Taxonomy and Technology Mapping of Mobility Assistance Systems

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Report on R&D 1
Taxonomy and Technology Mapping of Mobility Assistance Systems

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Abstract

Population ageing and growing prevalence of disability have resulted in a growing need for personal care and assistance. The insufficient supply of personal care workers and the rising costs of long-term care have turned this phenomenon into a greater social concern. This has resulted in a growing interest in assistive technology in general, and assistive robots in particular, as a means of substituting or supplementing the care provided by humans, and as a means of increasing the independence and overall quality of life of persons with special needs. Although many assistive robots have been developed in research labs world-wide, very few are commercially available. One of the reasons for this, is the cost. One way of optimising cost is to develop solutions that address specific needs of users. As a precursor to this, it is important to identify gaps between what the users need and what the technology (assistive robots) currently provides. This information is obtained through technology mapping.

The current literature lacks a mapping between user needs and assistive robots, at the level of individual systems. The user needs are not expressed in uniform terminology across studies, which makes comparison of results difficult. In this research work, we have illustrated the technology mapping of assistive robots using the International Classification of Functioning, Disability and Health (ICF). ICF provides standard terminology for expressing user needs in detail. Expressing the assistive functions of robots also in ICF terminology facilitates communication between different stakeholders (rehabilitation professionals, robotics researchers, etc.).

We also investigated existing taxonomies for assistive robots. It was observed that there is no widely accepted taxonomy for classifying assistive robots. However, there exists an international standard, ISO 9999, which classifies commercially available assistive products. The applicability of the latest revision of ISO 9999 standard for classifying mobility assistance robots has been studied. A partial classification of assistive robots based on ISO 9999 is suggested.

The taxonomy and technology mapping are illustrated with the help of four robots that have the potential to provide mobility assistance. These are the SmartCane, the SmartWalker, MAid and Care-O-bot® 3. SmartCane, SmartWalker and MAid provide assistance by supporting physical movement. Care-O-bot® 3 provides assistance by reducing the need to move.

List of Abbreviations and Acronyms

ADL	**A**ctivities of **D**aily **L**iving
ARM	**A**ssistive **R**obotic **M**anipulator
ASOC	**A**ctive **S**plit **O**ffset **C**astor
AT	**A**ssistive **T**echnology
EADL	**E**nhanced **A**ctivities of **D**aily **L**iving
FIC	**F**amily of **I**nternational **C**lassifications
IADL	**I**nstrumental **A**ctivities of **D**aily **L**iving
ICD	**I**nternational Statistical **C**lassification of **D**iseases and Related Health Problems
ICF	**I**nternational **C**lassification of **F**unctioning, Disability and Health
ICIDH	**I**nternational **C**lassification of **I**mpairments, **D**isabilities and **H**andicaps
ISO	**I**nternational **O**rganization for **S**tandardization
NAN	**N**arrow **A**rea Navigation
PAMM	**P**ersonal **A**ids for **M**obility and **M**onitoring
RAPUDA	**R**obotic **A**rm for **P**ersons with **U**pper-limb **D**is**A**bilities
WAN	**W**ide **A**rea Navigation
WHO	**W**orld **H**ealth **O**rganization

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1 Introduction

[1]Population estimates [52] and reports on disability [61] indicate that the number of persons aged 60 years or above, and the number of persons living with disability are increasing at a significant pace. By 2050, the older population (60+ years) is expected to account for around 22% of world's population [52]. Population ageing, along with rising incidences of chronic health conditions and injuries, increase the prevalence of disability, which currently stands at about 10-15% of world's population [61].

Why does this situation call for attention and action? As the proportion of people with disabilities increases, the demand for personal care workers also increases. There is already a **large gap between the demand for, and supply of, personal care workers** [61]. In the face of the current demographic trends, bridging this gap would be very challenging. This situation would increase the pressure on the healthcare system [7], and reduce the quality of care provided.

Another reason that makes the situation alarming is the associated rise in the **direct and indirect costs** of disability. The costs of disability are discussed in the World Report on Disability [61]. Direct costs include cost of availing healthcare services, availing personal care services, buying assistive devices, adapting home and work environments, shifting to special care facilities, etc. Disability benefits and support programmes funded by governments also constitute direct costs. Indirect costs of disability include lost employment opportunities and associated loss of tax revenue. With rising prevalence of disability, the costs of long-term care can become a financial burden, not only for the persons with disabilities and their family and friends, but also for the entire society [61, 58].

In this context, assistive technology and assistive robots are gaining increasing importance. It has been shown that assistive technology, when chosen to match user's needs and preferences, and the context of use, can increase independence and improve participation [61]. According to studies identified in the World Report on Disability [61], the use of assistive devices like mobility aids can reduce the disability experienced by the user, substitute or supplement support and care services, reduce the need for support and care services, and thus reduce the costs associated with these services. According to a study

[1]A first draft of the sections 1 (Introduction), 2.4 (Disability: Caregiving and Costs), 3.2 (Related Work: Mapping Assistive Robots to Assistance Needs), 3.3 (Related Work: Assistance Needs and Functions in ICF Terminology), 4 (Problem Formulation) and 5 (Human Health and Assistive Technology Classification) was written as part of the assignments in Advanced Scientific Working (ASW) seminar. The draft was prepared in the form of bulleted lists. To write this report, these bullet points have been improvised, rearranged, combined and organized into sections and paragraphs. Additional information have also been added.

conducted in the United States [54], the increased use of assistive equipment was associated with the decline in the percentage of older adults living in long-term care facilities during the period 1992-2009.

Since the last few decades, assistive robots are being developed to provide greater autonomy to persons with severe disabilities, by assisting in the performance of various tasks associated with the activities of daily living, for example, autonomous mobility for persons with muscular dystrophy [65], cerebral palsy [50], etc. Robots have also been developed to assist and support caregivers in performing tasks such as lifting persons, making beds, delivering meals, etc. [76]. Literature surveys [12, 69, 76, 72] and books [28] on assistive technology provide more examples of assistive robots which have been developed.

Some assistive robots are commercially available, while others are research prototypes [72, 23]. Commercial assistive robots, like Assistive Robotic Manipulator (ARM), have been found to have the ability to increase the user's quality of life, and generate cost benefits in the form of saved labour costs of personal care workers, and enhanced employment opportunities of the users [67]. However, very few assistive robots are commercially available, one of the reasons for which is the cost [69, 48]. The commercial rehabilitation robot, ARM, that provides manipulation assistance, costs around €25,000 [67], which is not equally affordable to people with disability across the different economic strata.

Identifying the real needs of users, prioritizing the needs, and mapping the functionality of assistive robots to these needs help in identifying the unmet assistance needs of users, and the functionalities of assistive robots which are not relevant for the users. This helps in increasing the usefulness of assistive robots and in optimizing its cost. The significance of needs-oriented design and evaluation of assistive robots has been supported in [48, 10].

In this work, we discuss two international classification systems- **ISO 9999** [1] and the **International Classification of Functioning, Disability and Health (ICF)** [56]. We examine the applicability of these systems for classifying assistive robots, and for describing the assistive robot functionalities in terms of human health aspects. ISO 9999 classifies assistive products based on its primary function [4]. The ICF classifies aspects of human health. The focus is on classification and mapping of **mobility assistance robots**, due to the prominence of mobility assistance needs among persons with disabilities. Four well-known robots that can provide mobility assistance have been chosen as representative examples, to demonstrate the classification and technology mapping. These are the SmartCane [74], SmartWalker [74], MAid [65, 66] and Care-O-bot® 3 [40]. The

SmartCane and SmartWalker are together referred to as PAMM (Personal Aids for Mobility and Monitoring) [74].

1.1 Why Mobility Assistance?

The World Report on Disability [61] has identified arthritis and rheumatism as the major causes of disability among persons aged 15 or above. Arthritis and rheumatism impair motor skills, thereby impairing mobility [25, 26]. Among typical activity limitations experienced by persons aged 65 years or above, difficulty in walking and getting in/out of bed/chairs have been identified as being prominent [55]. These two activities are part of the "Mobility" aspect of human health [56, 8, 9].

2 Background

2.1 Key Terms and Definitions

2.1.1 Ageing

Ageing is defined as "*the process of growing old*"[16]. In [22], **Ageing in humans** is defined as "*a multi-dimensional process of physical, psychological, and social change*". There is no global consensus on the definition of the term **elderly** or **older population**. The United Nations uses the term *older population* to refer to the age group of 60 years or above [57]. However, this is not a standard. In most developed nations, persons aged 65 or above are considered to constitute the *older population* [57]. Erber [17] defines an **older adult** as a person aged 65 years or above.

Population ageing, which is one of the key global demographic phenomena, is defined as "*the increase in the number and proportion of older people in society*" [82]. This occurs naturally as a result of increased life expectancy and decreased birth rate.

2.1.2 Disability

The International Classification of Functioning, Disability and Health (ICF) uses the term **disability** as "*an umbrella term for impairments, activity limitations and participation restrictions*"[56]. **Impairments** are defined as "*problems in body function or structure such as a significant deviation or loss*," **activity limitations** as "*difficulties an individual may have in executing a task or action*," and **participation restrictions** as "*problems an individual may experience in involvement in life situations*"[56].

A missing lower limb, loss of seeing function, and short-term memory loss are examples of impairment. Difficulties in handling objects, washing and drying oneself, walking long distances, and preparing meals are examples of activity limiations. Difficulties in engaging in remunerative employment, pursuing education, creating or maintaining relationships with friends and neighbours, and engaging in economic transactions such as buying or selling goods are examples of participation restrictions.[56]

The ICF provides a **biopsychosocial** model of disability[56]. ICF considers disability as a universal phenomenon, applicable to all humans[3]. It views disability as a complex phenomenon arising out of "*the interaction between attributes of the person and the overall physical, human-built, attitudinal, and social environment in which the person lives and acts*"[3]. The positive aspects of this interaction is termed **functioning**, and the negative aspects constitute disability [56].

The nature of influence of various environmental factors on the different components of functioning, and hence on disability, differs from person to person [3]. Three examples are provided here, for illustration. Indoor air quality is of paramount importance to an asthmatic person. While good air quality facilitates normal respiration function, poor air quality causes abnormalties in respiration. Audio traffic signals enable persons with difficulties in seeing to cross roads more safely. Social stigma generally discourages individuals with special needs from participating in social life.

2.1.3 Activities of Daily Living

Activities of daily living (ADL) are "*those activities or tasks that people undertake routinely in their every day life*" [20]. ADLs can be categorized into: self-maintenance ADLs [41] (or Basic ADLs [20]), instrumental ADLs [44] and enhanced ADLs [72]. **Self-maintenance ADLs** include activities associated with personal care and functional mobility, like feeding, dressing, personal hygiene and grooming, bathing, toileting, and ambulating [41, 20, 72, 80, 43]. **Instrumental ADLs (IADL)** include activities that are key to living independently in a community [80], like using telephones, shopping, preparing food, housekeeping, doing laundry, managing medications, managing finances, and using transportation (self-driving, riding in a taxi, using public transport, etc.) [44, 72, 80, 43]. **Enhanced ADLs** include learning new skills, pursuing hobbies, engaging in leisure activities, and participating in social activities [72].

2.1.4 Assistive Technology

According to ISO 9999:2011 [1], an **assistive product** is "*any product (including devices, equipment, instruments and software), especially produced or generally available, used by* *or for persons with disability- for participation; to protect, support, train, measure or substitute for body functions/structures and activities; or to prevent impairments, activity limitations or participation restrictions.*" Wheelchairs, walkers, crutches, white canes, screen magnifiers, screen readers, prostheses, orthoses, personal digital assistants, bed lifts, support rails, vacuum cleaning robots, and workplace robots are some examples of assistive products [1].

2.1.5 Mobility Assistance Systems

Mobility assistance systems are (semi-)autonomous devices that provide assistance to enhance mobility of persons with mobility impairment and/or mobility limitations [1, 56, 81]. As part of the ACCESS Project, the Department of Occupational Therapy at Colorado State University defined **mobility impairment** as "*the inability of a person to use one or more of his/her extremities, or a lack of strength to walk, grasp, or lift objects*" [79]. This is consistent with the definition of mobility provided in the ICF classification of human health. However, the literature on rehabilitation robotics [12, 73] considers mobility assistance devices as those that provide assistance to persons with lower-limb impairments. The devices, which provide assistance in performing activities that normally involve the use of upper extermities, are termed as **manipulation assistance systems** [12]. ISO 9999 classification also uses two distinct classes to represent assistive products for mobility and assistive products for handling objects.

In this work, we focus on robots that provide assistance to persons who have difficulties in moving from one place to another. Such assistance may be provided either by supporting physical movement or by reducing the need to walk or move around [72, 23]. Walkers and wheelchairs support physical movement [72, 83]. Mobile home robots that are capable of fetching and carrying objects reduce the need for a person to move around often [72]. Section 6 discusses four well-known mobility assistance systems.

2.2 Facts about Ageing

According to the statistics published by the United Nations [52], the percentage of world population aged 60 years or above would be around 22% by 2050, which is twice the current statistical figure. By 2050, more than one-third of the population of Europe would be aged 60 years or above [52]. Figure 1 shows the region-wise proportion of population aged 60 years or above. Figure 2 shows the country-wise proportion of population aged 60 years or above.

According to the statistical figures of 2010 [51], the median age is highest in Europe.

Country-wise, Japan tops the list with a median age of 44.7 years, followed by Germany (44.3 years), and Italy(43.2 years) [51].

Figure 3 shows the proportion of the population aged 60 years or above, who are living independently[2]. From the figure, it is clear that approximately three-quarters of the older male and female population in Europe and North America live independently.

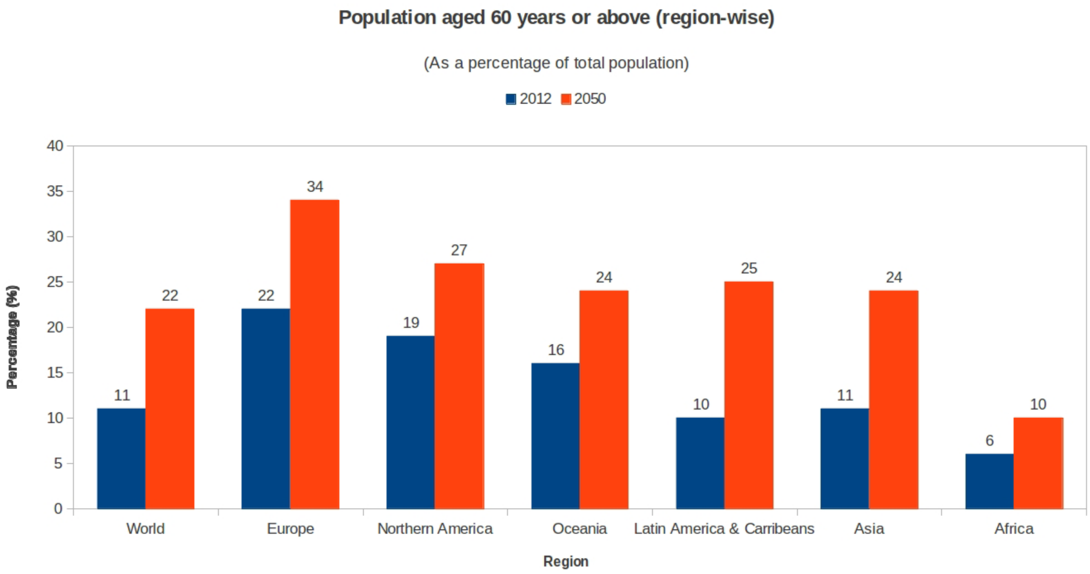

Figure 1: Population aged 60 years or above (region-wise). Data source:[52]

2.3 Facts about Disability

The World Report on Disability [61] is a comprehensive report on disability published jointly by the World Health Organization and the World Bank. It compiles and analyses information about all different aspects of disability, ranging from prevalence to policies adopted by nations. The facts presented in this section are sourced from the World Report on Disability.

Some information about the prevalence of disability in the world:

- The global disability prevalence estimates of 2004 reveal that around 785 to 975 million people in the age group of 15+ years possessed some form of disability. Among these, between 110 million and 190 million experienced significant difficulties in functioning.

[2]living alone or with spouse

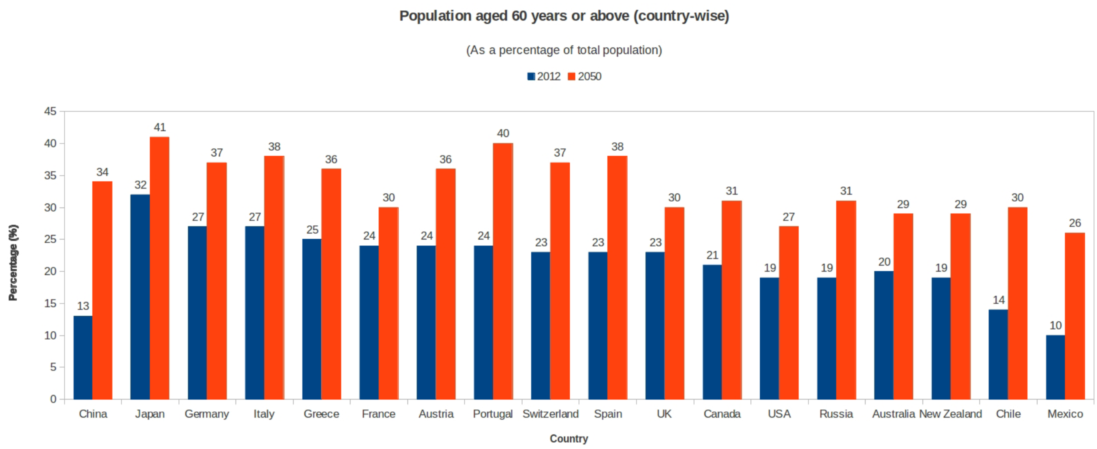

Figure 2: Population aged 60 years or above (country-wise). Data source:[52]

- The prevalence of disability was higher in females than in males. The prevalence of disablity among persons aged 45 years or above was higher in low-income countries than in high-income countries.
- The disability rates are higher among persons aged 65 years or above. For example, in 2003, in Australia, 10.3% of the total population, and 35.2% of those having disabilities, belonged to the age-group of 65+ years. In Germany, in 2007, 54.3% of persons having disabilities were from the age-group of 65+ years.

The prevalence of disability is increasing due to:

- Rising incidence of chronic health conditions like diabetes, cardiovascular diseases, mental disorders, cancer, and respiratory illnesses.
- Rising incidence of injuries arising out of accidents and violence.
- Population ageing.

People with disabilities need services, which include health services, welfare services, counselling, access to assistive technology devices, educational services, and vocational training, among others. They also need different types of assistance such as support for independent living and community participation. However, significant proportions of people with disabilities do not receive the services and assistance that they need. When it comes to healthcare, it is reported that people with special needs have more unmet healthcare needs than others. The reasons for this include inaccessible buildings and equipments, unaffordable travel and health care expenses, unavailability or poor availabilty of healthcare services, lack of skilled health professionals and health workers, and lack of quality care.

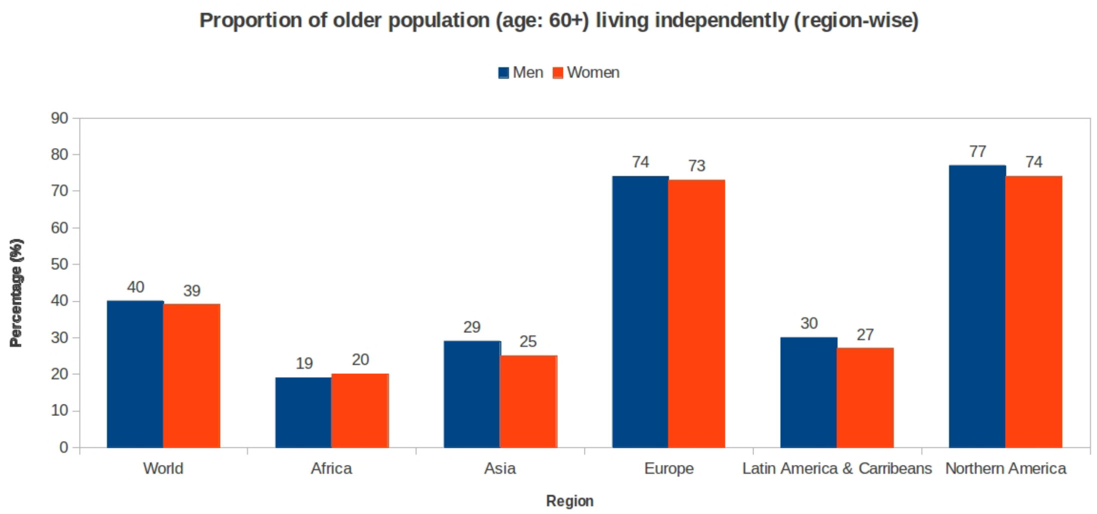

Figure 3: Proportion of older population living independently (region-wise). Data source:[52]

2.4 Disability: Caregiving and Costs

People with disability need support and assistance to compensate for their functional impairment, and/or to overcome the activity limitations and participation restrictions imposed on them by the disability [61, 77]. There are two types of sources for the provision of such support and assistance- informal and formal. **Informal caregivers** include family (parent, spouse, child [77]) and friends of the person with disability [61]. **Formal caregivers** include certified nursing assistants in nursing homes, home health aides, and personal care attendants [75]. Formal care services are provided by the government, not-for-profit organizations and for-profit organizations [61]. Most of the support and assistance needed for independent living and community participation is provided by informal caregivers, majority of whom are women [61]. When informal care is not available, or is inadequate, formal care is sought [61].

Informal care, although indispensable and cost-efficient, involves **indirect economic and non-economic costs**. Stress, depression, isolation and loneliness experienced by the caregivers constitute the non-economic costs [61]. Caregiving takes its toll on the mental and physical health of informal caregivers, incurring additional health-care expenses, and increasing the demand on health services [61, 77].

Formal care, on the other hand, involves **direct cost**, which can be met through state funding, social insurance schemes, charitable contributions, or out-of-pocket financing [61].

The costs of long-term care can be burdensome to individuals and society [61, 58]. Low wages, and lack of training, skills or qualification among personal care workers can result in poor quality of provided care [61]. Care work, which includes tasks like, lifting persons to transfer them from bed to wheelchair, can be demanding both physically and mentally, resulting in high rates of **workplace injury** [75].

2.5 ADL Limitations among Elderly

Figure 4 shows the basic ADLs for which the older adults living in non-institutionalised settings in the United States need the most assistance. These include walking, bathing/

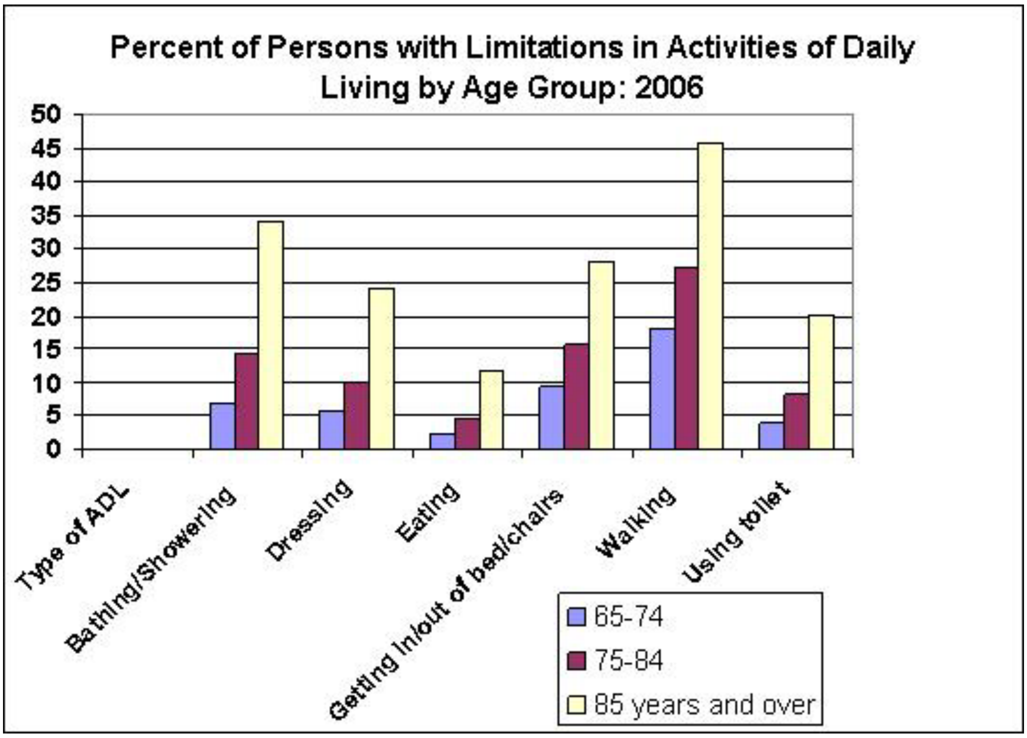

Figure 4: Prevalence of ADL limitations in older adults living in non-institutionalised settings in the U.S. in 2006. Source: Figure 9 in [55]

showering, getting in/out of bed/chairs, dressing, using toilet, and eating [55]. More than 25% of these older adults experienced difficulty in walking, whereas, only 6% experienced difficulty in eating [72]. As is evident from figure 4, ADL limitations increase with age. Persons belonging to the age group of 85 years and above experienced more difficulty in performing ADLs than persons belonging to the age-group of 65-74 years [72]. For example, less than 20% of persons in the age group of 65-74 years experienced difficulty in walking, whereas, more than 45% of persons over the age of 85 years experienced difficulty in walking [72].

[21] is a compilation of statistics and information about the services for elderly in Germany. This report includes data about the ADL and IADL limitations of older adults living in senior homes (see table 1). The original source of this data is the “Dritter Bericht zur Lage der älteren Generation” [18], published by the German Federal Ministry for Family Affairs, Senior Citizens, Women and Youth in January 2001.

Activities of Daily Living	**Cannot perform at all (%)**	**Can, but with difficulties (%)**
Clean the room/apartment	71.0	14.2
Use public transports	66.7	15.1
Buy food	65.6	14.0
Prepare meals	62.0	17.4
Take medicine	59.4	14.7
Manage financial matters	55.9	16.1
Find one’s way outside the institution	49.1	19.5
Make visits	45.0	26.4
Dress/undress	34.1	23.6
Use the toilet	32.1	16.5
Use the phone	31.2	20.4
Go to bed/ get out of the bed	31.1	17.3
Control urine and bowel movement	30.3	19.3
Walk within the room/apartment	27.3	14.9
Be alone during the day for a few hours	22.7	21.5

Table 1: ADL and IADL limitations among older adults living in senior homes in Germany. Source: [18, 21]

In 2009, in the United States, 1.5% of persons belonging to the age-group of 65-74 years, 3.8% of persons belonging to the age-group of 75-84 years, and 14.2% of persons aged 85 years or above lived in long term-care facilities like nursing homes [54]. 94% of them experienced one or more ADL or IADL limitations [54]. Around 2.7% of older adults lived in community housing that provided one or more support services such as meal preparation, housekeeping, laundry services and helping with medication [54]. 65% of them experienced one or more ADL or IADL limitations [54]. Among the older adults who lived in non-institutionalised settings, 39% experienced one or more ADL or IADL limitations [54]. These data show that the highest prevalence of ADL limitations was among those who lived in nursing homes, and the lowest prevalence was among those who lived in traditional residential settings.

3 Related Work

3.1 Classification of Assistive Robots

3.1.1 Literature Review

Tejima [76] classifies rehabilitation robots into augmentative manipulation systems, augmentative mobility systems, therapy robots and robots for helping caregivers. The complete classification is shown in figure 5. The robotic systems that are grouped under the category of robots for helping caregivers include robots that assist in lifting persons, robots for meal delivery, robots for floor cleaning and robots for bed making.

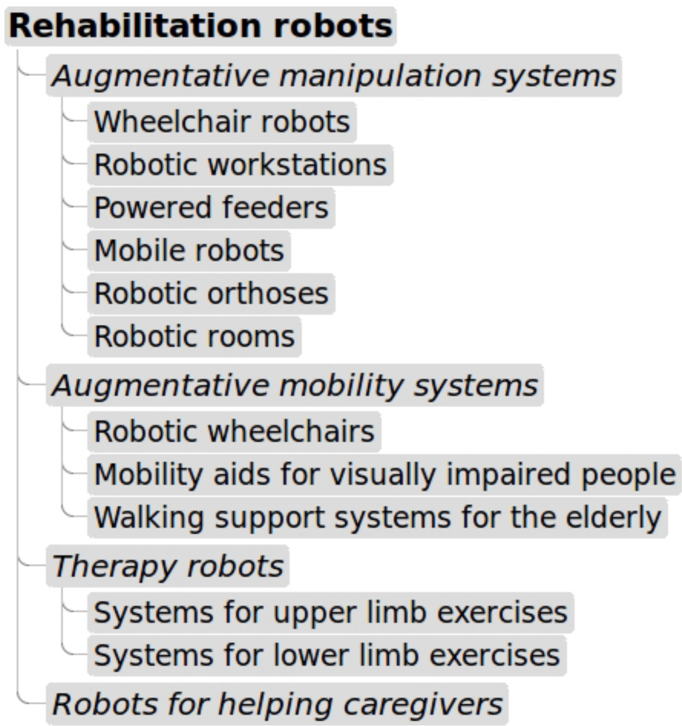

Figure 5: Classification of rehabilitation robots by Tejima [76]

In [12], **Van der Loos and Reinkensmeyer** categorize rehabilitation robots into therapy robots and assistive robots. Therapy robots are further categorized based on the type of therapy administered. Assistive robots are categorized on the basis of the type of assistance provided. The complete classification is shown in figure 6. Prosthetics and orthotics are considered as "allied" fields of rehabilitation robotics, since these fields are increasingly incorporating robotic technology. Technology for monitoring health during the performance of activities of daily living is also considered as a related field of rehabilitation robotics.

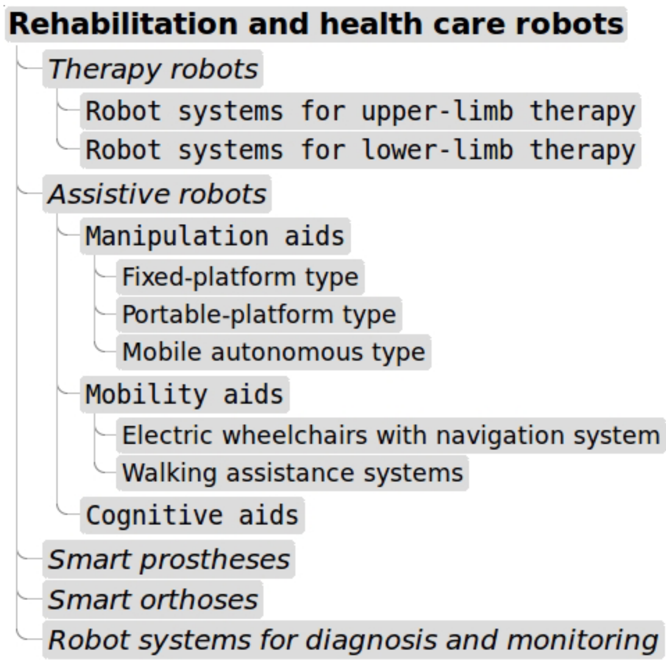

Figure 6: Classification of rehabilitation robots by Van der Loos and Reinkensmeyer [12]

In [73], **Speich and Rosen** categorize rehabilitation robots into assistive robots, robotic prosthetics, robotic orthotics and therapeutic robots. Assistive robots are further categorized into robots for assisting individuals with upper-limb disabilities, mobility assistance devices and vocational assistance devices. Therapeutic robots are categorized into upper-limb devices and lower-limb devices. The classification is shown in figure 7.

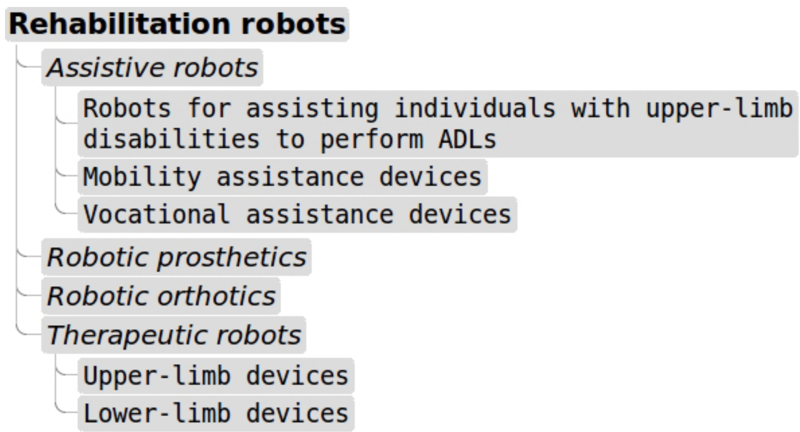

Figure 7: Classification of rehabilitation robots by Speich and Rosen [73]

3.1.2 Comparison

While there are similarities between classifications suggested in the literature cited above, there are also dissimilarities between them. A comparison of the three classifications is provided in table 2.

Similarities
• Therapeutic robots and assistive robots constitute separate categories. • Manipulation and mobility assistance robots constitute separate categories. • Therapeutic robots are categorized on the basis of the type of therapy administered. • Assistive robots are classified on the basis of the type of assistance provided.
Dissimilarities
• Tejima has explicitly categorized robots for helping caregivers. • Van der Loos and Reinkensmeyer have identified a separate sub-category for cognitive aids. • Speich and Rosen have identified a separate sub-category for vocational assistance robots. • Robotic orthoses are considered by Tejima as a part of augmentative manipulation systems. The other two classifications consider it as being outside of assistive robots. • Speich and Rosen do not further classify mobility assistance devices. The other two classifications have identified sub-categories for it.

Table 2: Comparison of classifications for assistive robots

3.1.3 Deficits

The deficits of the existing classifications for assistive robots are summarized in table 3. Non-intuitive names for categories affect readability and usefulness of a taxonomy. Non-uniform terminology hampers smooth flow of information between researchers and other stakeholders.

Deficits
• **Non-intuitive names** for categories. For example, "Feeding robots" would have been a more intuitive name instead of "Powered feeders" in [76]. • **Non-uniform terminology**: Similar categories do not have identical names in the classifications. For example: – "Robotic wheelchairs" in [76] and "Electric wheelchairs with navigation system" in [12] – "Wheelchair robots" in [76] and "Portable-platform type manipulation aids" in [12] – "Mobile robots" in [76] and "Mobile autonomous type manipulation aids" in [12] – "Therapy robots" in [76, 12] and "Therapeutic robots" in [73] • **Lack of agreement** between the classifications (see table 2 for dissimilarities).

Table 3: Deficits of existing classifications for assistive robots

3.2 Mapping Assistive Robots to Assistance Needs

3.2.1 Literature Review

Studies [72, 23] have been performed to identify the assistance needs of elderly adults, and to identify automation technology and robots that have the potential to provide such assistance.

Harmo et al. [23] has provided a consolidated mapping between needs of elderly and disabled, and the currently available solutions and research prototypes. Needs were identified mainly by conducting interviews and analysing responses to questionnaires. The respondents to questionnaires were mainly care professionals. The interviews and discussions were also conducted mainly with rehabilitation and care professionals from Finland, Germany and Japan. The discussions reportedly revealed that, for care workers, lifting, dressing and undressing persons were the most difficult tasks to perform. This was followed by feeding, personal hygiene, washing and bathing assistance. The responses to questionnaires revealed great interest in assistive solutions, especially mobility aids, and lifting aids. The identification of technology was based on interviews, questionnaires and literature review.

Harmo et al. [23] presents the mapping between needs/problems/difficulties and technology solutions in the form a four column table. The first column lists the assistance needs (for example, eating, walking, shopping, cleaning, etc.) and problems (for example, reduced vision, memory loss, etc.) of elderly and disabled. The second column lists the known solutions (for example, walking sticks, reminder devices, Braille writing, etc.). The third column lists the smart solutions that are commercially available today (for example, intelligent medicine dispensers, floor cleaning robots, speech recognition software, etc.). The fourth column lists the technology under research (for example, robotic walkers, robotic wheelchairs, etc.).

However, the study [23] does not provide a mapping at the level of individual products. It also does not look at specific needs in detail. For example, there are many aspects to walking, like, walking short distances, walking long distances, walking around obstacles, walking on different surfaces, etc. [56]. Some walking aids may be usable only indoors, while others may be usable outdoors as well. Only a mapping of products at the detailed level of needs will reveal gaps between user needs and specific technology.

Smarr et al. [72] has reviewed literature to understand how robots could potentially help the elderly to live independently. The study identified the activities of daily living (ADLs) for which the elderly need assistance, identified the existing robots that have the potential to provide assistance for such activities, and identified assistance needs that are not met by the existing robots. Among the assistive robots available till 2011, 147 robots were shortlisted. This list includes Paro, Care-O-bot® 3, PR2, MAid, PAMM, GuideCane, Roomba, and many more. These robots were classified on the basis of the ADLs that they could support. Most robots have the potential to provide assistance for multiple tasks belonging to different ADLs. Of the 147 robots, 70 were identified as having the potential to support basic ADLs, 42 for instrumental ADLs and 61 for enhanced ADLs. 63 robots had the potential to support ambulation. Ambulation, housekeeping, and social communication were supported by a significant number of robots. Very few or no robots could be identified that provided assistance for transportation, money management, grooming, doing laundry, dressing, toileting, bathing, and telephone use.

Smarr et al. [72] presents a consolidated view of the available robot support for different ADLs in the form of numbers that indicate how many of the 147 robots support a specific ADL. For example, among the 147 robots shortlisted, the number of robots that could support ambulation is 63. The authors have not described which robot provides which types of assistance. Thus, this study also does not provide a mapping at the level of individual robots. It also does not look at specific needs in detail. As explained earlier in this section, there are many variants to each of the activities that are performed in everyday life. Hence, a mapping at the detailed level of needs is required.

In the introduction to the book titled "The Engineering Handbook of Smart Technology for Aging, Disability, and Independence," **Helal et al.** [29] has provided a consolidated mapping between the needs of persons with different types of disabilities and the technologies discussed in the book. Five types of disability are discussed, namely, motor disability, visual disability, hearing disability, cognitive disability and communication disability. Impairments associated with each of these disability types are identified, along with the associated needs. The impairments and the needs are mapped to the assistive technologies, and the mapping is presented in tabular form (one table for each type of disability). In certain cases, the needs are divided into more common and less common needs. In most cases, technologies are grouped into more common and less common technology. The technologies listed in the tables and discussed in the book include assistive robots.

The mapping presented by Helal et al. [29], like the other two studies [23, 72], lacks a mapping at the level of individual devices/products, and does not look at specific needs in detail. In addition, the tables contain too much detail, which makes comprehending the provided information difficult.

A key point to be noted is that the terminology used in [23], [72] and [29] to express the needs of elderly and disabled are not identical. For example, [23] uses the term "Walking," while [72] uses the term "Ambulation" to refer to the same activity of moving from one place to another by foot. In [29], this activity is included in more generic terms like "Navigation" and "Mobility." Such terminological differences make comparison and merging of information provided in related studies difficult. Therefore, it is important to use internationally accepted terminology to describe assistance needs of users.

3.2.2 Comparison

A comparison of the existing mapping of assisitive robots is provided in table 4.

3.2.3 Deficits

The deficits of existing mapping of assistive robots are listed in table 5.

Harmo et al. [23]	**Smar et al. [72]**	**Helal et al. [29]**
Needs identified based on interviews, questionnaires, literature review	Needs identified based on literature review	Needs identified based on contents of the book
Technology identified based on interviews, questionnaires, literature review	Technology identified based on literature review	Technology identified based on contents of the book
Mapping presented in tabular form	Mapping presented in tabular form	Mapping presented in tabular form
A single table presents the mapping	Separate tables for ADL, IADL and EADL	Separate tables for each type of disability
Table maps needs to known solutions, commercially available automation technology and automation technology under research	Tables list ADLs and the number of robots that support each ADL	Tables map impairments and associated needs to technologies
Needs listed in table are not sorted according to importance	ADLs listed in each table are sorted in non-increasing order of number of robots that support it	Needs associated with motor disabilities are categorized into more common and less common needs
Needs are not classified	Needs are classified as ADL, IADL and EADL	Needs are classified according to Maslow's hierarchy of needs[a]

Table 4: Comparison of existing mapping of assistive robots to user needs

[a]A pyramidal hierarchy of human needs, proposed by Abraham Maslow [47]

Deficits
• Mapping is not at the level of individual robots. • Assistance needs are not expressed in detail. • Non-uniform terminology used for expressing assistance needs.

Table 5: Deficits of existing mapping of assistive robots to user needs

3.3 Assistance Needs and Functions in ICF Terminology

[8, 9] describe how health-status measures can be linked to the ICF. Health-status measures provide information about human functioning and disability. Thus, assistance needs of users can be measured clinically, and can be expressed in terms of ICF. It is also possible to describe the functionality of assistive products in terms of ICF. This has been illustrated in the working document published jointly by the Dutch Normalisation Institute and the Dutch WHO FIC Collaborating Centre [5]. This document encodes the functionality of ISO 9999 assistive product categories in terms of ICF classes.

In [48], **Matsumoto et al.** describe a method for analysing the activities performed in daily life and generating evidence of real needs of users. The method involves logging the activities performed by a healthy individual, and analysing the log to identify which activities were performed, how many times each activity was performed, which activities were performed to achieve a specific goal (for example, cook a meal), etc. Here, the activities are coded in terms of ICF classes. The authors illustrate how ICF can be used to describe the assistance needs of users in detail. For example, to cook a meal, tasks like lifting objects, carrying objects, pushing, pulling, etc. are involved, and each of these can be coded in ICF. This is more detailed than specifying the activity as the ADL "Meal preparation".

Matsumoto et al. [48] also illustrates that functions provided by assistive robots can be described qualitatively in terms of ICF classes. The tasks that can be performed by a manipulation assistance robot, the RAPUDA (Robotic Arm for Persons with Upper-limb DisAbilities), have been coded using ICF.

3.4 Mobility Assistance Systems

Many intelligent mobility aids have been developed as research prototypes. Some of these were studied as part of the seminar "Introduction to Scientific Working" [24]. These include intelligent wheelchairs, scooters, carts, canes and rollators.

VAHM developed by Bourhis et al. [6], MAid developed by Prassler et al. [66], Hephaestus developed by Simpson et al. [71] and NavChair developed by Borenstein et al. [45] are examples of wheelchair-based intelligent mobility aids. A detailed review of smart wheelchairs has been performed by Simpson in [69]. The smart wheelchairs discussed can be operated independently by users only in indoor environments [69]. The need for inexpensive sensors, a standard communication protocol, and system effectiveness studies is emphasized in [69].

Intelligent walking aids include PAMM developed by Dubowsky et al. [74], GuideCane developed by Borenstein et at. [78], PAM-AID developed by MacNamara et al. [46], RTWalker developed by Hirata et al. [30], etc. The recent trends in intelligent mobility assistance systems are discussed in [11]. No radically new technologies have emerged [11]. The need for more effective control algorithms, and the need for involving potential users in the development of assistive robots are highlighted in [11].

4 Problem Formulation

Based on the literature review in section 3, two key problems were identified, one relating to classification of assistive robots, and the other relating to mapping of assistive robots to user needs. These problems and the suggested solutions are described below:

- From section 3.1, it is evident that there exists no commonly accepted classification system for assistive robots within the robotics research community. Three classifications were reviewed, and the deficits are summarized in table 3. To solve the problems identified, a standardized, comprehensive, exhaustive taxonomy is needed for assistive robots. There exists an international standard, namely, ISO 9999 [1], for classifying commercially available assistive products. Commercially available robots, such as workplace robots, vacuum cleaning robots, certain therapeutic robots, and lifting and positioning robots, are included in the standard. The ISO 9999 classification might also be applicable for assistive robots that are under research.
- As described in section 3.2, a mapping of assistive robots to user needs, at the level of individual devices, and at the level of detailed assistance needs, is lacking in the current literature. The terminology used to express assistance needs is not uniform across different studies. To solve these problems, an internationally accepted taxonomy of assistance needs is required. The functionality of assistive robots should be described in terms of such a taxonomy. The literature reviewed in section 3.3 support the use of ICF to express the assistive needs of users in detail, and to describe the functionality of assistive robots.

A summary of the problems and suggested solutions is provided in table 6.

	Problems	**Suggested Solution**
Taxonomy	• Non-intuitive terminology • Non-uniform terminology • No widely accepted taxonomy	• Use ISO 9999 to classify assistive robots
Technology Mapping	• Assistance needs not detailed • Non-uniform terminology for needs • Mapping not at device level	• Use ICF to express assistance needs • Describe assistance functions of robots in ICF terms

Table 6: Taxonomy and technology mapping of assistive robots: Problems and suggested solutions

4.1 Proposed Work

As part of this research work, we do the following:

- Study ISO 9999:2011 [1] and ICF [56]
- Study four well-known robots that can provide mobility assistance, namely, the SmartCane [74], SmartWalker [74], MAid [65, 66] and Care-O-bot® 3 [40].
- Examine the applicability of ISO 9999:2011 to classify these robots.
- Describe the assistive functionalities of these robots in terms of ICF classes.
- Suggest a taxonomy for mobility assistance robots based on ISO 9999.
- Illustrate technology mapping of mobility assistance robots using ICF terminology.

4.2 Method Used for Research

This research work is based on information gathered from the sources listed below:

- Literature databases: IEEE, ACM, ScienceDirect
- Online journals published by Sage Publications, Elsevier
- Online publications of WHO, and the United Nations
- Other online resources discovered through Google Scholar and Google Web search.
- Books on assistive technology

The literature search focused on the following categories of information:

- Population surveys showing demographic trends of world's population, with a focus on aging and prevalence of disability
- Literature (surveys, reports, articles) relevant for understanding disability- major causes, costs, care needs, care providers, common activity limitations
- Literature (surveys, reports, papers) on mapping of assistance needs to assistive robots
- Literature on selected mobility assistance systems
- Literature on utilization, benefits and cost-effectiveness of mobility aids.

The classification and mapping were performed based on the following:

- Rules of classification listed in ISO 9999:2011 [1]
- Mapping of ISO 9999:2007 codes to ICF classes presented in [5]
- Explanatory notes, inclusions and exclusions associated with the classes and categories of ISO 9999:2011 and ICF
- Evaluation results of the four robots published in the corresponding literature.

5 Human Health and Assistive Technology Classification

5.1 International Classification of Functioning, Disability and Health

5.1.1 Brief History

Since 1947, mortality[3] statistics is reported in terms of World Health Organization's (WHO) International Statistical Classification of Diseases and Related Health Problems (ICD) [3]. As the name suggests, ICD is used to classify diseases and other health problems [60]. It is used to compile mortality and morbidity[4] statistics on the basis of medical diagnostic records [60]. However, such information do not describe the overall population health status [3]. To describe health status, information on "*the lived experience of health*" or "*the condition of one's life*" is needed [3]. This information is obtained from data on functioning and disability levels.

In 1980, WHO released the International Classification of Impairments, Disabilities and Handicaps (ICIDH) for field trials [3]. The ICIDH provided a conceptual framework for describing disability from a medical perspective [63]. However, there were growing demands to revise ICIDH so as to use etiologically[5] neutral and linguistically neutral terminology [63]. The revision process began in 1993 [3]. The revision also incorporated environmental factors that affect disability [63]. After the revision and review by technical experts, field trials were conducted to validate the cross-cultural applicability and linguistic neutrality of the revised ICIDH [3]. The ICIDH was later renamed as the International Classification of Functioning, Disability and Health (ICF), and endorsed by WHO in May 2001 [3]. The ICF is a member of the WHO Family of International Classifications (WHO-FIC) [56].

Information about population health status is crucial for framing health and social policies, and for planning and managing health services. Information on functioning and disability levels of individuals is useful for determining assistance and healthcare needs, identifying suitable assistive technology intervention, determining eligibility for disability benefits, etc. [3].

[3]the proportion of deaths to population [15]
[4]the relative incidence of disease [14]
[5]etiology: the cause of a disease or abnormal condition [13]

5.1.2 Synopsis

As stated in the official document [56] released by World Health Organization (WHO), "*the overall aim of the ICF classification is to provide a unified and standard language and framework for the description of health and health-related states.*" The same document describes the structure of the framework, which is summarized in the paragraphs below.

The ICF consists of two parts- **Functioning and Disability**, and **Contextual Factors**. Each of these parts consists of two components. Functioning and Disability is composed of the components **Body Functions and Structures**, and **Activities and Participation**. Contextual Factors is composed of **Environmental Factors** and **Personal Factors**. The components that constitute Functioning and Disability can be used to express positive or negative aspects of health. Positive aspects of health are collectively termed functioning, and negative aspects of health are collectively termed disability. The Environmental Factors component can be used to express positive or negative influences on functioning. Those environmental factors that have a positive influence on functioning are termed as **facilitators**, and those that have negative influence on functioning are termed as **barriers** or **hindrances**.

Each component is composed of domains. Body Functions and Structures is composed of domains which represent physiological functions and anatomical structures. Activities and Participation is composed of domains which represent different areas of life, including tasks and actions. Environmental Factors is composed of external factors that influence functioning and disability. Personal Factors is composed of factors internal to a person that influence functioning and disability.

The domains of all components except Personal Factors are organised into four levels of hierarchy. The first level is termed **chapter**. Each level of classification is assigned an alphanumeric code. The first element of every code is an alphabet from the set {b, s, d, e}. 'b' stands for Body Functions, 's' for Body Structures, 'd' for Activities and Participation, and 'e' for Environmental Factors. This is followed by a single-digit chapter number that identifies the chapter. The second level of classification is coded using two digits, which follow the alphabet and chapter number. Third and fourth levels of classification are coded using single digits. Examples illustrating the classification hierarchy are provided in section 5.1.3.

5.1.3 Examples

The first level of ICF classification for each of the components is listed in tables 7 and 8. The second level of ICF classification for the chapter 4 (Mobility) of the component Activities and Participation is listed in table 9. The complete classification hierarchy of ICF is available online in the form of an application named **ICF Browser** [59]. The information listed in the tables are sourced from [56].

Body Functions	
Chapter 1	Mental functions
Chapter 2	Sensory functions and pain
Chapter 3	Voice and speech functions
Chapter 4	Functions of the cardiovascular, haematological, immunological and respiratory systems
Chapter 5	Functions of the digestive, metabolic and endocrine systems
Chapter 6	Genitourinary and reproductive functions
Chapter 7	Neuromusculoskeletal and movement-related functions
Chapter 8	Functions of the skin and related structures
Body Structures	
Chapter 1	Structures of the nervous system
Chapter 2	The eye, ear and related structures
Chapter 3	Structures involved in voice and speech
Chapter 4	Structures of the cardiovascular, immunological and respiratory systems
Chapter 5	Structures related to the digestive, metabolic and endocrine systems
Chapter 6	Structures related to the genitourinary and reproductive systems
Chapter 7	Structures related to movement
Chapter 8	Skin and related structures

Table 7: First level of classification of the ICF component Body Functions and Structures [56]

Activities and Participation	
Chapter 1	Learning and applying knowledge
Chapter 2	General tasks and demands
Chapter 3	Communication
Chapter 4	Mobility
Chapter 5	Self-care
Chapter 6	Domestic life
Chapter 7	Interpersonal interactions and relationships
Chapter 8	Major life areas
Chapter 9	Community, social and civic life
Environmental Factors	
Chapter 1	Products and technology
Chapter 2	Natural environment and human-made changes to environment
Chapter 3	Support and relationships
Chapter 4	Attitudes
Chapter 5	Services, systems and policies

Table 8: First level of classification of the ICF components Activities and Participation, and Environmental Factors [56]

5.2 ISO 9999: Assistive Products for Persons with Disability

5.2.1 Brief History

[4] describes the events that led to the development of ISO 9999, and its adoption by countries world-wide. These events and milestones are summarized in the paragraphs below.

The adoption of inclusiveness policies in North America and Europe, the stimulation of open markets for technical aids, and the emergence of globalization, raised demands for an international standard and a common terminology for technical aids. Following these demands, the ISO/TC173 technical committee was setup in 1973 for the standardization of technical aids for the disabled. A sub-committe (ISO/TC173/SC2) on classification and terminology of technical aids for the disabled was setup later in the same year. This sub-committee developed the ISO 9999 standard, and is responsible for releasing its revisions.

ISO 9999 was released in 1978. It was an adoption and adaptation of the Nordic Classification, a common classification used in Denmark, Norway and Sweden to classify the commercially available technical aids. Revisions are made to the standard so as to add products that are newly available in the market, and to remove those that are no longer available. The first revision of ISO 9999 was released in 1992, the second in 1998, the third in 2002, the fourth in 2007, and the fifth in 2011 [1]. The sixth is expected in 2015, and might include harmonization of the classification with ICF and the addition of a fourth

Changing and maintaining body position (d410-d429)	
d410	Changing basic body position
d415	Maintaining a body position
d420	Transferring oneself
d429	Changing and maintaining body position, other specified and unspecified
Carrying, moving and handling objects (d430-d449)	
d430	Lifting and carrying objects
d435	Moving objects with lower extremities
d440	Fine hand use
d445	Hand and arm use
d449	Carrying, moving and handling objects, other specified and unspecified
Walking and moving (d450-d469)	
d450	Walking
d455	Moving around
d460	Moving around in different locations
d465	Moving around using equipment
d469	Walking and moving, other specified and unspecified
Moving around using transportation (d470-d489)	
d470	Using transportation
d475	Driving
d480	Riding animals for transportation
d489	Moving around using transportation, other specified and unspecified
d498	Mobility, other specified
d499	Mobility, unspecified

Table 9: Second level of ICF classification for the chapter d4 (Mobility) [56]

hierarchical level [27].

ISO 9999 was originally titled "Technical Aids for Persons with Disabilities-Classisifcation and Terminology". In the 2007 revision, the title was changed to "Assistive Products for Persons with Disability- Classification and Terminology." All references to "technical aids" were changed to "assistive products". In the 2011 revision, a new ISO 9999 class, "28 Assistive products for employment and vocational training," was introduced.

From 1992 onwards, ISO 9999 is adopted as the Europoean CEN standard (CEN 9999) through the Vienna Agreement. The ISO 9999 is adopted as a national standard in Denmark, France, Germany, The Netherlands, Spain, Colombia, and the United Kingdom.

Data collected from 15 national standardization bodies and 18 user institutions in different countries revealed that ISO 9999 is being used for legislative and regulatory purposes, administrative purposes, and for dissemination of information on assistive devices, among others. National databases on assistive products, like REHADAT (Germany) `www.rehadat.de`, AbleData (the United States) `www.abledata.com` and HANDY-WIJZER (Netherlands and Belgium) `www.handy-wijzer.nl`, are organized based on the ISO 9999 classification. EASTIN (European Assistive Technology Information Network) provides information on assistive products available across Europe. It provides a search interface based on ISO 9999:2011.

5.2.2 Scope

The reference document of ISO 9999 [1] states the scope of the standard as follows:
"*This International Standard establishes a classification of assistive products, especially produced or generally available, for persons with disability. Assistive products used by a person with disability, but which require the assistance of another person for their operation or administration, are included in the classification. The following items are specifically excluded from this International Standard:*

- *items used for the installation of assistive products;*
- *solutions obtained by combinations of assistive products that are individually classified in this International Standard;*
- *medicines;*
- *assistive products and instruments used exclusively by healthcare professionals;*
- *non-technical solutions, such as personal assistance, guide dogs or lip-reading;*
- *implanted devices;*
- *financial support.*"

5.2.3 Synopsis

ISO 9999 [1] is an international standard that provides a classification of assistive products based on its principal function [4]. The standard specifies a classification scheme that consists of three hierarchical levels, namely classes, subclasses and divisions. Each of these classes, subclasses and divisions is assigned a two-digit code. Thus, codes for assistive products consist of three pairs of digits, one for each level, in the order- class, subclass, division. Originally, codes were assigned to classes, subclasses and divisions in intervals of three. In subsequent revisions, new classes, subclasses and divisions were introduced by assigning intervening digits from this interval. If an item has been removed from the standard in a revision, then the corresponding code is not reused to identify a new item in any subsequent revisions.

In addition to codes, the standard specifies titles, explanatory notes, inclusions, exclusions, and cross-references for each level. All titles are in the plural form. Titles of classes describe a broad area of functions [4]. Titles of subclasses describe a specific function within the broad area of functions represented by the class [4]. Titles of divisions refer to particular products that provide the specific function of the subclass [4]. Explanatory notes describe the content of the corresponding ISO 9999 level [4]. Inclusions provide examples of products which are included in the level, and exclusions provide examples of products which are excluded from the level [4]. Cross-references separate classes, subclasses, or divisions, and provide information about related products [1]. Examples illustrating the classification hierarchy and structure are provided in section 5.2.4.

The standard includes a conversion table to map the previous revision to the current revision [4]. It also includes an alphabetical index to make the use of the classification easier [4]. Certain codes are reserved for use at national or regional level. The code 89 represents the class/subclass/division titled “other” [1]. The class codes 00, 01, 02 and 90-99 are reserved for assistive product classes defined at national level [1].

5.2.4 Examples

The structure of an item in ISO 9999:2011 [1] is shown in figure 8. The classes (level-1 items) in the ISO 9999 standard, 2011 revision [1], are listed in the table 10. The subclasses (level-2 items) of the class 12 (Assistive products for personal mobility), as specified in the ISO 9999 standard, 2011 revision [1], are listed in table 11. The divisions (level-3 items) of the subclass 12 23 (Powered wheelchairs), as specified in the ISO 9999 standard, 2011 revision [1], are listed in table 12.

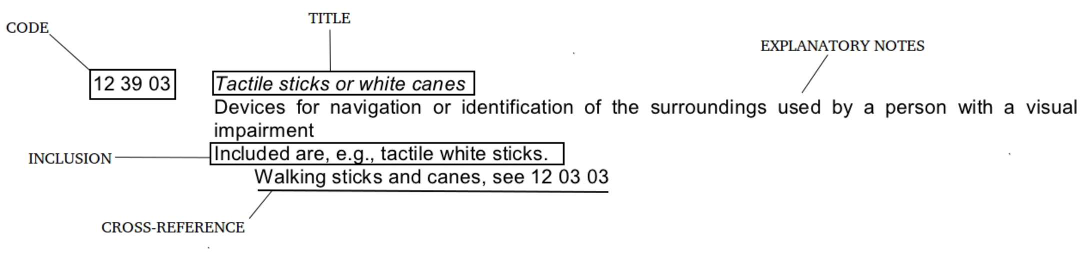

Figure 8: Structure of an item in ISO 9999:2011 [1] classification

Code	Title
04	Assistive products for personal medical treatment
05	Assistive products for training in skills
06	Orthoses and prostheses
09	Assistive products for personal care and protection
12	Assistive products for personal mobility
15	Assistive products for housekeeping
18	Furnishings and adaptations to homes and other premises
22	Assistive products for communication and information
24	Assistive products for handling objects and devices
27	Assistive products for environmental improvement, tools, and industrial machinery
28	Assistive products for employment and vocational training
30	Assistive products for recreation

Table 10: Classes of assistive products as specified in ISO 9999:2011 [1]

5.2.5 ISO 9999 and ICF

ISO 9999 is "*a related member of the WHO Family of International Classifications (WHO-FIC)*" [19]. ISO 9999 uses the terminology of ICF [27]. The sub-committee ISO/TC173/SC2 has developed **a cross-reference between ISO 9999:2007 and ICF**, which is specified in the working document [5]. The ISO 9999 codes are mapped to one or more ICF classes, based on a set of rules, which are described in the document. The mapping describes the functionality of assistive products using ICF terminology. Functionality of an assistive product includes the activities that can be performed using it, and the body functions and structures that it supports. Table 13 provides a few examples of the mapping.

Code	Title
12 03 [a]	Assistive products for walking, manipulated by one arm
12 06	Assistive products for walking, manipulated by both arms
12 07	Accessories for assistive products for walking
12 10	Cars, vans and trucks
12 11	Mass transit vehicles
12 12	Vehicle accessories and vehicle adaptations
12 16	Mopeds and motorcycles
12 17	Alternative motorized vehicles
12 18	Cycles
12 22	Manual wheelchairs
12 23	Powered wheelchairs
12 24	Wheelchair accessories
12 27	Alternative human-powered vehicles
12 31	Assistive products for transfer and turning
12 36	Assistive products for lifting persons
12 39	Assistive products for orientation

Table 11: Subclasses of class 12 of ISO 9999:2011 [1]

[a] The code 12 03 represents the subclass 03 of class 12

Code	Title
12 23 03 [a]	Electrically powered wheelchairs with manual steering
12 23 06	Electrically powered wheelchairs with powered steering
12 23 09	Combustion powered wheelchairs
12 23 12	Assistant-controlled electrically powered wheelchairs
12 23 15	Stair climbing wheelchairs

Table 12: Divisions of subclass 12 23 of ISO 9999:2011 [1]

[a] The code 12 23 03 represents the division 03 of subclass 23 of class 12

Assistive Product (in terms of ISO 9999)	**Functionality (in terms of ICF)**
12.03.03 Walking-sticks	Gait pattern functions (b770) Walking (d450) Moving around in different locations (d460)
12.06.06 Rollators	Gait pattern functions (b770) Maintaining a sitting position (d4153) Maintaining a standing position (d4154) Walking (d450) Moving around in different locations (d460)
12.23.06 Electric-motor-driven wheelchairs with powered steering	Maintaining a lying position (d4150) Maintaining a squatting position (d4151) Maintaining a sitting position (d4153) Maintaining a standing position (d4154) Moving around using equipment (d465)
22.27.15 Calendars and timetables	Orientation to time (b1140) Memory functions (b144) Organisation and planning (b1641) Time management (b1642) Experience of time (b1802) Carrying out daily routine (d230)

Table 13: Mapping of ISO 9999 codes to ICF classes. Source: [5]

6 Mobility Assistance Systems: Case Studies

In this section, four well-known robotic systems that can provide mobility assistance are described, and the applicability of ISO 9999 and ICF to these systems are studied. The systems are the SmartCane (a robotic cane), the SmartWalker (a robotic walker), MAid (a robotic wheelchair)[6], and Care-O-bot® 3 (a service robot).

6.1 PAMM

PAMM is an acronym for Personal Aids for Mobility and Monitoring, and refers to two robotic mobility aids developed by Dubowsky et al. [49, 74] at MIT's Field and Space Robotics Laboratory [49]. These systems are called the **SmartCane** and the **SmartWalker** [74]. These smart walking aids were developed with the objective of providing assistance for walking to the elderly living in eldercare facilities, so as to delay their movement into nursing homes [74]. Images of the two devices can be found in [74].

6.1.1 Technical Specification

The technical details of SmartCane and SmartWalker are discussed in [74, 49], and are summarized in the paragraphs below.

The SmartCane and the SmartWalker are provided with a six-axis force-torque sensor for measuring the forces and torques applied by the user on the handle. An admittance-based control system running on a PC104 computer determines the user-intended direction and speed of motion based on the force and torque readings. A dynamic admittance model allows the system to dynamically vary the "*feel*" (Example: slow and stable; fast, light and responsive) at different stages of the walk. An array of sonars is provided for obstacle avoidance. An CCD camera that faces upwards, and passive signposts placed on the ceiling, support vision-based self-localization.

The SmartCane has two front wheels driven using a non-holonomic skid-steering drive mechanism, and one undriven castor wheel at the rear. Each of the drive wheels operate independently. The system is powered by two 13Wh NiCd batteries. The SmartWalker has two active split offset castor (ASOC) units at the front, and two undriven castor wheels at the rear. An ASOC unit consists of two conventional wheels separated by a distance and connected to the base through an offset link. Each wheel in an ASOC unit is driven independently, thereby providing omni-directionality. SmartWalker requires more power than SmartCane.

[6] SmartCane, SmartWalker and MAid were also studied as part of the seminar "Introduction to Scientific Working" [24].

Three control modes are supported in the SmartCane and the SmartWalker, namely user-controlled mode, fully autonomous mode and semi-autonomous mode. In user-controlled mode, the user has full command of the system, while the device provides only physical support. In the fully autonomous mode, the user only proivdes a destination, while the device performs path planning, navigation and localization. In the semi-autonomous mode, the device performs path planning and obstacle avoidance, while the user responds to the device or provides directions to the device by pushing or twisting the handle. In this mode, an adaptive control-sharing strategy is used. The trajectory from the planner is combined with the velocities provided by the admittance-based control system and the feedback provided by the sensors, to provide a safe and smooth motion.

Health monitoring sensors are provided on the SmartWalker to monitor the activity level. ECG-based pulse monitoring and gait analysis are also supported on the SmartWalker. The data and measurements recorded over time can be analysed by doctors to identify major or minor changes in the health of the user.

6.1.2 Key Evaluation Results

In this section, the evaluation of the three control modes of the PAMMs is summarized, based on the details provided in [74]. The PAMMs were tested on three different paths, one along the middle of a corridor in an eldercare facility, and two along the sides of the same corridor. Six elderly persons belonging to the age-group of 85-95 years participated in the experiment. The performance was found to be better in the semi-autonomous mode than in the user-controlled mode with regard to the distance maintained from the wall. The fully autonomous mode was not liked by the users, because it disallowed deviations from the planned path even when the user was within a safe distance from the wall. The users complained that (in the fully autonomous mode) "PAMM has a mind of its own."

6.1.3 Classification based on ISO 9999:2011

The applicability of ISO 9999:2011 [1] to classify the SmartCane and the SmartWalker was studied. The observations are presented below:

1. The SmartCane belongs to the ISO 9999:2011 subclass **12.03 Assistive products for walking, manipulated by one arm**. However, none of the divisions of the subclass 12.03 are applicable to the SmartCane. The reasons are two-fold. One of the reasons is that, the SmartCane is different from the conventional canes in mechanical construction. While the conventional canes have legs and tips, the SmartCane has

a three-wheeled base. The other reason is that, the (semi-)autonomous navigation capabilities of the SmartCane are not captured in the existing divisions.

2. Therefore, a new division should be created for the subclass 12.03 to represent robotic canes.

3. The SmartWalker belongs to the ISO 9999 subclass **12.06 Assistive products for walking, manipulated by both arms**. Going by the explanatory note, the division **12.06.06 Rollators** suits the SmartWalker. But, the division does not explicitly capture the (semi-) autonomous navigation capabilities of the SmartWalker.

4. The inclusion section of the division 12.06.06 may be modified to make the inclusion of robotic rollators explicit.

5. Alternatively, an additional level of classification may be added to the division 12.06.06 to distinguish between robotic and non-robotic rollators.

6. The SmartWalker supports health monitoring. But its primary function is to provide mobility assistance. Therefore, the SmartWalker is classified under the subclass/division of class "12 Assistive Products for Personal Mobility."

6.1.4 Functionality in ICF Terminology

The use of ICF to describe the functionality of assistive products has been illustrated in [5, 48]. In section 6.1.3, the ISO 9999 subclass and/or division that are applicable to the SmartCane and the SmartWalker were identified. In section 5.2.5, the mapping of ISO 9999:2007 codes to ICF was briefly discussed. Using these pieces of information, an attempt was made to describe the functionality of the SmartCane and the SmartWalker using ICF terminology. The results are described in table 14. The observations and comments regarding the functionality mapping that was performed are summarized below:

- The cross-references provided in [5] cannot be used as is for describing the functionality of the SmartCane and the SmartWalker. For example, the ICF class "Maintaining a sitting position (d4153)" is generally applicable to rollators. But, it is not applicable to the SmartWalker, because the SmartWalker does not provide this type of support.

- Higher levels of classifcation are aggregations of all the sub-levels that come under it. Therefore, if all sub-classes belonging to a particular higher level category are applicable to a device, then these sub-classes can be replaced with the higher level class. Otherwise, the sub-classes that are individually applicable should be specified.

Assistive Product	ICF Classes
SmartCane	Gait pattern functions (b770) Walking short distances (d4500) Walking around obstacles (d4503) Moving around within the home (d4600) Moving around within buildings other than home (d4601)
SmartWalker	Gait pattern functions (b770) Walking short distances (d4500) Walking around obstacles (d4503) Moving around within the home (d4600) Moving around within buildings other than home (d4601) Maintaining one's health (d5702)

Table 14: Functionality of SmartCane and SmartWalker in ICF terminology

  - For example, the sub-classes of "Walking (d450)" include "Walking short distances (d4500)," "Walking long distances (d4501)," "Walking on different surfaces (d4502)" and "Walking around obstacles (d4503)." Based on the description of these classes provided in [56], and the description of PAMM systems provided in [74], only "Walking short distances (d4500)" and Walking around obstacles (d4503) are applicable to the SmartCane and the SmartWalker. Hence, we do not use the higher level category "Walking (d450)" to describe the functionality of the devices.
  - For the same reason, the category "Moving around in different locations (d460)" is not used. Instead, the sub-levels of this category, namely, "Moving around within the home (d4600)" and "Moving around within buildings other than home (d4601)" are used to describe the functionality of the devices.

- "Moving around within buildings other than home (d4601)" is included in the functionality of the devices under the assumption that placing signposts on the ceiling, and obtaining a map of the building/floor from a server located in the building, would enable the use of these devices in any building and not just in the place of residence of the user. This assumption is supported by the conceptual diagram of PAMM system provided in [74].

- The SmartWalker supports continuous health monitoring, which is coded as "Maintaining one's health (d5702)" in ICF terminology. This functionality is not part of conventional rollators, and is hence not included in the cross-references provided in [5].

- The evaluation results of PAMM published in [74, 49] do not explicitly mention support for standing up or sitting down. If these functions can be validated, then the ICF classes “Sitting (d4103)” and “Standing (d4104)” can be added to the description of functionality of the devices.
  - Having said that, the cross-references provided in [5] for walking-sticks or rollators do not include the ICF classes “Sitting (d4103)” and “Standing (d4104).” However, it is included in the cross-references for walking tables (ISO 9999 division 12.06.12). Going by the mapping rules described in [5], the reason for this could be that, support for standing up or sitting down are not considered as amongst the most primary activities that are performed using a walking stick or rollator. But this claim needs to be validated through discussions with rehabilitation professionals.
- The evaluation results of PAMM published in [74, 49] do not explicitly mention that the SmartCane and the SmartWalker can provide physical support to the user while standing. [49] only says that the motion control system allows the user to stop when he/she desires. If the provision of physical support while standing can be validated, then the ICF class “Maintaining a standing position (d4154)” can be added to the description of functionality of the SmartCane and the SmartWalker.
  - Having said that, the cross-references provided in [5] for walking-sticks do not include the ICF class “Maintaining a standing position (d4154).” However, it is included in the cross-references for forearm support crutches and rollators. Going by the mapping rules described in [5], the reason for this could be that, support while standing is not considered as one of the most primary activities that are performed using a walking stick or cane. But this claim needs to be validated through discussions with rehabilitation professionals.

6.2 MAid

MAid (Mobility Aid for Elderly and Disabled People) is an robotic wheelchair developed by Prassler et al. at the Research Institute for Applied Knowledge Processing, in Ulm, Germany [66]. The objective was to develop an autonomous navigation system for commercial wheelchairs so as to enable navigation in narrow, cluttered spaces and in crowded, highly dynamic spaces [66]. Such a system would enable people with severe mobility impairments to move around without assistance from a human caregiver [66, 65].

6.2.1 Technical Specification

The technical details of MAid are discussed in [66], and are summarized in the paragraphs below. Additional sources of information are cited appropriately. For an image of MAid, see [65].

A commercial electrically powered wheelchair was used as the base for building MAid. The wheelchair has two standard wheels at the rear and two castor wheels at the front. The rear wheels are driven differentially. Two 12V (60Ah) batteries supply electrical power. Maximum achievable speed is 6km/h, and the user interface for wheelchair control is a joystick.

The wheelchair was augmented in hardware and software to provide autonomous navigation capabilities. The additions to the wheelchair include an on-board computer running the real-time operating system QNX, and a variety of sensors- two wheel encoders, one fiber optic gyroscope, 24 ultrasonic transducers (for localization and obstacle detection), two infrared scanners, and one 2D laser range finder. The laser range finder is "essential" for safe navigation in crowded and highly dynamic spaces. Two sonar sensors were later mounted on the footrest for detecting low-lying obstacles.

Two user interfaces are available, namely, a joystick and a notebook. The joystick is part of the commercial wheelchair, and provides the means to specify the desired direction of motion. The notebook allows the selection of operation mode, and goal positions and configurations.

Two modes of operation are supported. These are called narrow area navigation (NAN) mode and wide area navigation (WAN) mode. The NAN mode is a semi-autonomous mode, and is used for navigating in "*narrow, cluttered spaces.*" For example, NAN mode can be used when passing through a door, docking at a table, etc. In the NAN mode, the user specifies a goal configuration (2D position, orientation), and the system identifies an optimal collision-free path in the configuration space, and executes the path. If a collision is impending, the wheelchair is brought to a halt, and an alternative path is computed so as to get around the obstacle and move to the goal configuration. Emergency maneuvers such as moving back a little, can make identification of an alternative path easier.

The WAN mode, on the other hand, is a fully autonomous mode, and is used for navigating in "*wide, rapidly changing, crowded areas.*" For example, WAN mode can be used when moving through exhibition halls, shopping malls, airport terminals, etc. In the WAN mode, the user specifies a destination that is some distance away. Based on readings from the laser range finder, the system detects objects, and determines whether the objects are stationary or moving. It tracks moving objects, determines collision courses, and computes a course that avoids collision with moving objects. When a collision-avoiding maneuver cannot be computed, MAid stops [65]. It proceeds to the goal only after objects clear out [65].

6.2.2 Key Evaluation Results

In this section, the experimental validation of the two operation modes of MAid is summarized, based on the details provided in [66]. Additional sources of information are cited appropriately. The validation of NAN and WAN modes were done in real-life environments. The NAN mode was validated by performing the maneuver of reversing into a washroom for the disabled. MAid was able to perform the maneuver safely, with no collisions against the door-posts. The free space between the wheelchair and each door-post was only around 10 cm.

The WAN mode was tested "in the concourse of the central station at Ulm" during peak hours. The desired direction of motion and the distance to be moved were specified using the joystick and the notebook, respectively. It was observed that MAid moved towards the goal location. Whenever a collision was likely, an evasive course was followed until the goal direction became free of obstacles. A total of 18 hours of testing was done over many days at the Ulm central station [65]. MAid was also tested in the crowded exhibition halls of the 1998 Hannover Fair [65]. All-in-all, MAid has performed more than 36 hours of successful navigation in crowded, highly dynamic public envrionments [65].

6.2.3 Classification based on ISO 9999:2011

The applicability of ISO 9999:2011 [5] to the intelligent wheelchair system named MAid was studied. The observations are presented below:

1. MAid uses a commercial electrically powered wheelchair as the base system [66, 65]. This powered wheelchair can be classified under the ISO 9999:2011 division **12.23.06 Electrically powered wheelchairs with powered steering**. However, the division 12.23.06 does not explicitly capture the (semi-) autonomous navigation capabilities of MAid.

2. The subclass **"12.23 Powered Wheelchairs"** is an aggregation of wheelchairs that use powered propulsion. Robotic wheelchairs use powered propulsion. Therefore, they can be placed under the subclass 12.23. However, new divisions should be

Assistive Product	ICF Classes
MAid	Maintaining a lying position (d4150) Maintaining a squatting position (d4151) Maintaining a standing position (d4154) Maintaining a sitting position (d4153) Moving around within the home (d4600) Moving around within buildings other than home (d4601) Moving around using equipment (d465)

Table 15: Functionality of MAid in ICF terminology

created for the subclass 12.23 to explicitly state a robotic wheelchair's autonomous navigation capabilities, along with the type of powered propulsion used.

- For example, 12.23.xx Electrically powered wheelchairs with autonomous navigation system. The explanatory note of such a division can state that these wheelchairs support (semi-)autonomous operation mode. (Note: 'xx' represents a suitable two-digit code for the new division.)

6.2.4 Functionality in ICF Terminology

The use of ICF to describe the functionality of assistive products has been illustrated in [5, 48]. In section 6.2.3, the ISO 9999 subclass and/or division that are applicable to MAid were identified. In section 5.2.5, the mapping of ISO 9999:2007 codes to ICF was briefly discussed. Using these pieces of information, an attempt was made to describe the functionality of MAid using ICF terminology. The results are described in table 15. The observations and comments are listed below:

- All the five cross-references provided in [5] for the ISO 9999:2007 division 12.23.06 have been included in the table 15. These classes show the functionality that are inherited by MAid by virtue of it being based on a commercial electrically powered wheelchair. In addition to these, two ICF classes have been included, namely, "Moving around within the home (d4600)" and "Moving around within buildings other than home (d4601)." These classes describe the locations where MAid can be used. The evaluation results published in [66, 65] show that MAid was tested successfully in indoor environments. MAid was not validated in outdoor environment.
- The key feature that distinguishes a robotic wheelchair from conventional powered wheelchairs is the steering and control aspect. Autonomous navigation system would benefit users who lack the motor skills or the physical strength needed to steer

and control a conventional powered wheelchair [42]. ICF cannot be used to express characteristics like user-friendliness and comfort [5].

- Robotic wheelchairs may use alternate user-interfaces to suit the physical and cognitive capabilities of the user (Examples: [64, 31, 70]). These user-interfaces can be categorized under the ISO 9999 division “22.36.12 Alternate input devices,” and mapped to the ICF class “Using communication devices and techniques (d360),” as specified in [5]. A suitable user-interface for the robotic wheelchair can be selected with help from rehabilitation professionals.
  - The (residual) skills of the user plays a key role in the choice of the user-interface. For example, a person with limited motor skills to operate a joystick, may benefit from a touch screen or a speech interface. However, if the person is also vision impaired, then speech interface would be a better option. This example shows that specifying the minimum skills required to operate or use an assistive product plays a significant role in making the right choice about assistive products and configurations, and in speeding up the assistive technology selection process.
  - These minimum skill requirements can be expressed in ICF terminology. For example, for the use of speech interface, Voice and Speech Functions (chapter 3 of the ICF component Body Functions) are crucial. For operating a joystick, the ability to use hand and arm (Fine hand use (d440), Hand and arm use (d445)) is critical.
  - A similar case has been made in [48], for the description of capabilities required to operate an assistive robot in order to avoid inappropriate use and improve the prospects of commercialization.

6.3 Care-O-bot 3

Care-O-bot® 3 is the third generation of the mobile robot assistant series Care-O-bot®, developed by the Fraunhofer Institute for Manufacturing, Engineering and Automation (IPA) in Stuttgart, Germany [40]. It has been designed for use in daily environments [40]. One of its key functionalities is fetching and carrying household objects [40]. This reduces the need for people to move to fetch the objects themselves. This would promote the independence of the elderly and persons with mobility limitations. See figure 9 for an image of Care-O-bot® 3.

Figure 9: Care-O-bot® 3: A mobile robot assistant. Image source: [35]

6.3.1 Technical Specification

The technical details of Care-O-bot® 3 are provided in [38, 39], and are briefly summarized in this section. The hardware components of Care-O-bot® 3 include an omni-directional mobile base, a sensor head, a 7 degrees of freedom arm, a 3 finger gripper and an optional flexible casing [38]. Each of these hardware components are independently operable, thus providing a modular platform [38]. The omni-directional mobile base consists of 4 wheels [38], each of which is controlled by two motors- one for steering and one for driving [39]. The base houses the lithium-ion battery pack and three laser scanners [38]. The laser scanners support safe navigation by detecting obstacles [34].

The sensor head comprises of a stereo camera and a 3D time-of-flight camera [38, 39], which enable object perception, and monitoring of manipulation operations of the arm to enhance safety. The sensor head is mounted on the torso, which is a manipulator having 4 degrees of freedom [38] provided by two pan/tilt units [39]. This allows the torso to perform gestures like nodding and bowing [38, 34]. The sensor head itself can be rotated about the horizontal axis [38].

The arm has 7 degrees of freedom and can handle a maximum payload of 3-4 kg, including the gripper [38]. The gripper is attached to the end of the arm, and also has 7 degrees of freedom, which allows it to perform different types of grasps [38]. The tactile sensors on the fingers provide feedback about the grasping force applied [34]. The robot's casing is made of special material that is flexible and does not retain any fold marks [38].

The primary user interface is a tray, on which objects are placed during transport [34]. The tray consists of a touch screen and an LCD display [39]. When not in use, the tray is rotated away to the side [34]. Care-O-bot® 3 is provided with a pair of loudspeakers [39]. 3-5 PCs can be included to perform various computational tasks [39] like speech recognition, navigation, vision-based perception, etc.

6.3.2 Demonstrated Functionalities

The videos of demonstrations of the abilities of Care-O-bot® 3 are provided in [34, 36]. The images of demonstrations are available at [36]. The demonstrated abilities include autonomous navigation in indoor environments, fetching and carrying a wide variety of household objects, opening doors, providing primary assistance after falls, communication of health-related data, teleconferencing, entertainment, etc [34, 36]. Among these abilities, what is the most interesting, from the perspective of mobility assistance, is the fetch-and-carry functionality. The Care-O-bot® 3 can detect and grasp a wide variety of household objects [34]. The arm can reach high shelves and around obstacles [34]. It can also reach objects on the floor [34]. The grasped objects are lifted and placed on the tray, and autonomously transported to the destination. The object to be fetched can be specified through user interfaces provided on hand-held mobile devices, or through voice commands. Other modes of interaction include gestures and haptics [37].

6.3.3 Classification based on ISO 9999:2011

The applicability of ISO 9999:2011 [1] to classify Care-O-bot® 3 was studied. The observations are presented below:

- Some of its hardware components of Care-O-bot® 3 can be classified under different categories. For example:
  - The arm-gripper system is used to reach for objects and grasp them. Therefore, it can be placed under the division "24.18.03 Devices for grasping," of the subclass "24.18 Assistive products to assist or replace arm function, hand function, finger function or a combination of these functions."
  - The tray is used to carry objects during transport, and therefore, can be classified under the division "24.36.03 Assistive products for carrying." It consists of a touch screen, which can be classified under "22.36.12 Alternate input devices." The LCD display can be classified under "22.39.04 Visual computer displays and accessories."
- But, not all components can be classified in this manner. For example, none of the ISO 9999 categories capture the autonomous navigation capabilities of the omnidirectional mobile base of Care-O-bot® 3.
- Such a component-wise classification is neither meaningful nor useful for classifying mobile robot assistants.
- Mobile robot assistants are intended to perform multiple activities, like, fetching and carrying objects, housekeeping, recreation, monitoring, etc. Assistive products that provide these functions are classified under different ISO 9999 categories. For example, assistive products that provide assistance to fetch objects are classified under the subclass 24.18. Assistive products that provide assistance to carry objects are classified under the subclass 24.36. The class 15 is dedicated for assistive products for housekeeping. Assistive products which provide recreation are classified under 22.18.03 (Sound recording and playing devices), 30.03.09 (Games), etc. depending on the type of recreational activity supported. Monitoring systems are classified under the division 22.27.24. Thus, it is evident that <u>mobile robot assistants cannot be described using a unique code</u> under ISO 9999:2011.
- Therefore, <u>a revision of ISO 9999 would be required</u> to accommodate mobile robot assistants.

6.3.4 Functionality in ICF Terminology

The use of ICF to describe the functionality of assistive products has been illustrated in [5, 48, 62]. An attempt was made to describe the functionalities of Care-O-bot® 3 using ICF terminology. The videos [34, 36] and images [36] of demonstrations are used to identify the functionalities provided by Care-O-bot® 3. The results of the mapping are listed in table 16.

The observations and comments are listed below:

- The fetch-and-carry function of Care-O-bot® 3 can be mapped to ICF classes, exactly as described in [48, 62].
- Care-O-bot® 3 provides mobility assistance indirectly by reducing the need for persons to move. The video demonstrations illustrate the use of Care-O-bot® 3 in indoor environments. Therefore, the ICF classes chosen are related to movement in indoor environments.
- Care-O-bot® 3 supports transmission of health-related data, such as blood pressure measurements measured using other devices, to the service center. It can manage medication and health-checkup schedules, by fetching and delivering medicines or health-check devices to the user as per the schedule. It can also deliver drinks to ensure sufficient amount of fluid intake per day. Therefore, the ICF class "Maintaining one's health (d5702)" is applicable to Care-O-bot® 3.
- Users can play games on the touchscreen of Care-O-bot® 3. This maps to the ICF class "Play (d9200)." Another form of recreation is provided by playing music, which can be mapped to "Listening (d115)" and "Arts and culture (d9202)."
- Teleconferencing functions can be mapped to the ICF classes "Conversation (d350)" and "Discussion (d355)," because this function enables remote interactive communication with family members or service center personnel.
- The user interfaces, like, the touchscreen, voice interface, etc. belong to the ISO 9999 division "22.36.12 Alternate input devices," and can be mapped to the ICF class "Using communication devices and techniques (d360)," as specified in [5].

Care-O-bot® 3 Functions	**ICF Classes**
Fetch and carry objects	Picking up (d4400) Grasping (d4401) Manipulating (d4402) Releasing (d4403) Pulling (d4450) Pushing (d4451) Reaching (d4452) Turning or twisting the hands or arms (d4453)
Mobility assistance (by reducing need to move)	Moving around within the home (d4600) Moving around within buildings other than home (d4601)
Health-care	Maintaining one's health (d5702)
Recreation	Play (d9200) Listening (d115) Arts and culture (d9202)
Teleconferencing	Conversation (d350) Discussion (d355)
User Interaction	Using communication devices and techniques (d360)

Table 16: Functionality of Care-O-bot® 3 in ICF terminology

7 Results

The results of the study on applicability of ISO 9999 to classify mobility assistance systems are summarized below:

- The subclasses of ISO 9999 can be used for classifying the SmartCane, the SmartWalker and MAid.
- Modifications are required at the level of ISO 9999 divisions to suit these systems.
  - New ISO 9999 divisions should be created for the SmartCane and MAid, in order to capture the (semi-) autonomous navigation capabilities.
  - The existing ISO 9999 division "12.06.06 Rollators" should be modified to include robotic rollators.
- Mobile robot assistants, like Care-O-bot® 3, cannot be classified under a unique category of the current version of ISO 9999.
- Some of the hardware and functional components of mobile robot assistants can be classified under different ISO 9999 subclasses.
- But, the component-wise classification is insufficient. ISO 9999 should be revised to facilitate classification of mobile robot assistants.

A partial classification of assistive robots suggested based on ISO 9999:2011 and based on the findings of this research work is shown in figure 10.

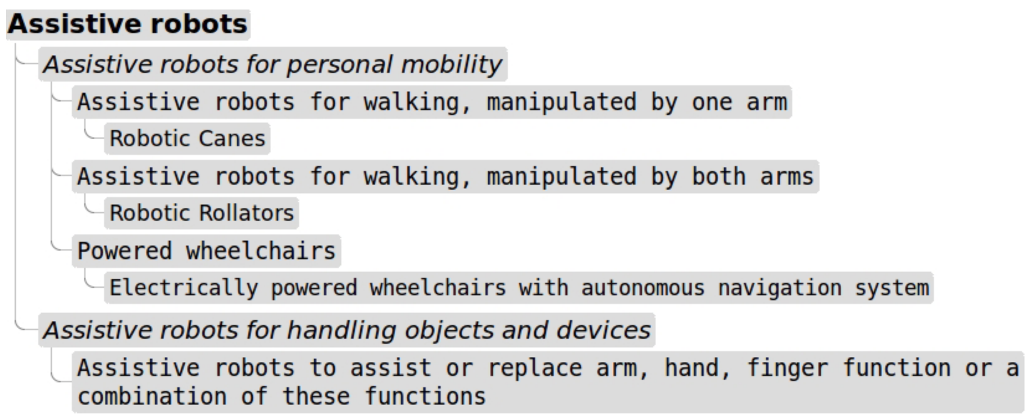

Figure 10: A partial classification of assistive robots suggested based on ISO 9999:2011

The results of the study on applicability of ICF to describe the functions provided by mobility assistance robots are summarized below:

- The assistive functions provided by all the four robots can be described in detail using ICF classes.
- Higher level classes aggregate the functions represented by their sub-classes. If all the sub-classes are applicable to an assistive device, then the corresponding higher level class can replace the set of sub-classes.
- The functions provided by the robotic systems differ from those provided by conventional mobility aids.
    - Conventional mobility aids are usable both indoors and outdoors. But the robotic systems studied in this work can only be used in indoor environments.
    - Robotic systems support additional functions like continuous health monitoring.
- Autonomous navigation capabilities are intended to make mobility assistance systems easier to use for persons with severe impairments [69]. The advantage of autonomous navigation reflects in the degree of support provided. Expressing such quantitative information is currently under research [62].
- It is important to express the minimum skills required to operate a device, so as to make the process of device selection easier and more effective. These skills can be expressed in terms of ICF classes.

The table 17 illustrates how technology mapping can be performed with assistance needs expressed in ICF terminology.

A comparison of costs of the mobility assistance robots and conventional mobility aids was performed. The results are presented in table 18.

Need (in terms of ICF)	Direct support[a]	Indirect support [b]
Walking short distances (d4500)	SmartCane SmartWalker	-
Walking long distances (d4501)	-	-
Walking on different surfaces (d4502)	-	-
Walking around obstacles (d4503)	SmartCane SmartWalker	-
Moving around within the home (d4600)	SmartCane SmartWalker MAid	Care-O-bot® 3
Moving around within buildings other than home (d4601)	SmartCane SmartWalker MAid	Care-O-bot® 3
Moving around outside the home and other buildings (d4602)	-	-
Moving around using equipment (d465)	MAid	-
Maintaining a sitting position (d4153)	MAid	-
Gait pattern functions (b770)	SmartCane SmartWalker	-

Table 17: Technology mapping of mobility assistance robots based on ICF: An illustration

[a]By supporting physical movement
[b]By reducing the need to move

Robotic Mobility Aid	Product Type	Cost (in $)	Cost[a] of Conventional Mobility Aids (in $)
SmartCane	Cane	2500[b]	30-50[c]
SmartWalker	Walker	5000[d]	100-300[e]
MAid	Electric wheelchair	13,500[f]	6500[g]

Table 18: Comparison of costs of mobility assistance robots and conventional mobility aids

[a]Approximate price range or average cost
[b]Target retail cost specified in [74]
[c]Based on prices listed in [32]
[d]Target retail cost specified in [74]
[e]Based on prices listed in [33]
[f]Estimated based on approximate cost of components
[g]Source:[2]

8 Summary

Existing classifications of assistive robots use non-intuitive or non-uniform terminology to describe assistive robot categories. There is also a lack of agreement between the classifications. This reveals the need for standardizing assistive robot classification. In this work, we investigated the applicability of the international standard ISO 9999 to classify mobility assitance robots. The robots which provide mobility assistance by supporting physical movement, and are designed to function primarily as a mobility aid, can be classified under the appropriate subclass of the ISO 9999 class 12 that represents "Assistive products for Personal Mobility." However, new categories at the third level of hierarchy are required to represent the autonomous navigation capabilities of these robots. Robots, such as Care-O-bot® 3, that are fundamentally designed to provide more than one assistive function cannot be classified under a unique ISO 9999 category.

Existing technology mapping of assistive robots do not map individual systems to the detailed needs of users. The terminology used to express assistance needs varies among different studies. In order to describe the assistance needs in detail, and to express the functions of assistive robots, ICF can be used. ICF, being an international classification, provides standard terminology to express assistance needs. In this work, we have illustrated a mapping of mobility assistance robots to the needs of users based on ICF. ICF can describe the type of assistance provided by an assistive product. But, it cannot be used to express technical characteristics, user-friendliness and cosmetic features of assistive products [5]. To represent these characteristics, other classification systems and ontologies for assistive technology should be used.

9 Future Work

In this work, we focused on robots that provide mobility assistance. Applicability of ISO 9999 to other types of assistive robots have to be studied in detail in order to complete the suggested classification for assistive robots. Technology mapping based on ICF terminology should also be performed for robots that provide other types of assistance, such as, manipulation and cognitive assistance.

The qualitative description of functionalities provided by assistive robots using ICF terminology was illustrated[7]. However, quantitative description of assistance functions is required for comparison of assistive robots, so as to make the process of selecting appropriate intervention more effective [48, 62]. Therefore, a mapping of assistive robots to the

[7] This was also illustrated in [48].

degree of assistance required, would be useful, although very challenging.

10 Open Issues

The data published [21, 23, 55] on the assistance needs of elderly or disabled describe the needs in terms of ADL. The publications do not use identical terminology and are not detailed. As specified in the World Report on Disability [61], there is a need for comparable, comprehensive, and reliable data on the prevalence of disability, both at national and global level. For gathering such data, the use of ICF classication is recommended [61].

Assistive technology outcomes is a field that lacks research. There are very few studies about effectiveness and cost-benefits of assistive technology intervention [53]. Given the urgency of the need for research in this area, projects like the ATOMS project [53] were executed. The need for quality research to establish the effectiveness and benefits of using mobility aids is elucidated in [68].

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