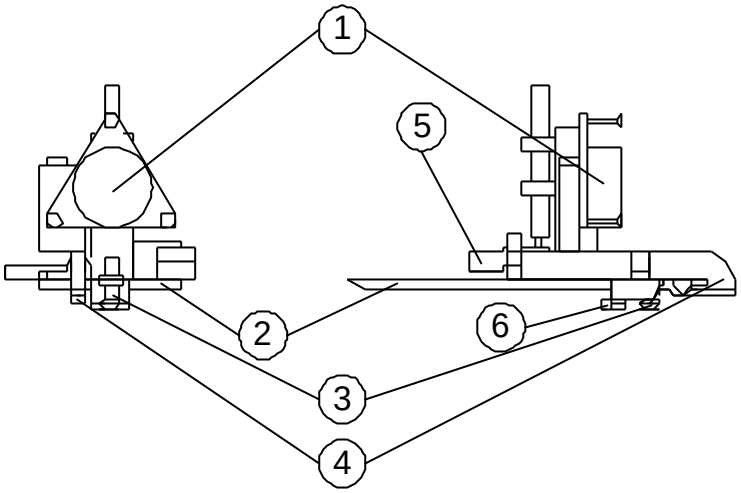

Fig. 3. The page-turner viewed from the top (left) and from the side (right). (1) Tool changer interface, (2) "knife" for turning multiple pages, (3) suction cup for lifting a single page, (4) clamp for grasping single pages, (5) clamp for paper handling, and (6) push button/switch for detecting page surface.

The page-turner is designed to open a books at any point and to turn pages forward or backward from that point. The page-turner can also grasp papers and move them between the printer, the reader board, the storage racks, and the input and output trays. The page-turner is also designed to handle disks, as well as beverages served on a specially designed tray.

The three main parts of the page-turner are a "knife", a suction cup, and a clamping device placed close to the suction cup. The "knife" is a plastic plate the size of a human hand. It is used for opening books and turning multiple pages simultaneously. The suction cup and clamping device are used for single page turning. The bellow-type suction cup lifts a single page when it reaches the page surface. A push-button is mounted next to the suction cup and detects when the suction cup has reached the page surface. The activated push-button stops the approaching movement of the robot arm. The page is then lifted and grasped with the clamping device, which is connected to a double-acting pneumatic cylinder.

The reader board has been designed to prevent small books from moving when they are opened and to prevent unwanted movements when pages are turned in small books with stiff pages. A big suction cup, placed in a hole in the reader board, will prevent small books from moving. A "finger" has been added to the lower part of the reader board to press against the pages to prevent unwanted page movements. The "finger" is connected to a double-acting pneumatic cylinder, which is controlled by the

robot. The "finger" is removed for a short time during the page turning process.

The "knife" is also used when handling papers (up to approximately 50 pages) and disks, and when serving beverages. The clamping force is produced by a single-acting pneumatic cylinder (6 mm diameter). The clamping device is activated toward the knife, which is used as a supporting surface for the papers, disks, and beverage tray. A force of 15 N will hold the objects if the air pressure is set to 0.6 MPa (6bar). The approximate friction coefficient of the surface of the clamping device is 1 and the weight of the page-turner is 0.7 kg. A photoelectric switch detects whether an object is in the gripper.

The end-effectors are mounted on a robot tool changer, which makes it possible for the robot to change end-effectors automatically. The tool changer also increases the flexibility of the RAID workstation. New handling tasks, which may require a separate gripper, can then be added more easily. The possibility of adapting RAID to individual needs is an important user requirement.

1 Book Gripper: It takes 60 s to move a book from the bookshelf to the reader board. It is expected that this can be reduced by 40% during an optimized work cycle. Grasping a book from the shelf has not caused any problems. When positioning soft catalogs on the reader board, the robot has to carry out some extra movements to prevent the pages from bending. In addition, grasping a book from the reader board has caused some difficulties with varying positions of the book in the gripper. However, this does not cause any problems when returning the book to the shelf, except in the case of catalogs, which have a tendency to bend.

2 Page-Turner: When opening a book it is only possible to achieve an accuracy of +10 pages. To get to a specific page, the user then has to turn the pages one page at a time. The cycle time for turning one page is 15 s. In order to test the performance of the page turner at higher speed, the page turner was mounted and tested on an ABB Irb1000 industrial robot. The cycle time obtained with full functionality of the page-turner was 3 s and approximately 100 pages could be turned without errors. Furthermore, in the case of an error, the robot could still proceed with the operation by turning backward or forward. Errors occurring during page turning were: 1) failure to lift and turn a page, 2) two or more pages turned at one time, or 3) an incomplete page turn. In all cases, a subsequent page turn without human interaction corrected any problems caused by the error.

At this stage, it is not possible to have one task program for all types of books. Our approach is to make one program for each book size. Furthermore, the tilt angle of the reader board has to be

specified. It is anticipated that the angle can be a parameter in the program. Page turning at the beginning and end of books causes some problems because the corners are not in the same position. Some user interaction may be needed during robot execution. The upper corners of stiff pages get slightly bent by the clamping device on the page-turner. The vacuum ejector and pneumatic valves produce a certain amount of noise during operation. An electric vacuum pump was tested but rejected by the user.

Disk handling tasks have proven successful. Straight line interpolation and good robot repeatability are needed during this operation. However, the page-turner is not ideal for this task because of geometrical constraints.

A special tray was adapted to the page-turner in order to serve refreshments. No problems have occurred.

Results from User Trials

The first RAID prototype workstation has been evaluated by a group of potential users [18]. RAID was well accepted because it addresses an occupational need. The overall impression of the workstation was positive, in terms of both size and appearance.

The major concern of users was reliability of the robot tasks, e.g. turning pages in a pile of paper sheets and returning them to the storage compartment. Occasionally, the sheets were not aligned and fell on the floor. The users divided errors into two categories, recoverable and unrecoverable. A stapler not feeding a staple every time was considered a typical recoverable error. This task could be repeated by trying a second time. Paper sheets falling on the floor was considered as an unrecoverable error and was not accepted.

The end-effectors were found to be highly reliable in the paper and document manipulation tasks. However, the reliability of the tasks is not a function of the end-effector itself, but also includes the robot and peripherals. Therefore, necessary improvements were identified concerning the robot (motion control) and peripherals (document storage). An improved version of the RAID workstation is now undergoing evaluation at three rehabilitation centers in Sweden, France, and the U.K.

The user input device, integrating the wheelchair joystick with the computer, was part of the RAID prototype workstation. It resulted in a drastic decrease in typing speed compared to input devices normally used. Thus, the input device should not be a part of the RAID workstation but should be supplied by the rehabilitation center responsible for the installation. Only preprogrammed tasks were evaluated. Large buttons were used to represent different robot tasks. The user interface was found to be easy to use and understand.

Further Development

Based on the results of the user trials, the RAID workstation will be further developed in a second stage with increased reliability and autonomy. Thus, the mechanical functionality of the end-effectors will be redesigned with respect to integration with the necessary sensors. Much work will be devoted to increasing the degree of flexibility and autonomy so that the workstation can operate in a less structured environment, as well as to developing process models for generic tasks, such as grasping different types of books and turning to specific pages.

The modularity of the workstation will also be improved to allow the user to specify the hardware and software components, e.g., the number of compartments in the bookshelf and automatic recognition of book sizes. In this context, users will be involved in the development of the workstation.

5 Walky - A Mobile Robot System for Rehabilitation

A mobile robot system is being developed for use in laboratory environments (typically chemical, medical and biological) by people with disabilities. This will widen the range of occupations open to people with physical disabilities, whose career opportunities are often limited to office type work. We have found three different areas that are suitable for robotization:

1) Microscopy, for example cell examination and cell and chromosome counting.
2) Blood group determination.
3) Culture analysis.

Fig. 4. Walky mobile robot system with (1) mobile base, (2) on-board computer, (3) sensor system, and (4) robot manipulator.

Working Scenario

The system is intended for workplaces with varying workloads at different locations during normal work hours, such as hospital laboratories, where tests may come in batches that require different routines and equipment. A mobile robot may be well-suited to this kind of workplace, which uses different equipment and procedures that may take up to a few hours for each working session.

The robot task can be divided into two different problems:

1) the mobility of the system,
2) the robot operations involved in performing the specific tasks.

It is preferable to change as little as possible in the environment of the laboratory. Thus, the size of the mobile base has to be small enough to enable it to move around in a normal laboratory, as well as to move through a doorway, etc. The robot tasks have been analyzed in order to adapt grippers and special tools, and to specify the working procedure for each task. From a user point of view, it is important to use the robot for manipulative tasks and to leave decision-making and analysis work to the individual.

Manipulator System

The mobile robot system consists of the following parts:

- Mobile base, LabMate (TRC), with sensor system (ultrasonic), including a local network.
- Five-axis robot, Scorbot ER VII.
- On-board computer and wireless communication link to main computer.

The robot is mounted on the mobile base, which is equipped with eight ultrasonic sensors (see Fig. 4). The sensors are used to detect obstacles and to guide the robot into position for a new task. Safety aspects are taken care of by the ultrasonic sensors (software routine) and the bumpers on the LabMate. The on-board computer holds all necessary information for path planning and programs for different robot tasks and, if necessary, it can receive new information via a wireless modem.

Programming and Control

As with the RAID workstation, the Walky mobile robot system is designed to integrate with the user's own input devices, such as voice control or mouse emulation devices. These are normally connected to a computer via a serial line (COM-port on a PC) and, consequently, they are not used by the system for the purpose of interfacing with user devices.

In most cases, it is assumed that all working positions, equipment, walls, etc. are fixed and a map is created using simple objects (rectangles, circles, etc.), in a CAD-system. When the user wants to tell the system where to go, he or she picks a location on the map on the screen and invokes a path planning routine to generate a path between the two locations. In general, each object is associated with paths around it, which will be evaluated through a search routine to check if there is an object in between the start and stop locations. The method used is a combined depth-first and breadth-first search and picks the best-first solution to the problem. In case of unknown obstacles during run-time, a local path planning routine will take over to either guide the system back to an earlier position or around the obstacle. The path planner can be overridden by manually inserting the solution on the map as via-points.

Results and Future Work

Investigations in laboratories connected to Lund University Hospital show that there are several possible workplaces that are suitable for Walky. Various tasks have been analyzed and simulated for robot trials. The path planner for the mobile base was tested in an environment similar to that at its final destination. In order to cope with non-fixed objects, such as chairs, boxes, etc., the mobile base is equipped with a set of eight ultrasonic sensors for reactive planning. By utilizing the existing eight ultrasonic sensors in different configurations, trials on wall-following and detection of various obstacles (table leg, chair, book shelf, etc.) show that it is possible, in a partly known environment, to use ultrasonic sensors for collision avoidance and for guiding the mobile system. Results from trials show that small objects lying on the floor, doorsteps, table edges, etc. are difficult to detect. Consequently, it is necessary to increase the number of sensors in order to ensure a reliable system. Trials will be carried out in laboratories during 1995, and further developments needed will be defined based on the results of these trials. Future work will be directed toward increasing the level of autonomy for unstructured environments, such as home-based activities, and toward enabling two or more disabled individuals to share the same robot station for vocational tasks similar to those described with respect to the RAID station.

6 Concluding Remarks

Rehabilitation robotics is an emerging field with many connections to service robotics. However, special attention must be paid to the specific needs of individual users and their physical handicaps. Thus, each individual case must be carefully studied in

order to design and build a system that can be utilized by the user in an efficient manner. As described in this paper, much research has been devoted to mechanical design, including mobility and end-effectors, as well as programming and control. Much of this work is based on experience from industrial robotics. Although results are promising, it is important to recognize the need for research and development which is free from the influences of industrial robotics and which looks instead for functional specifications in service and rehabilitation robotics and how these can be transformed into technical solutions. This work, which is a part of new research currently underway a Lund University, will include advances in robotics design, including the use of reinforced composite materials and event-based programming with model representation to generate autonomous functionality. The utilization of such systems for rehabilitation and their human benefits may well be the starting point of a revolution similar to the one which began when the personal computer came on the market.

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In 1986, he became associated with the Department of Production and Materials Engineering at Lund University and was appointed Professor of Robotics in 1987. His research interests include robotics in rehabilitation and industrial processes, such as arc welding and grinding. Areas of research include control structures, including task level programming, multisensor feedback, process models, and simulation.

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Håkan Eftring received his M.Sc. in mechanical engineering from The Royal Institute of Technology of Stockholm, Sweden, in 1985 and received his licentiate degree in engineering in manufacturing systems in 1990 from the same institute.

Between 1985 and 1992, he worked at The Royal Institute of Technology and The Swedish Institute of Production Engineering Research in the field of CAD/CAM, robotics, and FMS technologies. Since 1992, he has been working at Certec at Lund University in the areas of robotics, end-effectors, and sensors in rehabilitation robotics.

Walky, a summary of five conference papers

Håkan Neveryd, Gunnar Bolmsjö

Abstract. A mobile robot system, called Walky, is being developed for use by people with disabilities in laboratory environments (typically chemical, medical, and biological). This will widen the range of occupations open to people with physical disabilities, whose career opportunities are often limited to office type work. We have found three different areas that are suitable for robotization:

- microscopy, for example cell examination, cell and chromosome counting.
- blood group determination
- culture analysis.

Walky is equipped with ultrasonic sensors for obstacle avoidance and path planning in a laboratory environment. Laboratory tests have shown promising results and future development will be carried out in cooperation with a rehabilitation center.

Figure 1. Walky, a mobile robot system.

Background

The aim of this project is to enable people who have suffered an injury to return to work earlier and to increase the employment opportunities of people with disabilities, including those with severe disabilities. Earlier attempts at designing service robots for the disabled in Sweden have involved robots for use in an office

environment. However, people with disabilities are neither more nor less interested or competent in administrative work than people without disabilities. We have found that a laboratory may also be a good working environment for the disabled [1].

The Design of the Mobile Robot System

Walky consists of the following main components:

- Mobile base, LabMate, with a sensor system and a local network.
- 5-axis robot, Scorbot ER VII.
- Wireless radio modem.
- Communication computer.

The outside dimensions of Walky's base are 700 x 750 mm and the robot's maximum height is 1350 mm (when the elbow is in the upper position).

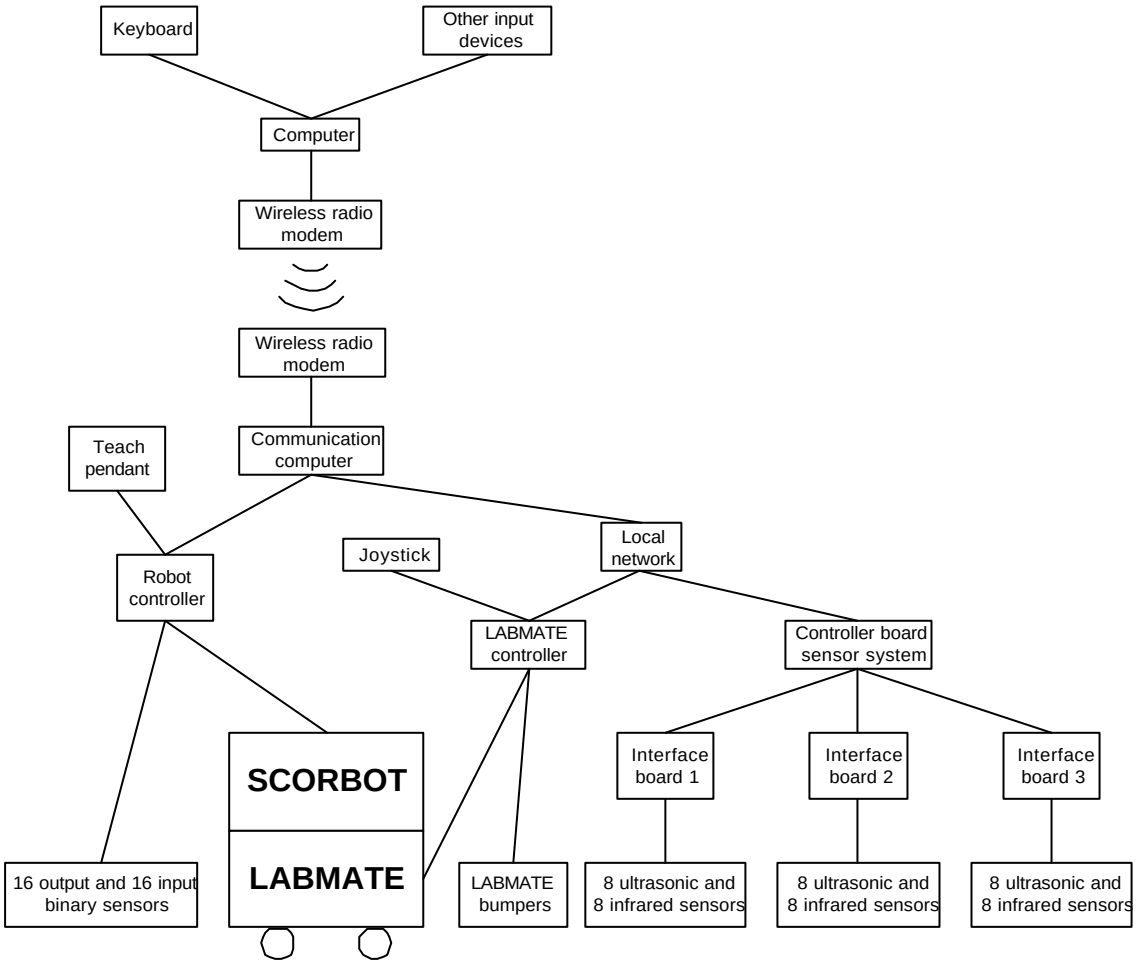

Figure 2. Diagram showing the design of Walky.

Scenario

The functionality of mobile systems can be described by the following scenario.

A user is sitting at his/her workstation and would like to fetch an object from another workstation. Using the computer, he/she commands the mobile robot to go to a predetermined position at that workstation. The communication between the computer and the mobile robot system is handled by a wireless network (see Figure 2). If there are no obstacles between the start and end positions, the mobile robot system goes directly to the end position, where it grasps the object specified.

If an obstacle is detected, for example a chair, the mobile robot tries to find a way around that obstacle. If the ultrasonic sensor system fails, the emergency system stops the mobile robot when one of the bumpers on the mobile base hits the obstacle.

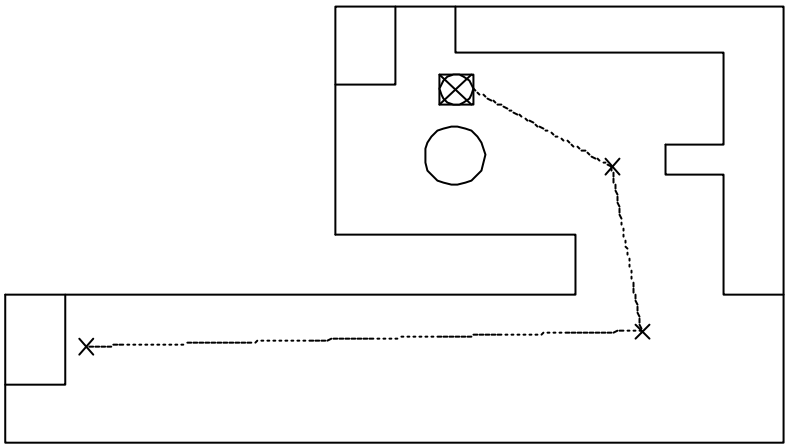

Figure 3. Part of the user's screen, with point to point control.

User Interface

An Autocad drawing defines the space in which the robot base can be maneuvered. The drawing contains walls, doors, furniture, and other objects which limit the movement of the robot base (see Figure 3).

The user can move the robot base in two ways: in manual or automatic mode. In manual mode, the arrow keys on the keyboard are used. In automatic mode, the obstacle avoidance algorithm is active and menus are used to command the robot base to a target position. The program then calculates the best path to that position and moves the robot base according to that path [1, 2, 3, 4]. In automatic mode, it is also possible for the user to specify intermediate positions for the path of the robot base - point to point control.

Sensor System

It is possible to connect three interface boards to the sensor system. Eight ultrasonic and eight infrared sensors can be connected to each interface board. The sensors on Walky are used for measuring distance. In the first phase of the project, we chose to use eight ultrasonic sensors [5, 6], (see figure 4). Phase 1 of Walky's sensor configuration was a modified variant of the IPAMAR [7] mobile robot. Tests showed that the information obtained from the sensors was limited and that more information was needed when the environment was partly unstructured and unknown.

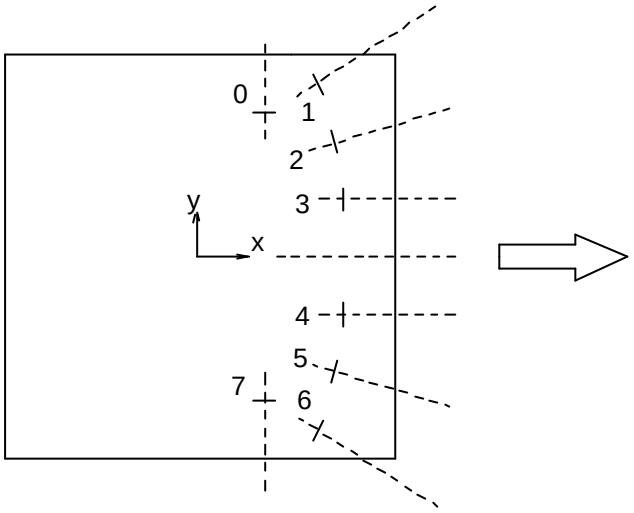

Figure 4. The sensor configuration phase 1.

Ultrasound sensing, based upon the speed of sound, depends on producing a high frequency sound wave (above 20 kHz), transmitting the sound wave, and then measuring the time interval from the sound burst until a reflection returns from a target surface. A problem with ultrasonic sensors is that the speed of sound is a function of temperature (see figure 5). The speed of sound also varies slightly with humidity, max 0.35% at 20°C. The Polaroid ultrasonic sensor [8] is capable of detecting the presence and distance of objects within a range of approximately 27 cm to 10.7 m. Other problems of ultrasonic sensing are false detection and the fact that an object must be non-porous in order to be detected.

We tested phase 1 of the sensor configuration in an office environment with respect to what the system could detect (1), what it sometimes could detect (2), and what it could not or very infrequently could detect (3).

1. Different dimensions of chair legs and desk chairs.
2. Table-edges and bookshelves (empty, half-full, and full) could sometimes be detected. Half-full and full

bookshelves could be easily detected, like a wall, but if the bookshelf contained few books or was empty, the result depended on the detection angle. The system could not detect a 25-mm standard table-edge, but it could detect a 25-mm standard table-edge with a 32 mm strengthening beam. The detection of bookshelves was satisfactory, while the detection of table-edges was unsatisfactory.

3. It was possible to detect an obstacle on the floor (a pen or a threshold) only if its height was over 45 mm.

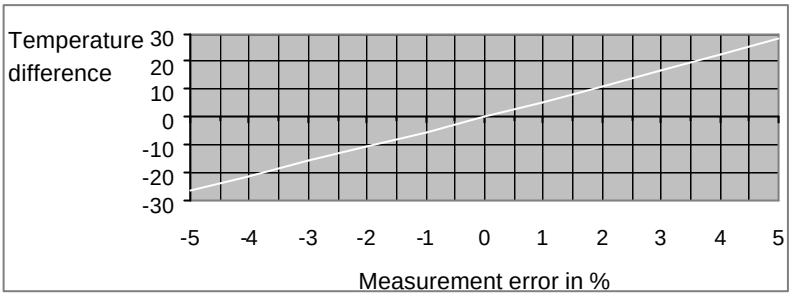

Figure 5. Measurement error in % for ultrasonic sensors when the temperature changes compared to the reference temperature.

The system needed one more sensor on each side to make wall-following easier. Moreover, to give Walky the capability to back up, additional sensors were required on its back, and a calibration sensor to detect temperature changes was also needed.

We have tried to solve the problems of sensor configuration 1 with an extended sensor configuration (phase 2). In this phase, we have added one interface board with eight ultrasonic sensors and we have developed this extended configuration further.

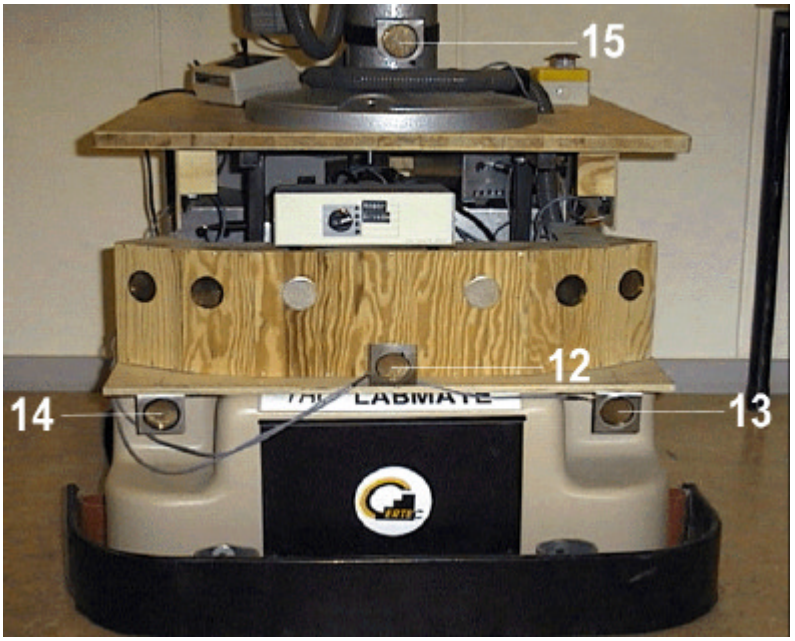

Figure 6. The front of Walky with the extended sensor configuration.

The problem of detecting table-edges has been solved with sensor 15 (see Figures 6 and 7), which has the same height as a normal table (73 cm).

The problem of detecting of an obstacle on the floor has been solved with sensors 12, 13 and 14 (see Figures 6 and 7). The extended system can detect an obstacle with a height of 3 mm. Sensors 13 and 14 also make it easier to measure the clearance on each side. Sensors 9 and 10 have been added to make it possible to detect obstacles behind the robot. Sensors 8 and 11 have been added for better wall-following.

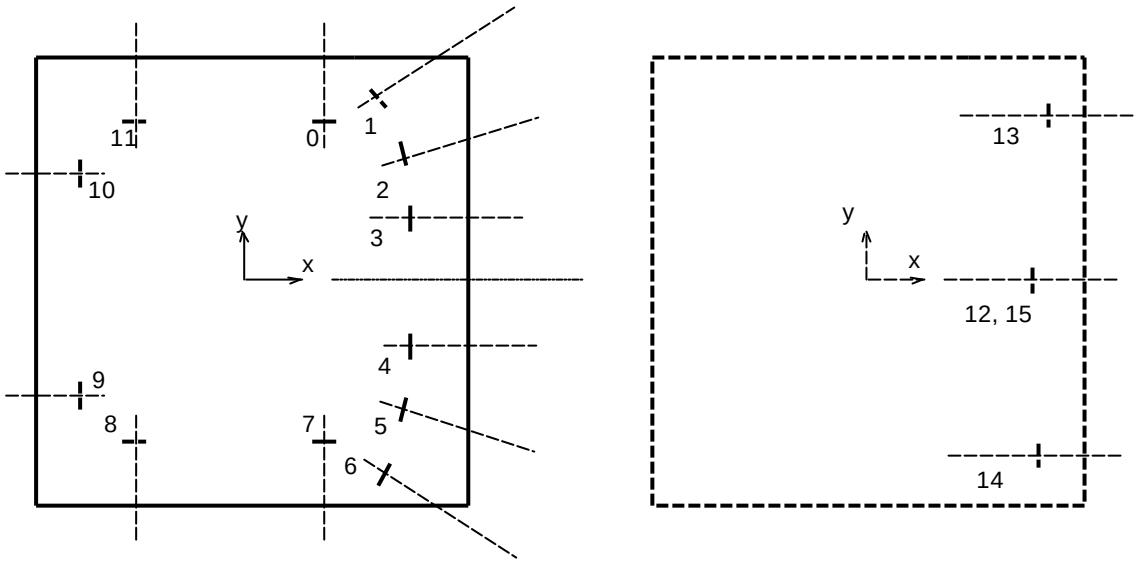

Figure 7. The extended sensor configuration.

Temperature changes will be calibrated by a sensor set to a fixed distance and placed on top of the mobile base. When the temperature (or the humidity) changes, it is easy to calibrate the distance measurement. We plan to add this sensor in the third phase of the project.

Path Planning

As mentioned above (see USER INTERFACE), the user can move the robot base in manual or automatic mode. In automatic mode, two different methods of path planning can be used, both of which work without the sensors. The sensors are used for obstacle avoidance in order to cope with changes in the environment.

Method 1

The objects on the map (see Figure 2) are circles, lines, rectangles and polygons [7]. Obstacles are defined as "things which are not on the map".

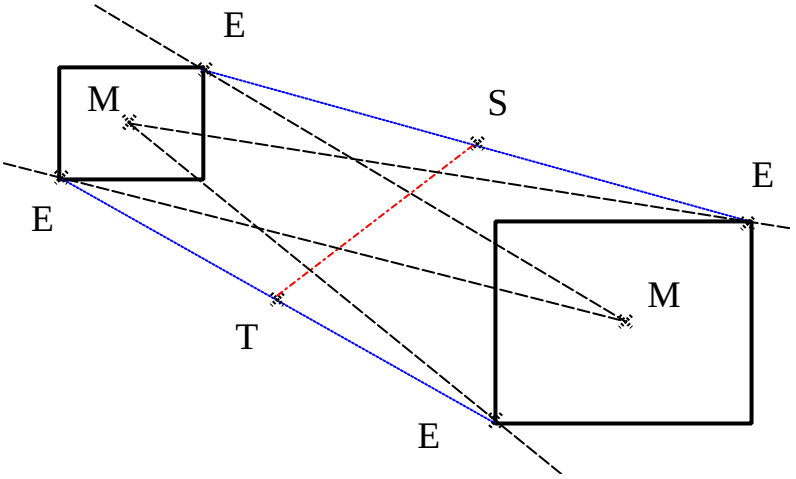

Figure 8. Calculating the start point (S) and target point (T) for the path between two objects.

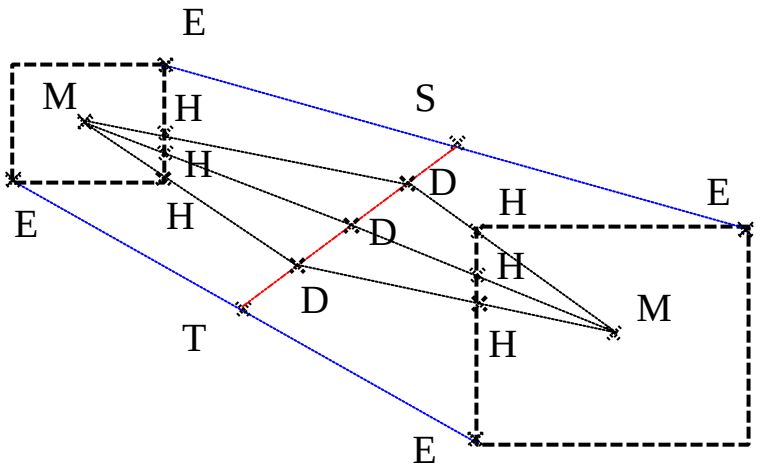

Figure 9. Calculating help points (*H*).

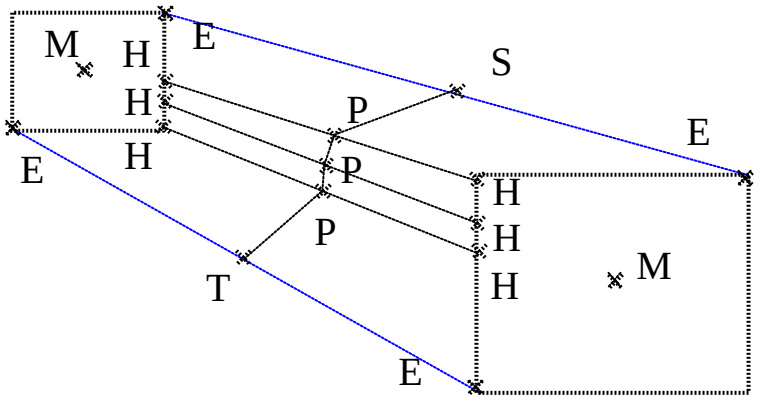

Figure 10. Calculating subtarget points (*P*).

Segments of the path are created by building all possible pairs of the different objects and subsequently calculating the path between the two objects. The start point (*S*) and target point (*T*) are the mid points of the lines between the edge points (*E*) of the two objects. The edge points (*E*) of one object are defined as the

outermost points which can be observed from the mid point (*M*) of the other object (see Figure 8). The line between the start point (*S*) and the target point (*T*) is divided into four segments of equal distance. By using three help points (*D*) and the mid point (*M*) of each object, three more help points (*H*) are created on the edge of each object. (see Figure 9). The subtarget points (*P*) are the mid points of the lines between the help points (*H*) on the two objects. The path between the two objects is *S-P-P-P-T* (see Figure 10).

When combining all the paths into one path, we have chosen to use the A* search algorithm [10]. This search starts by expanding the root node by one step to form a tree of depth two. The cost (length) of each path from the root to the subnodes is calculated. The cost of the set of new paths is also calculated. The costs of all paths (the old one-step paths and the new two-step paths) are compared and the path with the lowest cost is chosen. This process is repeated until the goal is reached.

Method 2

In this method, we define subtargets in each room [11]. The subtargets can be defined automatically or manually. The number of subtargets depends on the area of the room. It is easy to add extra subtargets, for example around a doorway, to create a smoother path through geometrically complicated areas. All possible paths between the subtargets in one room and the subtargets in another room are precalculated and stored in Walky's onboard computer. The computer only calculates the path from the start point to the nearest subtarget and the path from the end point to the nearest subtarget (see Figure 11). These paths are calculated using method 1.

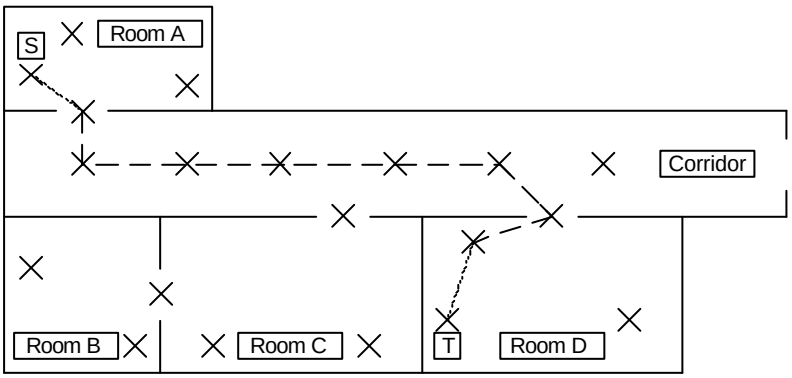

Figure 11. The path from the start point (S) to the target point (T). The precalculated path, which is stored in Walky's onboard computer, is indicated by dashed lines and the segments from the start point and the target point to the nearest subtarget are indicated by dotted lines.

The difference between the two methods is the waiting time when calculating the path. For method 1, the waiting time is measured in minutes but for method 2 it is in seconds. Of course, in method 1, the length of the path influences the waiting time. Method 2 requires some extra work when a new map is added.

When Walky's sensors detect an obstacle, at a distance of:

- 210 cm, nothing happens. (the ignore zone)
- 130-210 cm, Walky's speed is slowed down to 70% of the normal speed. (the obstacle detection zone)
- 40-130 cm, Walky's speed is slowed down to 50% of the normal speed and the obstacle avoidance algorithm starts. (the reflex zone)
- < 40 cm, Walky stops immediately. (the safety zone)

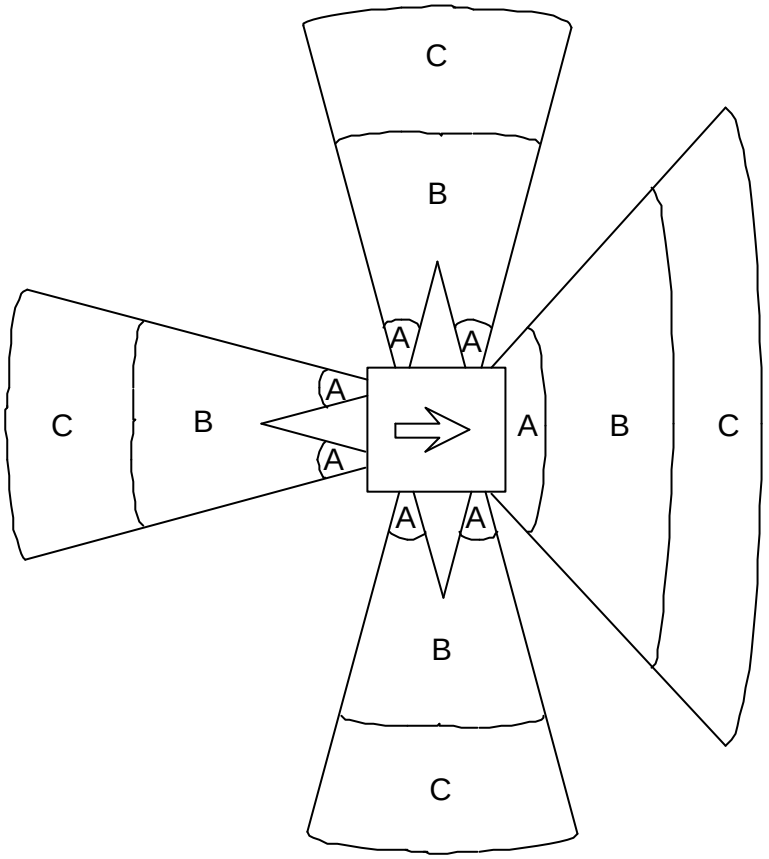

Figure 12. The detection zone, A= the safety zone, B= the reflex zone and C= the obstacle detection zone.

The obstacle avoidance algorithm uses the subtargets from the path planning algorithm. When Walky has bypassed an obstacle (see Figure 13, point A), it tries to go to the nearest subtarget and then continue along its path. If the nearest subtarget is too close and Walky has to turn at a large angle or if Walky has passed the subtarget, it will go to the next subtarget. Walky has an internal

system of co-ordinates and the map has a global system of co-ordinates. When these two systems of co-ordinates are compared, Walky's position and direction can be determined.

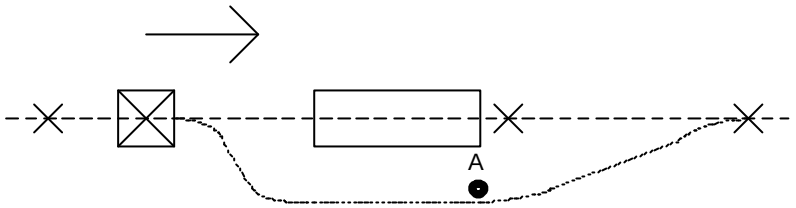

Figure 13. Walky's path around an obstacle. The precalculated path is indicated by dashed lines and the segment path around the obstacle, calculated with an obstacle avoidance algorithm, is indicated by dotted lines.

Conclusion

Laboratory tests with users have shown that the waiting time, i.e. the calculation time for the path planning in method 1, is too long. Users feel that it is important to be able to see a quick result when sending a command to Walky. This was the reason for developing method 2. An experienced rehabilitation robotic user is wary of "what is happening around the corner". The user feels that he has no control over Walky, when he cannot see what it does.

Users find it very convenient that the robot system can be kept out of view behind a curtain when not in use. Another advantage of a mobile robot system is that it can serve more than one user compared to a RAID [12, 13] or DeVAR [14] type workstation.

In the next phase we plan to integrate a mini-camera into Walky. The user will be able to see the view from Walky on the screen. We are also planning to test Walky in a training apartment at a rehabilitation center. The purpose of the test is to collect user experience and subsequently develop Walky further.

Acknowledgements

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