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iROS Hamburg 2015

# IROS'2015 Full day Workshop

# Cognitive Mobility Assistance Robots: Scientific Advances and Perspectives

Organisers: C. Tzafestas, P. Maragos, A. Peer, K. Hauer

http://robotics.ntua.gr/IROS2015-Workshop-Cognitive-Mobility-Assistance/

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## Objectives

Mobility disabilities are prevalent in our ageing society and impede activities important for the independent living of elderly people and their quality of life. Designing and controlling robotic devices that can assist frail elderly people and generally people with mobility impairments constitutes an emerging research field in robotics. Many challenging scientific and technological problems need to be addressed in order to build efficient and effective assistive robotic systems, including: (i) human motion tracking, action and intention recognition fusing multimodal sensorial data, (ii) analysing and modelling human behaviour in the context of physical and non-physical human-robot interaction, (iii) developing context-aware, human-centred robot control systems that can act both proactively and adaptively in order to optimally combine physical, sensorial and cognitive assistance modalities, (iv) to foster intuitive and natural human-robot communication ultimately achieving assistive robotic behaviours that emulate the way a human carer would operate while taking into account social interaction and ethical constraints. This workshop aims to gather researchers covering different topics within this multi¬disciplinary and challenging research field. The objective is to provide a review of recent scientific and technological advancements in the field, as well as to highlight novel application perspectives, both from a clinical and an industrial viewpoint, that may have a significant societal impact in the near future.

## Topics of interest

- Multimodal sensory processing for human-robot interaction
- Physical human-robot interaction
- Human-aware interaction control of assistive robots
- Cognitive robot control architectures
- Context and intention awareness
- Human behavioral modeling
- Human-robot communication in assistive robotics
- Elderly care mobility assistive robots

## Invited Speakers:

1. **Ko Ayusawa**, CNRS-AIST JRL UMI3218/CRT, Tsukuba, Japan
2. **Etienne Burdet**, Imperial College, London, UK
3. **Rajiv Dubey**, University of South Florida, Center for Assistive, Rehabilitation and Robotics Technologies, USA
4. **Naohisa Hashimoto**, AIST, Japan
5. **Yasuhisa Hirata**, Tohoku University, System Robotics Lab, Japan
6. **Barbara Klein**, Frankfurt University of Applied Science, Germany
7. **Cristina Santos**, University of Minho, Industrial Electronics Department, Portugal
8. **Batłomiej Stańczyk**, ACCREA Engineering, Polland
9. **Panagiotis Vartholomeos**, Omega Technology, Greece

## Program

| Time | Talk |
|---|---|
| 8:30-8:45 | Workshop Opening |
| **Session 1. Clinical Motivation and User Perspectives** | |
| 8:45-9:30 | **Klaus Hauer**, University of Heidelberg, Germany<br>Title: *Mobility assistance devices: Clinical motivation and perspectives* |
| 9:30-10:00 | **Barbara Klein**, Frankfurt University of Applied Science, Germany<br>Title: *The role of culture and gender in the robotic design process* |
| 10:00 - 10:30 | **Coffee Break** |
| **Session 2. Devices, Interaction and Control (1)** | |
| 10:30-11:00 | **Angelika Peer**, Bristol Robotics Lab, Univ. of the West of England<br>Title: *Shared control for mobility assistive robots* |
| 11:00-11:30 | **Cristina Santos**, University of Minho, Portugal<br>Title: *A smart Walker for Gait rehabilitation of people with cerebellar ataxia* |
| 11:30-12:00 | **Yasuhisa Hirata**, Tohoku University, Japan<br>Title: *Mobility Assistance Robots Controlled by Servo Brakes* |
| 12:00-12:30 | **Rajiv Dubey**, University of South Florida, USA<br>Title: *Evaluating and Optimizing Gait Enhancing Technologies Using a Virtual Reality Environment* |

**Poster Session**

| | |
|---|---|
| 12:30-12:35 | **Jorge Solis**, Dept of Eng & Physics, Karlstad University, Sweden<br>Title: *Development of a Human-Friendly Walking Assistive Robot Vehicle* |
| 12:35-12:40 | **Rajiv Khosla**, La Trobe University, Australia<br>Title: *Socially Assistive Robot for People with Dementia in Home-Based Care* |
| 12:40 - 14:00 | **Lunch Break** |

**Session 3. Devices, Interaction and Control (2)**

| | |
|---|---|
| 14:00-14:30 | **Costas Tzafestas**, National Technical University of Athens, Greece<br>Title: *User-oriented human-robot interaction for an intelligent walking assistant robotic device* |
| 14:30-15:00 | **Etienne Burdet**, Imperial College, London, UK<br>Title: *Intention reading and intuitive shared control for mobility assistive devices* |
| 15:00-15:30 | **Naohisa Hashimoto**, AIST, Japan<br>Title: *Promoting independent mobility: Assistance mobility and evaluation technology in robotic wheelchair* |
| 15:30 - 16:00 | **Coffee Break** |

**Session 4. Multimodal Sensory Processing and Human Identification**

| | |
|---|---|
| 16:00-16:25 | **Petros Maragos**, National Technical university of Athens, Greece<br>Title: *Multimodal sensory processing for human action recognition in mobility assistive robotics* |
| 16:25-16:50 | **Ryad Chellali**, Nanjing Robotics Institute – CEECS, China<br>Title: Measuring Human movements in the wild for HRI Contexts |
| 16:50-17:15 | **Ko Ayusawa**, CNRS-AIST JRL, Japan<br>Title: *Identification of human body dynamics for evaluating assistive devices* |

**Session 5: Application and Industrial Perspectives**

| | |
|---|---|
| 17:15-17:35 | **Jonathan Kelly**, University of Toronto, Institute for Aerospace Studies<br>Title: *Towards a Low-Cost Autonomous Wheelchair Navigation System Using COTS Components* |
| 17:35-17:55 | **Panagiotis Vartholomeos**, Omega Technology, Greece<br>Title: *I-SUPPORT: ICT Supported Bath Robot* |
| 17:55-18:15 | **Batłomiej Stańczyk**, ACCREA Engineering, Poland<br>Title: *Design and implementation of new robotic walker devices: Lessons learned and SME perspectives* |
| 18:15-18:30 | **Discussion, Closing** |

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# WORKSHOP PROCEEDINGS – PAPERS

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### Regular and Invited Papers



### Poster Papers

# Evaluation Studies of Robotic Rollators by the User Perspective: A Systematic Review

Klaus Hauer[1], Christian Werner[1], Phoebe Ullrich[1], Milad Geravand[2], Angelika Peer[3]

*Abstract*— **Robotic rollators enhance basic functions of established devices by technically advanced physical, cognitive, or sensorial support to increase autonomy in persons with severe impairment. In the evaluation of such Ambient Assisted Living (AAL) solutions, the user perspective is essential to ensure the safety, prove the usability and demonstrate the effectiveness for the target user group. This work presents a systematic review of studies that evaluated robotic rollators with focus on the user perspective. The literature search was conducted in PubMed and IEEE Xplore. Twenty-eight studies were identified that met predefined inclusion criteria. There was a large heterogeneity in definitions of potential users, study population, study design, and assessment methods. We found major methodological shortcomings related to sample descriptions, sample sizes, assessment instruments, and statistical analyses of study results. Recommendations for future evaluation studies include: clear definition of target user group, adequate study subjects, and adequate user-focused assessment strategy with established, standardized and validated methods to allow comparability of study results. Assessment strategies may focus on specific robotic functionalities allowing an individually tailored assessment of innovative features to document their added value.**

## I. Introduction

The ability to move independently represents a hallmark of autonomous living [1] and quality of life [2]. However, motor, sensory or cognitive impairment restrict mobility in frail, older persons [3]. To overcome or compensate such impairments, in the field of Ambient Assisted Living (AAL), robotically augmented rollators with various robotic features and functionalities have been developed providing physical support, sensorial assistance, cognitive assistance, and/or health monitoring [4]. The development and evaluation of such high-tech devices is still a new, emerging research field which have been so far mainly driven by technical engineering goals. However, in addition to the technical perspective, which focused predominantly on the functional capability of devices, the user perspective including users' performance, experience, and physical demands with the robotic devices, is essential to ensure the safety, prove the usability and demonstrate the added value for the target user group, and should guide the development and evaluation of assistive devices [5]. However, the change from technical to user perspective may lead to specific methodological challenges including the study design and assessment strategies. To our knowledge, no systematic review on the evaluation of robotic rollators with focus on the user perspective has been published. Therefore, the objective of this systematic review was to summarize methods and results of studies which evaluated the interaction between users and robotic rollators, and to give recommendations for future evaluation studies.

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[2] M. Geravand is with the Institute of Automatic Control Engineering, Technische Universität München, Munich, Germany (e-mail: milad.geravand@tum.de)

[3] A. Peer is with the Bristol Robotics Laboratory, University of the West of England, Bristol, United Kingdom (e-mail: angelika.peer@brl.ac.uk).

## II. Methods

The literature search was conducted using the electronic databases PubMed and IEEE Explore. Initial search terms were compiled and iteratively refined by team members with expertise in the clinical and in the technical area. Search terms were adapted to the databases and comprised both controlled vocabulary (i.e. MeSH Terms, IEEE Terms) and keywords of relevance identified during searches. Manual searching was performed to identify additional studies by hand-searching reference lists of relevant articles and reviews and by reviewing key authors' own databases.

Titles and abstracts of retrieved references were screened if they met pre-specified inclusion criteria. Studies were searched with focus on evaluation or clinical results of an experiment, trail, or intervention in human beings with a robotic rollator (or wheeled walker) independent of type of outcome measurements. Single case reports were excluded. For the purpose of this review the term "robotic" includes the normal function of a rollator enhanced by additional physical, cognitive or sensorial robotic support while walking, also including STS transfers. The search was limited to articles in English language, and databases were searched until December 31st, 2014.

The study selection process was conducted following the methodology as suggested by the method guidelines of the Cochrane Collaboration [6]. After inclusion, data on definition of user group, study sample, study design, assessment methods, and study results were extracted for each study..

## III. Results

A total of 8,989 articles were identified through database searching, and another 79 were added by manual searching. After removing duplicates and screening title and abstracts, 235 were found to be related to the search topic. After reviewing full text and applying our inclusion criteria, we identified 28 studies published between 2001 and 2014 to be included in the review.

### A. User Group Definitions

For almost all robotic rollators, a target user group was mentioned; however, definition of potential users differed considerably in accuracy and explicitness. Most articles provided a generic description in broad terms (e.g. elderly people), defined users based on setting characteristics (e.g. persons in nursing and assisted living homes), or gave nonspecific impairment-/disease-related definitions (e.g. patients with mobility problems, post-stroke patients). Specific impairment-related definitions based on established, validated assessment methods (e.g. Functional Ambulation Classification, Walking Index for Spinal Cord Injury) were documented in only few articles.

### B. *Study Samples*

The mean sample size of studies providing precise information on number of subjects was 7.2 ± 4.3. Study samples differed substantially with respect to age, impairments, or diseases. Subjects' age ranged from 14 to 97 years. Half of the studies included subjects with motor, functional, cognitive, visual and/or neurological impairments. In the other half, a convenience (e.g. ordinary adult males), mixed (e.g. healthy subjects and subjects with motor/cognitive impairment) or setting-specific sample (e.g. residents of retirement facility) was used. In only few studies, subjects' motor-functional or cognitive impairment level was defined based on established and validated screening instruments or assessment methods (e.g. Mini-Mental State Examination, 4-meter walk test, Timed Up and Go). In a number of studies, subjects did not match with the predefined user group of the developed device.

### C. *Design of Studies*

Depending on study objectives, three different types of studies/experiments were performed:

(1) *Observational studies/experiments* which focused predominantly on the verification of technical capability and/or on the subjective user evaluation of robotic devices and which presented relevant information or data solely descriptively without providing any reference values.

(2) *Comparative studies/experiments* in which (a) robotic devices and conventional devices (e.g. folding walker, wheeled walker) or unassisted walking/STS transfers were compared; (b) different assistance levels (e.g. activated vs. non-activated obstacle avoidance), interface designs, or development stages of functionalities within the same robotic device were compared; (c) the user experience with the robotic device or the motion behavior of the robotic device was compared before and after/over a series of trials, and (d) in which outcomes of a newly developed robotic functionality and those of an external reference measurement was compared.

(3) *Interventional studies* in which some type of training opportunities with the robotic devices were offered to the subjects.

### D. *Statistical Analysis*

A statistical analysis of outcomes was included in only few studies identified in this review. In the vast majority of studies, results were presented using solely descriptive data.

### E. *Assessment Methods*

Assessment measures used in identified studies were distinguished into five categories:

(1) Established *clinical performance-based measures* (e.g. 4MWT, TUG) to assess subjects' functional ability to complete a requested task with or after the use of the robotic device mainly by simple quantitative outcomes (e.g. gait speed, walking distance, rating score).

(2) Self-designed performance-based measures (e.g. navigational tasks, walking/obstacle courses) specifically tailored to specific functionalities of the robotic device (e.g. guidance system, obstacle avoidance). Such *tailored assessment methods* predominantly used more technique-based and qualitative outcomes (e.g. path deviation, distance to obstacle).

(3) Assessment methods to evaluate subjects' *physical and physiological demands* during the use of the robotic devices (e.g. respirometry, electromyography, force measurements).

(4) *Technical evaluation measures* to assess the technical capability of the robotic device and its integrated functionalities. (we renounce more detailed information on these measures since they have very limited relevance for the user perspective)

(5) *Subjective evaluation measures* to assess the user experience with the robotic device (e.g. user comments, non-standardized surveys, structured questionnaires).

### F. *Study Results*

In *clinical performance-based measures*, subjects showed most frequently inferior user performance (i.e. gait speed, task completion time) with the motorized high-tech rollators when compared to conventional walkers. However, robot-assisted ambulation training was reported to result in improved gait and functional performance, compared to conventional ambulation training on parallel bars.

In *tailored assessment methods* covering technically advanced outcomes specifically adjusted to the specific functionality (walking distance, path deviation, distance to obstacles), study results suggest that activated high-tech functionalities (i.e. obstacle avoidance, guidance/navigational assistance) allow superior performance when compared to conventional devices or to the same robotic device with non-activated functionalities. In less specific outcomes such as walking time or walking speed, subjects seemed, however, to achieve superior performance with the non-motorized, low-tech devices.

Studies assessing subjects' *physical and physiological demands* with robotic devices showed heterogeneous results. Overall, the use of motorized high-tech devices seem to be not less physically or physiologically demanding than the use of low-tech devices.

Independent of the different assessment methods (i.e. user comments, structured questionnaires), results of *subjective evaluation measures* showed that robotic devices or specific robotic functionalities were generally positively perceived by the subjects. Only few device properties were negatively commented (e.g. bulkiness, portability, adaptability, full robot motion control mode) by the subjects.

## IV. DISCUSSION

The purpose of this systematic review was to summarize assessment strategies and results of evaluation studies on robotic rollators with focus on the user perspective. Identified studies showed large heterogeneity in definitions of potential users, study population, study design, and assessment methods. We found major methodological shortcomings related to insufficient sample descriptions and sample sizes, lack of appropriate, standardized and validated assessment instruments, and lack of statistical analysis of study results. No generic assessment strategy could be identified, while objectives of studies and study designs differed substantially. Consequently, it was not appropriate to conduct a meta-analysis.

## V. CONCLUSIONS

Apart from the heterogeneity of studies methodological deficits in most of the identified evaluation studies became apparent. Recommendations for future evaluation studies include: (1) clear definition of target user group by valid, impairment-based criteria; (2) adequate selection of study subjects representative of potential users; (3) selection of established, standardized, and validated assessment methods to allow comparison of study results; (4) specifically tailored assessment strategy focusing on specific robotic functionalities to document the added value of the innovative features; and (5) statistical analyses of study results. These recommendations given for robotic rollators may also apply in general for the development and evaluation of AAL systems with a focus on the user perspective.

## ACKNOWLEDGMENT

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# The Role of Culture and Gender in the Robotic Design Process*

B. Klein, S. Kortekamp, H. Roßberg, *Frankfurt University of Applied Sciences*

*Abstract*— **Technical aids and assistive technologies are not widespread due to a variety of factors. Acceptance is low because often the design is judged as stigmatizing, not fashionable enough or does not fit into individual, culturally shaped life styles. In the HORIZON 2020 I-Support project design thinking is utilized in order to analyze cultural impact factors for developing a robotic shower system for frail and disabled people.**

## I. Introduction

Acceptance of technical aids and assistive technologies is influenced by a variety of factors. It is widely acknowledged that the ease of use and perceived usefulness are essential key parameters [1]. However, they do not explain why for example personal alarm systems are not widely accepted although they are easy to use and contribute to more safety for independent living. A recent study on acceptance showed that gender culturally shaped life styles influence acceptance and usage of these technologies [2]. The very often found belief that a person is willing to use assistive devices in order to enable or enhance independence and quality of life, is not mirrored in the actual practice of individuals (Klein et al).

Designing assistive service robotic devices has to take into account culture, gender and age. In the European I-SUPPORT project a robotic shower system for (very) frail and disabled people will be developed from 2015 till 2018.

Utilizing design thinking can be a means to explore needs and possibly overcome gender and cultural issues such as objections to technology, especially robots.

## II. Methods

### A. Design Thinking in the Robotic Design Process

Design Thinking can be viewed as an attitude which enables a successful approach for the development of innovative products. Developing according to design thinking requires an empathic understanding of user needs and early product ideas, mockups, prototypes which are evaluated with users in several iterative processes [3, 4].

In the European I-SUPPORT project design thinking is implemented as it is seen as necessary in order to understand the complexity and the level of intimacy of the showering process. Objective of I-SUPPORT is to develop an intelligent robotic shower system in order to support primarily users who are very frail or suffer from functional loss in their personal hygiene. Alternatively, it might be also used in inpatient healthcare institutions. Developing such a system implies an empathic understanding of the needs and requirements of the primary user, i.e. the person who is (very) frail and/ or is suffering from functional loss. Also, it is critical to understand the tasks, needs and requirements from the perspective of the secondary user, i.e. care staff and professionals in the healthcare sector as well as the interests of relevant stakeholders. Therefore, a range of methods is utilized:

- Qualitative interviews with primary users (e.g. frail persons) and 15 secondary users (formal and informal cares) in order to understand the showering process with its pitfalls and in consideration of different perspectives (culture, gender, age, etc.). Also, they will be asked for feedback on first drafts and materials of the I-Support system
- Exchange and workshops with stakeholders and potential producers in order to get a feedback on the next developmental stage
- Focus groups with primary and secondary users as well as stakeholders and potential producers to get an early feedback on the first and second prototype
- Pilot studies with potential users in geriatric clinical environments to evaluate usability and acceptance .

### B. Health, Age and Gender

Anthropometric research shows that in the North of Europe people are taller than in Central Europe, also in South Europe people are smaller compared to Central Europe. This concerns men and women. In general women are smaller than men [5]. In the last decades the average body length increased with each new generation. Today, also the girth increases as a consequence of changed movement habits [6].

The transition from persons aged 65 – 80 years to the age group of over 80ies is characterized by an increase of health problems, functional loss and chronic diseases [7]. The risk increases for people with low educational background and fewer resources to compensate health problems [7]. Sensory (hearing, vision) and mobility impairments (climb stairways, walking a longer distance) are influenced by age. The percentage of persons needing a cane or walking frame increases exponential from 4% of the age groups 65-69 old, to 8% of 70-74, 15% of 75-79, and 34 of 80-85 year old [7].

**"**Gender refers to the socially constructed characteristics of women and men – such as norms, roles and relationships of and between groups of women and men. It varies from society to society and can be changed." [8]

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The following is an intermediate analysis of the interviews with 23 users and 12 experts at an early stage of the project. 13 of the users are female and 10 are male. Average mean of age is 69.8 years (SD= 11.1; range 49 to 90). Countries they originated were Germany, Turkey, Japan, Serbia, Czechoslovakia, Afghanistan. Religions they belonged to were Protestantism, Catholicism, Orthodoxism, Islam and Buddhism.

## III. FIRST RESULTS

Showering is a process which can be divided into 3 major steps:

1 Preparation for showering, which entails activities such as fetching the necessary utensils e.g. towel, clothes, soap, and shampoo etc. preparing the room: heating, chair etc. and moving/entering into the shower cabin.

2 Showering process which entails wetting with water, soaping and rinsing hair and body, as well as leaving the shower cabin

3 Follow-up phase which entails drying with towel and/or hair dryer, lotioning the body, dressing, cleaning the shower cabin and tidy up bathroom.

However, the different steps can be influenced by a variety of factors.

### A. *Personal Preferences*

Personal preferences do not develop independently but are also influenced by gender, age or culture. Most men (70%) take up to max. 10 minutes for their shower; more than 50% of women need 10 minutes and more. Putting on some lotion on the body after showering is mostly done by women.

In Japan, showering is a part of an enlarged cleaning process. Traditionally, Japanese persons clean themselves before taking the daily hot bath. Private showers often consist of a hose. In India, people might shower up to ten times due to climatic conditions. All persons with Islamic belief use kese for washing themselves.

### B. *Organizational and structural requirements*

From the view of the professional experts also other factors play a key issue in personal hygiene. Persons with Islamic beliefs prefer their family members to support personal hygiene. If they are willing to be supported by a carer, it has to be somebody with the same gender. For healthcare institutions it is sometimes difficult to fulfill these requirements due to the fact that approx. 80-85% of the healthcare workforce is women.

Following pictures demonstrate typical German bathroom showers. Often there is a bathtub equipped with a shower valve or alternatively the "typical" shower cabin which can be characterized by a high step into the shower and relatively narrowness so that it might be difficult to implement a robotic shower system.

Figure 1 Typical bath with shower valve and shower environment

## IV. DISCUSSION

First results demonstrate that a variety of factors have to be considered in the robotic design process. The Design Thinking method offers a variety of methods and tools, especially the participatory design and the inclusion of users and stakeholders in order to define requirements of the robotic artefact might contribute to innovative ideas to overcome structural hindrances and traditional ways and personal preferences.

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# ASBGo – Multimodal Smart Walker for rehabilitation assistance and clinical evaluation *

Maria Martins, Cristina P. Santos, *Member, IEEE*

*Abstract*— **This article presents a brief summary of the team work in the development of the ASBGo Smart Walker with the intent of helping patients with high disorders of balance, such as cerebellar ataxic patients. It also describes the first steps towards the proposal of a new treatment with the ASBGo with real, ataxic patients. It describes the walker and associated sensory systems; the implementation of four operating modes (autonomous, manual, safety and remote control) in the ASBGo and application of the developed gait and posture assessment tool into the rehabilitation of patients with ataxia.**

## I. Motivation and Scope

Locomotion is an important human faculty that affects an individual's life, bringing implications not only in social and personal development but also in the aspect of employment. Thus, it becomes necessary to find means and tools to improve or help to restore and increase the mobility of the affected people, so they can recover their independence. For that purpose walkers were designed to improve pathological gait, through the provision of a support base for the upper limbs that improves the balance of the individual and reduces the load on the lower limbs. However, a large number of walker owners experience problems related to use of a walker or to its design, and the number of accidents is increasing at a faster rate than the number of users. Therefore, smart walkers (SW) appeared to provide for a more stable gait and easy maneuverability, and became a clinical tool for gait evaluation, thus bringing more quality for the rehabilitation of its users and work of the physiotherapists.

## II. Overview of the Research

This article describes a new smart walker, ASBGo (Assistance and monitoring System Aid) that improves the stability of assisted gait of people with physical disabilities. Thus, four sensory subsystems were developed: (i) four operation modes that can be selected according with the rehabilitation purpose; (ii) a system that captures the relatives evolutions between the lower limbs of the user and the walker as well as the trunk, given us information related to gait pattern and stability for further clinical evaluation.

A smart walker is intended to be a device that can act as a versatile rehabilitation functional compensation. It should be adaptive considering the necessities of its user and its use should be safe. Patients present different necessities according to their intrinsic characteristics, their diseases and therapies. In order to help them, a smart walker should provide for different functionalities that adapt to user the needs. This project includes the implementation of four different operating modes (autonomous, manual, safety and remote control modes) that allow the physiotherapist to choose the most appropriate one for the type of difficulty of the patient. In addition, the design of the presented walker was planned for specifically help prescribed walker patients for gait therapy.

Besides these functionalities, the developed smart walker, ASBGo, will be turned into a measurement tool for evaluating the walker's user gait. The smart walker is integrated with sensory systems (active depth camera and accelerometer) that enable to evaluate, in real-time, the progress of the patient in terms of spatiotemporal and postural stability parameters. This information is then analyzed to follow the evolution of the patient and helps on deciding when the patient should leave the smart walker, to go to next stage of treatment.

Since the potential of using walking aids is promising and studies focusing on its use were not found, this project also includes the proposal of a new treatment with ASBGo, developed with the intent of helping patients with high disorders of balance, such as cerebellar ataxic patients (full description in [1]).

Thus, this article will be divided into three main goals: description of the ASBGo and associated sensory systems; implementation of four operating modes (autonomous, manual, safety and remote control) in the ASBGo and application of the developed gait and posture assessment tool into the rehabilitation of patients with ataxia.

## III. Methods

### A. *ASBGo Smart Walker*

The ASBGo walker (Fig. 1) has a mechanical structure that allows the installation of motors, sensors and other electronic components. ASBGo has four wheels and a supporting structure that partially supports the patient’s body weight Its front casters can freely rotate. Two motors drive its right and left rear wheels independently.

For rehabilitation purposes, the ASBGo provides adequate physical stability and safety that is required in early stages of treatments and is able to aid the progression of the patient, as the users become more independent to control the walker’s handling. The configuration of the handles can provide adequate stability levels and may also be used in man-machine interactions, such as detection of the user’s movement intentions [10]. Thus, the ASBGo walker design provides two types of grasping and support: forearm support

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with vertical handgrips, for users with extension problems on their arms; horizontal handgrips for users with shoulder problems.

The electronics and heavy components are installed in a lower level of the walker to improve the general stability of the ASBGo.

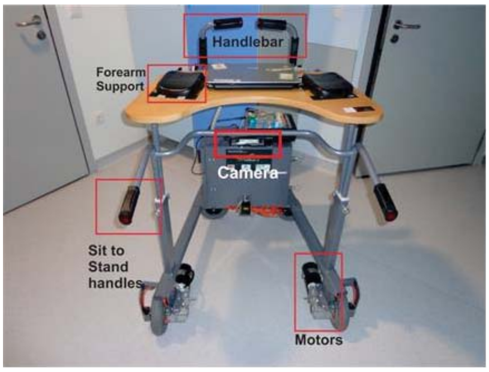


Figure 1. ASBGo walker.

An additional support base for the upper limbs is implemented with forearm and trunk support (this can be removed if not necessary for the patient) and is illustrated on Fig. 1. This support was developed with the aim of providing enough support for patients with high balance disorders. Also, two handles on the back of the walker were added to help the patient in sit-to-stand transfers. These latter handles were also added for the physiotherapist in case he wants to walk on the back of the patient, protecting him or correcting his movements.

The handlebar acts as an interface and is based on low cost electronics composed by potentiometers [10]. These sensors will be the interface for the user to command the walkers' movement. To guide the ASBGo, a minimum strength is required from the upper limbs. For safety measures, force sensors were installed in the forearm supports, to stop the walker in time in case of a backward fall.

The walker also has 9 sonar sensors distributed in a three layer configuration to maximize the detection area (see configuration in Figure 2). A low ring of 6 sonars mounted forward-oriented detects the majority of ordinary obstacles, like people, walls or other low obstacles.

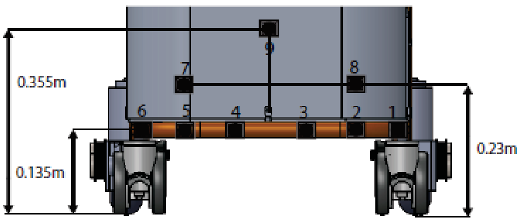


Figure 2. Frontal view of ASBGo. Conguration of the sonar sensors (Low ring, High ring and Stairs sonar).

High obstacles such as tables or shelves are more difficult to detect than ordinary obstacles since their support to ground can be undetected by the forward oriented sonars. They can lie in front of the walker and provoke a collision. Thus, a high ring of 2 sonars pointing upwards with an orientation of 30º is mounted to detect high obstacles. These 8 sonars are meant specifically for obstacle avoidance. An extra sonar pointing downwards with an orientation of 30º is mounted on the walker to detect stairs. This sonar does not contribute to the obstacle avoidance task, but stops the walker when changes in the ground, such as stairs or holes are detected. Sonars have a beam width of θ = 30º, a range of 1,5m and a dead zone of 0,15m. Low ring sonars are mounted such that any obstacle at a distance of 0,19m from the walker is detected.

## B. Four Operating modes

In this project four operating modes were implemented: autonomous mode, manual mode, safety mode and remote control mode. These are explained in detail in [15].

The autonomous mode allows the user or the physiotherapist to set the desired position to which the smart walker should autonomously move while avoiding any obstacles in the environment. This was implemented using a technique of local navigation, called Nonlinear Dynamical Systems Approach [16].

The manual mode is characterized by the smart walker's movement under the guidance of commands defined on the handlebar. As the movement is defined by the patient, this mode is only recommended for patients with minimum visual capacities and/or cognitive, that have sufficient motor skills on the upper limbs.

The safety mode is characterized by a warning system that alerts the presence of obstacles in front of the walker as well as the monitoring of users fall risk. However, the smart walker's movement is controlled by commands set by the patient, as in manual mode.

Finally, remote control mode has been developed in order to allow the physiotherapist to control the orientation and velocity of the SW. Physiotherapist have here the opportunity to examine the behavior of the patients and possible gait reactions and corrections from the patient to different directions and velocities given by him.

## C. Clinical, gait and postural stability assessment

Other important requirement of a SW is the possibility of doing clinical evaluation during walker-assisted gait. This is the first step to assess the evolution of a patient during rehabilitation and to identify his needs and difficulties. Advances in robotics made it possible to integrate a gait analysis tool on a walker to enrich the existing rehabilitation tests with new sets of objective gait parameters.

Postural disorders in cerebellar ataxia can be evaluated both qualitatively and quantitatively. Qualitative evaluations are based on a precise assessment of clinical symptoms. Also, certain generic evaluations of balance disorders and ordinal scales evaluating the various components of ataxia can be used to quantify the severity of postural disorders in cerebellar ataxia. The generic evaluations of balance include the Berg Balance Scale (BBS), time standing tests, like the Time Up and Go (TUG) and posturography [6]. Generic gait assessments are also useful and include basic spatiotemporal gait parameters (stride length, stance duration, etc) [6].

In this study, explained in detail in [1, 17], (a) balance was evaluated with BBS and TUG (b) spatiotemporal gait parameters (stance and swing duration, stride and step time and length, double support duration, step width and cadence) were measured with an active depth sensor technique [11] and (c) postural stability (trunk range motion, sway length, center of mass displacement and acceleration) was evaluated with accelerometers placed at the trunk.

## IV. Operating Modes

The main goal of SW is the rehabilitation and functional compensation of patients with mobility and balance problems. Since patients can present different types of difficulties and disorders associated with locomotion, the SW has to adapt to these limitations. Thus, through four operating modes is possible to adapt the operation of ASBGo depending on the difficulties of the patient and provide for a safer, comfortable and efficient rehabilitation.

### *A. Autonomous Mode*

Autonomous mode allows the user or physiotherapist to define the desired position coordinates while guiding the SW in the environment. In the case of locomotion recovery in the hospital, the physiotherapist initially defines the possible different targets to be achieved and the walker starts the process. The locomotion recovery starts and continues without any intervention of the patient and without the need for outside help, such as physiotherapists or family. Simultaneously, the autonomous mode allows monitoring the patient's behaviour, so that the physiotherapist can assess his progress in recovery. To turn the ASBGo autonomous is necessary to integrate a module to ensure obstacle avoidance and movement to the target.

In [8], the authors presented an obstacle avoidance technique for SW based on Nonlinear Dynamical Systems [18] approach (DSA) and in [19] the stability of DSA for obstacle avoidance was addressed. In this presentation, real experiments on a lab and a hospital environment will be presented.

### *B. Manual Mode*

The Manual mode is characterized by the movement of the ASBGo under the guidance of commands defined on the handlebar. In this way, the patient is responsible for supervising the ASBGo movement while not getting any feedback controller to avoid the obstacles in front of the SW. As the movement is defined by the patient, this mode is only recommended for patients with visual and cognitive capabilities, as well as motor coordination and strength to manipulate the handlebar. To implement this mode of operation it was necessary the development and installation of a handlebar [10]. The handlebar is shown in Figure 4. To acquire user's commands, the proposed handlebar has two potentiometers to detect the forward and turning directions. The control system will use these forces for forward and turning-speed control. With this system, the user can intuitively manipulate the smart walker at his own pace. If the user pushes or forces to a side the handgrips, the smart walker moves forward or turns accordingly. The smart walker interprets these two basic motions and controls the motors speed and direction, accordingly. It is not allowed to walk backwards.

The pre-processing of both potentiometers is presented in detail in [10]. A fuzzy control strategy classifies the signals sent by the potentiometers and transforms them into motor inputs, in such way that the SW drives the motors according to the user's commands [11].

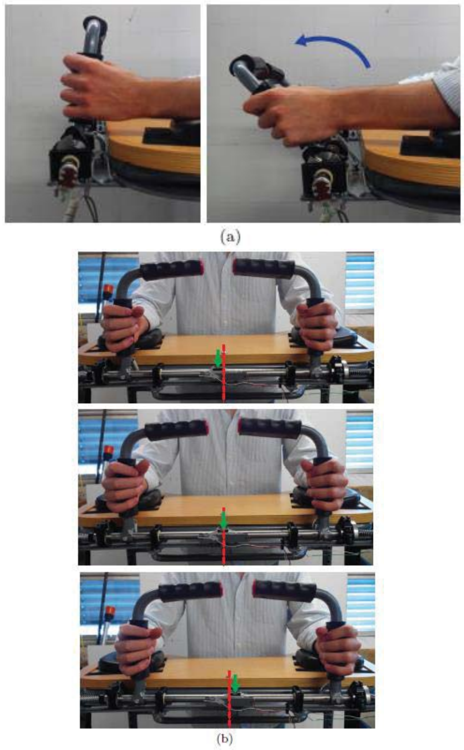


Figure 3. Schematic configuration of the two movements of the handlebar: linear and rotary potentiometer.

### *C. Safety Mode*

A very important aspect of smart walker is to provide for security/safety such that the user feels safe while controlling the smart walker. Otherwise, the user will not use this device and resort to others devices such as the wheelchairs. On the ASBGo safety mode, the patient guides the smart walker and a warning system is activated if a dangerous situation is detected. Both the environment and the patient are monitored. The monitoring of the environment is characterized by a warning system that alerts the presence of obstacles in front of the smart walker. Additionally, an audible alarm system, with different sound frequencies associated to these different distances, may also be triggered if the patient is visually impaired.

In addition to warn the patient of possible obstacles, it is necessary to monitor the risk of fall of the smart walker user. Thus, the detection of user's falls while walking with the smart walker was one of the aims integrated in this device [21].

### *D. Remote Control Mode*

The remote control mode was developed to allow the physiotherapist to monitor the user behavior and control the velocity and orientation of the smart walker accordingly.

## V. Clinical Assessment

### A. Berg Balance Scale (BBS) and Timed up and Go TUG)

BBS was developed to measure balance among older people with impairment in balance function by assessing the performance of functional tasks [13]. It is a valid instrument used for evaluation of the effectiveness of interventions and for quantitative descriptions of function in clinical practice and research. The BBS has been evaluated in several reliability studies [4]. The test takes 15–20 minutes and comprises a set of 14 simple balance related tasks, ranging from standing up from a sitting position, to standing on one foot. The degree of success in achieving each task is given a score of zero (unable) to four (independent), and the final measure is the sum of all of the scores (56) [13].

The Timed Up and Go test (TUG) is a simple test used to assess a person's mobility and requires both static and dynamic balance [2]. It uses the time that a person takes to rise from a chair, walk three meters, turn around, walk back to the chair, and sit down. During the test, the person is expected to wear their regular footwear and use any mobility aids that they would normally require.

### B. Spatiotemporal Gait Parameters

Clinical evaluation during walker-assisted gait is the first step to assess the evolution of a patient during rehabilitation and to identify his needs and difficulties. Advances in robotics made it possible to integrate a gait analysis tool on a walker to enrich the existing rehabilitation tests with new sets of objective gait parameters.

In [11], the team of this study developed a legs detection method to estimate legs position during assisted walking. Then, gait events were identified in order to calculate the corresponding spatiotemporal parameters. The following spatiotemporal parameters can be calculated with such method for each leg: step and stride length (STP and STR), stride width (WIDTH), gait cycle (GC), cadence (CAD), velocity (VEL), stance and swing phase duration (STAD and SWD), double support duration (DS) and step time (STPT). Through the video records and by knowing the distance walked by the subjects an average error of ±3cm in the measures of distance and ±0.1 s were obtained. This error is acceptable for gait evaluation.

With these spatiotemporal parameters, it is possible to calculate stride-to-stride variability. This is a strong indicator of risk of fall. Other important indicator is the symmetry of parameters. This can tell us if the coordination between legs is improving or not. Thus, these two indicators will be calculated.

### C. Postural Stability

To assess postural stability, an accelerometer is located near to the center of mass (COM) as suggested in [12]. In this work, an accelerometer is placed at the level of the sacrum and COM displacement parameters were based in [14]. However, the evaluation performed in [14] was done for the standing position and not during walk. So, in [12] the team of this study validated the use of such evaluation in assisted ambulation, concluding that it was suitable to infer postural stability parameters in such situation (assisted ambulation). Therefore, the same system was used on this study and tests were performed in two situations: standing position (3 conditions: comfortable stance, right and left semi-tandem stance) as shown in Fig. 2, and while the patient was walking with ASBGo. These two situations will help to infer the evolution of the static and dynamic postural stability of the patient as well as his risk of falling.

The calculated postural stability parameters are the root mean square of anterior-posterior (AP), horizontal (HOR) and medio-lateral (ML) accelerations (RMSAP, RMSHOR and RMSML), range of motion of AP and ML directions (ROMAP and ROMML) and sway length (SLML, SLAP and SLHOR). In addition, the COM trajectory in AP and ML directions was also acquired. The variability of these parameters will be also calculated to infer risk of fall.

Figure 4. Test Conditions: Comfortable stance (CS) on the left and semi-tandem stance (SS) on the right [13].

### D. Statistical Analysis

For each parameter the mean and standard deviation was calculated. Then, One-way ANOVA was performed for each parameter (spatiotemporal parameters and postural stability parameters) in order to verify if there were significant differences through the progression of the patient. Pearson correlation was also calculated between the set of spatiotemporal parameters as well as between the set of postural stability parameters for each condition in order to verify if the parameters show correlated behaviors between the weekly measures. To verify if the variability of parameters significantly decreased between Week 0 and Week 4, Levene's test (right tail) will be performed. The level of significance was set to $p<0.05$.

## VI. Results and Discussion

### A. Operating Modes

#### 1) Autonomous Mode

After implementing DSA in simulation [18], real experiments were performed in a lab environment. Before testing with patients it is fundamental to verify how the system behaves in a real environment. Thus, in order to be faithful to a Hospital environment, three different experiments were performed, with both static and dynamic obstacles. Finally, the ASBGo was brought to the hospital for the final tests with patients. In [22] it is possible to watch some seconds of the autonomous mode with a patient.

#### 2) Manual Mode

The manual mode is characterized by controlling the movement of the ASBGo under guidance of commands defined on the handlebar by the user. In this mode, the patient is responsible for taking the decisions regarding the ASBGo movement (Fig. 5).

The combination of the positioning of the two potentiometers allows the patient to move the ASBGo in the environment. Through fuzzy control system [10] the ASBGo acquires a smooth and safe motion for the patient who controls it.

In [22] it is possible to watch some seconds of the manual mode with a patient.

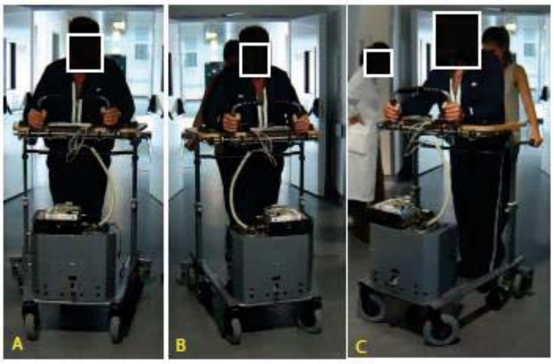


Figure 5. Patient with ataxic gait controlling the movement of the ASBGo through the handlebar. A: Walking forward; B: turning left; C: turning right.

*3) Safety Mode*

The safety mode implemented in ASBGo is characterized by a warning system that alerts in case obstacles in front of the ASBGo or a fall of the user are detected.

In this operation mode, the patient controls the ASBGo motion, like in the manual mode, but a warning system is triggered when a dangerous situation is detected like an obstacle or the risk of fall.

*4) Remote Control Mode*

The remote control mode was implemented in order to allow the physiotherapist to monitor and control the ASBGo speed and orientation. In this mode, the physiotherapist has the possibility to analyse the behaviour, compensations and reactions of the patient against sudden changes in speed and orientations given by the physiotherapist. Moreover, it is possible for the patient to concentrate in the correction of his gait pattern. This mode is controlled through a graphic interface.

## B. Clinical Assessment

*1) Participants*

Three ataxic patients were selected to validate the manual and remote control mode of the ASBGo inserted in their rehabilitation program. Herein are detailed results for one patient. In the presentation the three case studies will be discussed.

Male patient, 64 years-old. Right ataxic hemiparesis with brachial prevalence, in acute phase, aetiology is still under investigation. The diagnostic possibility of a neurobrucelose was placed and appropriate antibiotic therapy was started, adequate to this nosological entity. Inform consent was signed by the patient. The study was approved by Braga Hospital Ethical Committee.

*2) Examination/Evaluation*

Before beginning the gait training with the SW, all baseline data was collected. Patient was evaluated weekly by application of BBS and static and dynamic tests where information was gathered by several sensors integrated in the device, which allowed characterizing the assisted gait and stability.

The static and dynamic tests consisted on 3 conditions: (1) static stance, (2) static semi-tandem stance and (3) walk with the smart walker. In each condition several parameters were acquired. Conditions (1) and (2) consisted on 3 trials with 1 minute of duration each and in condition (3) the patient had to walk 20 meters. In this presentation will be presented 3 case studies.

*3) Intervention*

For three weeks, the patient trained, 5 days a week, during 30 min, his gait with the smart walker. Since he had enough cognitive capacity to guide the walker, such task was handled by him. Velocity was set by the physiotherapist. Such velocity was increased when the patient felt comfortable to do so. In addition to the smart walker therapy, he performed tonus training.

*A. BBS Results*

In fig. 6 it is shown some of the BBS tasks performed by the patient. On table I, one can see that the patient presented on its initial stage a score of 6 points, which means that he had a high risk of falling and was only capable of using a wheelchair to move [13]. At this stage, he needed two subjects alongside him in order to help him to stand, to sit and to walk. In one week of training with ASBGo, its score increased to 23 points, passing him to the category of medium risk to fall [13]. At the end of the $3^{rd}$ week he reached 38 points being capable of walking with crutches independently and walk without walking aids with supervision. At this stage, the clinician decided that the patient was capable of leaving the smart walker and continue its treatment with two crutches. At the end of his treatment, he presented a BBS score of 42 points, walking with one crutch or none.

Figure 6. Some tasks of Berg Balance Scale performed by the ataxic patient.

TABLE I. BBS RESULTS

| Week | 0 º | 1º | 2º | 3º | 5º |
|---|---|---|---|---|---|
| **BBS** | 6 | 23 | 35 | 38 | 42 |

TABLE II. PARAMETERS CALCULATED IN EACH EVALUATION. 'R' AND 'L' ON EACH CONDITION STANDS FOR RIGH AND LEFT LEG, RESPECTIVELY.

| Postural Stability Parameters | | ROMAP (mm) | ROMML (mm) | SLAP (mm) | SLML (mm) | SLHOR (mm) | RMSAP (g) | RMSML (g) | RMSHOR (g) |
|---|---|---|---|---|---|---|---|---|---|
| **Week 0** | **CS** | 2.19±1.44 | 6.71±0.42 | 12.71±2.30 | 4.93±0.94 | 13.63±5.65 | 0.26±0.33 | 0.19±0.10 | 0.33±0.12 |
| | **SSL** | 3.93±0.37 | 6.57±0.46 | 17.70±3.45 | 7.72±0.34 | 19.32±4.35 | 0.45±0.38 | 0.24±0.12 | 0.51±0.09 |
| | **SSR** | 2.10±1.12 | 7.29±0.70 | 13.69±3.46 | 6.70±0.25 | 15.24±3.54 | 0.30±0.12 | 0.24±0.19 | 0.39±0.17 |
| | **ASBGo** | 14.11±1.95 | 19.20±0.92 | 56.86±4.52 | 43.59±2.32 | 71.65±7.34 | 0.48±0.11 | 0.33±0.17 | 0.58±0.14 |
| **Week 1** | **CS** | 1.34±1.01 | 4.24±0.41 | 6.98±1.21 | 1.46±0.88 | 7.13±4.23 | 0.12±0.05 | 0.02±0.00 | 0.12±0.09 |
| | **SSL** | 1.09±0.27 | 5.70±0.36 | 7.44±1.03 | 1.83±0.32 | 7.67±4.12 | 0.14±0.13 | 0.08±0.01 | 0.16±0.05 |
| | **SSR** | 1.80±0.97 | 2.60±0.69 | 4.20±1.33 | 2.88±0.24 | 5.09±4.23 | 0.06±0.07 | 0.07±0.02 | 0.10±0.02 |
| | **ASBGo** | 3.63±1.45 | 12.84±0.83 | 12.76±1.04 | 16.28±1.32 | 28.23±5.23 | 0.45±0.07 | 0.28±0.01 | 0.53±0.11 |
| **Week 2** | **CS** | 0.76±0.04 | 2.16±0.31 | 4.50±1.11 | 1.67±0.78 | 4.80±3.21 | 0.13±0.10 | 0.05±0.00 | 0.14±0.07 |
| | **SSL** | 0.91±0.05 | 5.43±0.23 | 6.63±1.01 | 3.66±0.31 | 7.58±4.10 | 0.30±0.09 | 0.09±0.02 | 0.31±0.05 |
| | **SSR** | 0.86±0.09 | 2.83±0.56 | 2.83±0.56 | 2.30±0.21 | 4.65±3.87 | 0.09±0.07 | 0.09±0.01 | 0.13±0.01 |
| | **ASBGo** | 3.10±1.01 | 5.78±0.78 | 26.39±0.95 | 10.62±1.01 | 14.45±2.48 | 0.81±0.05 | 0.33±0.10 | 0.88±0.10 |
| **Week 3** | **CS** | 0.29±0.02 | 2.20±0.28 | 3.95±0.96 | 0.39±0.71 | 3.97±1.85 | 0.08±0.09 | 0.01±0.00 | 0.08±0.03 |
| | **SSL** | 1.32±0.05 | 3.52±0.12 | 5.62±0.89 | 2.77±0.21 | 5.68±1.73 | 0.07±0.05 | 0.04±0.00 | 0.09±0.01 |
| | **SSR** | 0.73±0.04 | 1.18±0.10 | 2.84±0.35 | 1.14±0.10 | 4.98±0.23 | 0.12±0.04 | 0.07±0.02 | 0.14±0.01 |
| | **ASBGo** | 1.91±1.00 | 3.62±0.51 | 10.24±0.87 | 10.04±0.62 | 10.96±1.35 | 0.20±0.05 | 0.11±0.05 | 0.33±0.05 |
| **Week 5** | **CS** | 1.08±0.02 | 0.83±0.13 | 6.23±0.58 | 4.58±0.34 | 7.74±0.98 | 0.21±0.23 | 0.02±0.05 | 0.21±0.07 |
| | **SSL** | 1.20±0.04 | 2.64±0.15 | 8.42±0.80 | 5.24±0.25 | 9.92±1.54 | 0.17±0.12 | 0.10±0.02 | 0.20±0.05 |
| | **SSR** | 0.59±0.01 | 0.95±0.13 | 4.17±0.32 | 5.96±0.20 | 7.28±0.32 | 0.23±0.09 | 0.09±0.02 | 0.25±0.04 |

TABLE III. GAIT PARAMETERS CALCULATED IN EACH EVALUATION. 'R' AND 'L' ON EACH PARAMETER STANDS FOR RIGH AND LEFT LEG, RESPECTIVELY. VALUES ARE PRESENTED AS MEAN±STANDARD DEVIATION (SD). SYMMETRY (SI) IS ALSO PRESENTED.

| Gait Parameters | Week 0 | | Week 1 | | Week 2 | | Week 3 | | Week 5* | | P-value |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Mean±SD | SI | Mean±SD | SI | Mean±SD | SI | Mean±SD | SI | Mean±SD | SI | |
| **STPR (cm)** | 25.57±4.65 | 0.214 | 24.02±3.52 | -0,227 | 24.05±1.96 | -0.196 | 26.06±1.66 | -0.033 | 90.00±2.33 | -0.021 | 0.050 |
| **STPL (cm)** | 31.94±6.45 | | 31.06±3.20 | | 29.95±4.13 | | 26.95±3.13 | | 92.00±2.35 | | 0.003 |
| **STRR (cm)** | 57.63±8.38 | 0.001 | 54.96±5.49 | -0.002 | 54.03±4.41 | 0.001 | 56.03±3.31 | -0.005 | 46.43±3.43 | -0,012 | 0.210 |
| **STRL (cm)** | 57.52±8.46 | | 55.09±5.94 | | 54.00±4.61 | | 56.32±3.61 | | 47.00±3.00 | | 0.230 |
| **GCR (s)** | 3.10±0.67 | 0.139 | 1.85±0.20 | -0.016 | 1.82±0.20 | 0.000 | 1.23±0.21 | 0.016 | 1.23±0.19 | 0.000 | 0.000 |
| **GCL (s)** | 2.72±1.40 | | 1.88±0.16 | | 1.82±0.11 | | 1.21±0.18 | | 1.23±0.17 | | 0.000 |
| **STPTR (s)** | 1.49±0.43 | -0.039 | 0.98±0.13 | 0.101 | 0.91±0.16 | -0.022 | 0.88±0.16 | -0.022 | 0.65±0.06 | 0,182 | 0.000 |
| **STPTL (s)** | 1.55±0.56 | | 0.89±0.18 | | 0.93±0.15 | | 0.90±0.06 | | 0.55±0.03 | | 0.000 |
| **WIDTH (cm)** | 12.94±1.62 | - | 15.66±1.66 | - | 15.35±1.65 | - | 15.10±0.32 | - | 14.00±0.23 | - | 0.000 |
| **STADR (%)** | 65.38±9.18 | -0.045 | 63.53±6.29 | 0.033 | 60.57±3.80 | -0.037 | 60.43±4.00 | 0.004 | 54.43±2.75 | -0.005 | 0.000 |
| **STADL (%)** | 68.47±9.66 | | 61.45±6.10 | | 62.93±3.72 | | 60.18±2.72 | | 54.74±1.63 | | 0.000 |
| **SWDR (%)** | 34.61±9.18 | 0.098 | 36.46±6.29 | -0.054 | 39.42±3.80 | 0.064 | 39.56±4.00 | -0.006 | 45.56±2.75 | 0.006 | 0.000 |
| **SWDL (%)** | 31.52±9.66 | | 38.54±6.10 | | 37.06±3.72 | | 39.81±2.72 | | 45.25±1.63 | | 0.000 |
| **DSR (%)** | 27.30±13.66 | -0.146 | 19.64±4.74 | -0.129 | 16.38±4.68 | -0.041 | 20.93±3.12 | 0.096 | 23.96±5.01 | 0.110 | 0.000 |
| **DSL(%)** | 31.98±18.60 | | 22.56±5.88 | | 17.70±4.12 | | 19.09±2.86 | | 21.59±2.63 | | 0.000 |
| **CAD (step/min)** | 38.00 | - | 60.00 | - | 68.00 | - | 70.00 | - | 91.00 | - | - |
| **VEL (m/s)** | 0.10 | - | 0.30 | - | 0.40 | - | 0.50 | - | 1.00 | - | - |

* walking without assistance.

*B. Spatiotemporal parameters Results*

Table II presents the gait parameter' results of the four evaluations with the ASBGo using LRF. Week 5 results were acquired before the patient is discharged from the Hospital.

It is possible to verify that all parameters follow a good evolution for the improvement of the patient's gait pattern. Stride (STR) length of both legs increase from week to week. However this increase is not significant (p>0.05) because ASBGo influences this parameter. Since velocity (VEL) is pre-defined by the physiotherapist and the device has dimension limits, this may force the patient to decrease its stride length and maintain it constant. Step length (STP) increases significantly (p<0.05) through time. However, this parameter can be also influenced by ASBGo dimensions. Gait cycle (GC) and Step Time (STPT) significantly (p<0.05) decrease since the velocity of gait increased. Looking at the values of step width (WIDTH), it can be seen that this parameter increases significantly (p<0.05) its base of support, learning how to walk with a more stable pattern. This patient presented at the beginning a very narrow step width, which was instructed to be extended. Thus, the increased in WIDTH that is verified on Table II is a very satisfying result. Observing the gait phases, stance duration (STAD), swing duration (SWD) and double support duration (DS) one can see that the patient improves its pattern by presenting values closed to healthy normal subjects [15], i.e. STAD and SWD approximately 60% and 40%, respectively, and DS approximately 20%. The progression of these values is also significant (p<0.05).

Stride-to-stride variability is an indicator of fall risk and stability of gait [13]. By performing Levene's Test, it can be verified that from week to week the variability of all parameters decrease significantly (p<0.05), meaning that the patient presents an increase stability and decreased risk of falling. Other indicator that the patient is improving its pattern it is Symmetry (SI). The absolute symmetry was calculated and the negative/positive values indicate that the left/right leg is responsible for the asymmetry of the parameter. Since most parameters present negative asymmetry (Table II), the left leg is the one responsible for the asymmetric gait. Looking for the evolution of SI, one can see that SI of all parameters tend to zero week to week.

Testing for correlations between parameters, it was only found a strong correlation (>0.7) between step and stride length parameters. Thus, only these parameters show a dependent behavior on the weekly measures. All the other parameters present an independent behavior between each other.

*4) Spatiotemporal parameters Results*

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*5) Postural Stability Results*

In fig. 7 the studied static and dynamic conditions are illustrated with the patient in study.

In Table III, all mean values of parameters present a significant decrease (p<0.05) through all conditions. Also, the variability decreased significantly (p<0.05) for all conditions through the weeks. This result is very satisfying since it means that the patient progressed week to week, gaining more and more stability to walk, decreasing his risk of falling.

COM displacement was acquired for all conditions (CS, SSL, SSR and ASBGo) and for better visualization the outside margins of the COM trajectory were fit into an ellipse, as illustrated on fig. 8. It is noteworthy that in all cases the ellipses decreased their radius. This result comes to reaffirm the gain of stability presented by the patient through its rehabilitation.


Figure 7. Postural stability evaluation tests with the patient in study:A- Comfortable stance (CS); B- Right semi-tandem stance (SSR); C- Left semi-tandem stance (SSL); D – Walk with ASBGo.

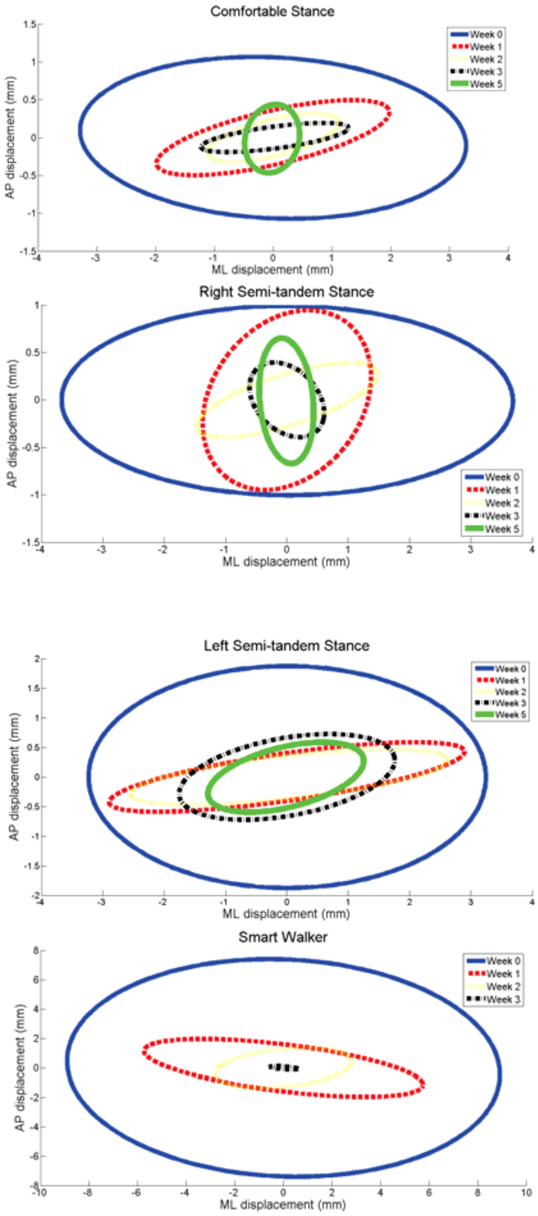


Figure 8. ML and AP COM displacement in comfortable stance, right and left semi-tandem stance and walking with smart walker ASBGo.

Results from these case studies suggest that the SW gait training is a promising intervention for improving gait in patients with cerebellar ataxia pathology.

### 1) *General Discussion*

The patient initially presented with an enlarged base of orthostatic position, unstable, unbalanced to right and a BERG scale of 6. On the first week, he did tone training and gait training with the walker for 10 minutes at a speed of 0.1 m/s. Three weeks later he exhibited good balance in orthostatic position and a BBS of 38. He was doing gait training with the walker for 30 minutes at a speed of 0.5 m/s. This velocity of the walker was predefined by the physiotherapist and it was very important for his gait training. This type of patient tends to have a very inconsistent velocity, presenting many accelerations and decelerations. The constant velocity obliges them to maintain the consistency of their gait. Despite not being the maximum velocity that he was capable of walking, the physiotherapist wanted to force him to control his velocity. Before discharging him, he could walk and climb stairs with vigilance at 0.9 m/s. There is no reported information about the recovery timeline of such type of patients.

In the presentation other patients will be discussed.

## VII. Conclusion

The work herein described synthesizes the team latest work and will enable a technological breakthrough in the field of human pathological gait assistance, by providing more functional compensations with higher safety. The motivation is that this will contribute towards better rehabilitation purposes by promoting ambulatory daily exercises and thus extend users' independent living.

In the long run, it will serve not only as a measure of a treatment outcome, but also as a useful tool in planning ongoing care for various gait disorders.

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# Mobility Assistance Robots Controlled by Servo Brakes

Yasuhisa Hirata

## I. Introduction

As societies age and experience a shortage of people for nursing care, handicapped people, including the elderly and blind, find it increasingly necessary to be self-supporting. However, many such people suffer from injuries, poor eyesight, or a general lack of muscular strength, and need the support of other people in daily activities. In recent years, we expect to utilize robot systems not only in industrial fields, but also in homes, offices and hospitals in cooperation with humans. Many robot systems have been researched to realize a physical support for human being.

This article especially focuses on mobility assistance robots such as walker-type walking support system and wheelchair, which work on the basis of the physical interaction between the robot systems and the user. Many intelligent systems based on robot technologies consist of servo motors and sensors such as force/torque and ultrasonic sensors. Information from many types of sensors controls the servo motors. By appropriately controlling the servo motors, these intelligent systems provide many functions, such as variable motion, obstacle avoidance, and navigation; thus, they provide a maneuverable system.

In this article, we consider a passive intelligent systems, which are not only simple structure and safe but also offers many functions similar to those found in active systems. We develop a passive intelligent walker called the RT Walker and a cycling wheelchair, which are controlled by servo brakes.

## II. Passive Robotics

For practical use of intelligent systems in the real world, we need to consider two main points: achieving high performance and user safety. Most conventional intelligent systems have servo motors that are controlled based on sensory information from sensors such as force/torque sensor, laser range finder and ultrasonic sensor. The high performance of intelligent systems is realized in the form of functions such as power assistance, collision avoidance, navigation, and variable motion.

However, if we cannot appropriately control the servo motors, they can move unintentionally and might be dangerous for a human being. In particular, in Japan, legislation must be formulated for using them in a living environment. In addition, active intelligent systems tend to be heavy and complex because they require servo motors, reduction gears, sensors, a controller, and rechargeable batteries. Batteries present a significant problem for long-term use because servo motors require a lot of electricity.

Goswami et al. proposed the concept of passive robotics [1], in which a system moves passively based on external force/moment without the use of actuators, and used a passive wrist comprising springs, hydraulic cylinders, and dampers. The passive wrist responds to an applied force by computing a particular motion and changing the physical parameters of the components to realize the desired motion. Peshkin et al. also developed an object handling system referred to as Cobot [2] consisting of a caster and a servo motor for steering the caster based on passive robotics.

Dissipative haptic devices using either brakes or clutches have been developed to dissipate or redirect energy in the required direction [3], [4]. In this article we also introduce the other passive motion support systems controlled by servo brakes developed by us. These passive systems are intrinsically safe because they cannot move unintentionally under a driving force. The passive robotics will prove useful in many types of intelligent systems for supporting the human motion based on the physical interaction between the systems and humans.

## III. Passive Intelligent Walker [5]

In this article, we pay special attention to the braking system, and propose a new passive intelligent walker (RT Walker), which uses servo brake control. The servo brakes can navigate the RT Walker, and its maneuverability can change based on environmental information or the difficulties and conditions faced by the user. The developed RT Walker is shown in Fig.1. This prototype consists of a support frame, two passive casters, two wheels with servo brakes (referred to as powder brakes), a laser range finder, tilt angle sensors, and a controller. The part of the rear wheel with the powder brake is shown in Fig.1; the brake torque is transferred directly to the axle. The brakes change the torque almost in proportion to the input current.

RT Walker is lightweight because its structure is relatively simple compared to active intelligent walkers, and it needs little electricity to operate the servo brakes. The driving force of the RT Walker is the actual force/moment applied by the user, and therefore, he/she can move it passively without using the force/torque sensor. By changing the torque of the two rear wheels appropriately and independently, we can control the motion of the RT Walker, which receives environmental information from its laser range finder and tilt angle sensors. Based on this information, the RT Walker can realize the collision avoidance, gravity compensation, and other functions.

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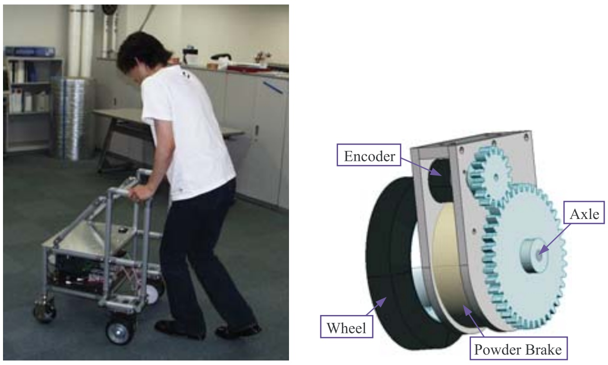


(a) Prototype of RT Walker (b) Wheel with Servo Brake

Fig. 1. Passive Intelligent Walker [5]


(a) Commercial Product (b) Developed System

Fig. 2. Cycling Wheelchair [6]

## IV. Cycling Wheelchair Controlled by Regenerative Brakes [6]

This section introduces a new wheelchair named "Cycling Wheelchair" shown in Fig. 2(a). The cycling wheelchair moves via a pedal-driven system similar to that of a bicycle. Typical wheelchair users have severe impairment of the lower extremities; thus, it is natural to assume that they cannot pedal a cycling wheelchair. However, the pedal can be easily rotated by wheelchair-bound patients with even slight leg mobility. Such a wheelchair would especially benefit hemiplegia patients, who can generate a large pedaling force with a healthy leg. We note that the disabled leg responds smoothly to the pedaling motion of the healthy leg without disturbing the pedaling motion.

Having learned to self-maneuver the cycling wheelchair after short-term training, patients wish to participate in the outdoor environment. However, the outdoor environment presents problems that are not encountered in hospital environments. Although the patients can generate a large pedaling force, their lower-limb disability prevents them from achieving precise velocity control of the pedaling motion. On downward slopes, patients cannot properly apply the braking force to the pedal. This inability to slow the wheelchair presents a dangerous situation. For safety reasons, the cycling wheelchair is equipped with a bicycle-like handbrake. Although users can halt the wheelchair by gripping the handbrake lever, they may panic in dangerous situations, consequently losing control of both pedaling force and handbrake.

On the other hand, because a large pedaling force is required for uphill travel, a single healthy leg may generate insufficient power for climbing a slope unassisted. If users stop on the upslope, gravity may prevent them from restarting the wheelchair. Other barriers in the outdoor environment are steps and obstacles. Falling from steps presents an especially perilous threat.

In this study, we propose a new cycling wheelchair supplemented with several assistive functions for use in the outdoor environment. Assistive functions are realized by a new control method using DC servo motors as a regenerative brake system. The braking control is safer than active control systems such as power assistance; moreover, the regenerative brake can charge a battery during the braking control process.

In special situations such as steep uphill climbing, the DC servo motors generate an active force that compensates for insufficient user force by extracting energy from the battery, which has been charged under braking control. Even under active force generation by the DC servo motors, the wheelchair motion is controlled passively by the applied force of the user. Such passive behavior has been shown to increase the safety of robotic systems using actuators.

## V. Conclusions and Future Works

In this article, we introduced a concept of passive robotics and proposed a passive intelligent walker and a passive cycling wheelchair controlled by the servo brakes. Realizing the many functions of these systems is challenging, because we control mainly the brakes. We proposed motion control algorithms considering the brake constraints and realized the several functions, which change the apparent dynamics of the passive systems to adapt to the states of the user and the environment.

In future work, we will consider the human adaptive and environmentally-adaptive motion control algorithms in more detail to improve the maneuverability of the passive systems.

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# Evaluating and Optimizing Gait Enhancing Technologies Using a Virtual Reality Environment*

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***Abstract:*** **The Center for Assistive, Rehabilitation, & Robotics Technologies (CARRT) at the University of South Florida is a multidisciplinary center that integrates research, education and service for the advancement of assistive and rehabilitation robotics technologies. This includes technologies that assess and improve mobility including for those with amputations, traumatic injuries, or stroke. Current research studies include using the state of the art CAREN (Computer Assisted Rehabilitation ENvironment) virtual reality system to assess outcome measures for prosthetics, to evaluate prosthetic technologies and assess related outcome technologies, to compare wearable sensors, to design rehabilitation devices, and to improve rehabilitation and training strategies. Amputation, stroke, and aging can lead to asymmetric and inefficient gait patterns that often lead to falls. This paper describes various methods used to evaluate and optimize gait-enhancing techniques using a virtual reality environment with preliminary results from several current projects.**

## I. Introduction

The use of virtual reality (VR) enables researchers to assess a subject's gait in an environment that more realistically mimics everyday life compared to a typical gait laboratory. VR also allows for the introduction of visual, auditory, vestibular, and tactile inputs into a testing environment in a controlled and systematic way. An integrated VR environment capable of creating realistic scenarios allows researchers to investigate and optimize gait-enhancing technologies in a scientific way. The CAREN virtual reality system, which includes a spilt belt treadmill, dynamic platform and motion tracking capabilities, is currently used to test, assess and improve the gait of prosthesis users and crutch users by providing controlled virtual environments and real-time, continuous gait tracking.

## II. Background

### A. Lower Limb Prosthetics

In the United States, there are more than 2 million people who have lost a limb and that number is expected to double by 2050 [1]. On average the healthcare costs are $500,000 per person over a 5-year period following limb loss, and additional prosthesis costs over the 5-year period can reach $450,000 [1]. The prevalence and expenses involved in lower limb amputation necessitates specific and effective tools and outcome measures for prosthesis prescription, evaluation, and rehabilitation. Evidence-based and effective prosthesis prescription can lead to improved rehabilitation, quality of life and reduced healthcare costs.

Lower limb amputees are classified by the Medicare Functional Classification Levels (MFCL) on a five level scale of K0-K4, where K0 represents an amputee who cannot walk and oppositely, K4 represents an amputee whose capabilities exceed basic ambulation. These K levels [2] are based on "past history, current condition, status of residual limb, desire to ambulate, clinical assessment of potential based on experience and reasonable expectations of a prosthetist and physician. Records must document current functional capabilities and expected functional potential" [3]. Insurance companies use this scale to determine which types of prosthetic components will be covered at each level [4].

One of the main differences between functional levels is the ability to walk and navigate obstacles, particularly at varying speeds. The use of this scale is particularly evident in the prescription and coverage of microprocessor knees, where a K3 amputee can qualify for a microprocessor knee due to their ability to vary their cadence; however, a K1-K2 does not qualify because of a fixed cadence [4]. Stevens, among others, suggests that the current method of determining candidacy for a microprocessor knee based on variable cadence needs to be revised because the stumble recovery, obstacle navigation and increased stability features could also benefit amputees at the K2 level [5]. The AAOP State of the Science Conference identified the need to consider revising the method of determining microprocessor knee candidacy [6].

According to Passero, the prescription of prosthetic components is "fundamentally based on the projected or otherwise documented functional level and weight of the patient"; however, "the prescription criteria for both populations [upper and lower limb amputees] are dependent on factors beyond anatomic involvement or the level of deficiency" [3]. Gremeaux et al. also emphasized the absence of a universally accepted or evidence-based method for defining a patient's functional level and the appropriate prosthetic prescription [7]. While there are many outcome measures available, there is not a gold standard that is objective, scientific, and evidence-based [8-11], no guidelines exist on when or which tool to use for a specific purpose [9], and there is a lack of consensus on which tool is best for determining function and prescription [7, 11].

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Performance-based measures to evaluate lower limb amputees and their prosthesis use include the following: Amputee Mobility Predictor (AMP) [12], Comprehensive High-Activity Mobility Predictor (CHAMP) [13], Timed Up and Go (TUG) test [14], six minute walk test (6MWT) [15], two minute walk test (2MWT) [16], 10 meter walk test (10mWT), Berg Balance Scale (BBS) [17], L-Test of Functional Mobility [18], Hill Assessment Index (HAI) [19], Stair Assessment Index (SAI), Lateral Reach Test, Four Square Step Test, and Symmetry in External Work (SEW) [20]. The 2MWT and 6 MWT are frequently used, but only test walking on level ground. The CAREN virtual reality system with motion tracking is currently being used to create patient-centric assessment selection algorithms based performance measures described for clinicians to determine the optimal lower limb prosthetic prescription and function. In conjunction with the VR simulator, prosthetic simulators can be used to quickly test concepts on unimpaired individuals prior to testing on amputees. Such prosthetic simulators are used to evaluate an upper limb prosthetic simulator for kayak hand testing [21] and the optimal location of a prosthetic knee [22].

### B. *Assistive Walking Devices*

In the United States, there are approximately six million people who use crutches for everyday mobility, and the number of individuals using assistive devices for mobility is growing more rapidly than the general population [23, 24]. However, this does not include partially-impaired persons using crutches as a supplement to other assistive mobility devices such as wheelchairs, scooters, or lower limb prosthetics [25]. While a crutch user may opt out of crutch walking to predominately use a wheelchair, the use of crutches encourages upright posture, remaining active, and more independence (maneuverability), all of which are highly beneficial for long-term health [26, 27]. Crutches are often used for people who cannot use their legs to support their weight for reasons ranging from short-term injuries (<6 months) to lifelong chronic disabilities.

Short-term injuries that may require crutches include acute conditions such as foot and leg sprains, fractures, tendon tears, hip and knee replacements, or other lower extremity injuries. Short-term crutch users mainly use a swing-through crutch gait where the user ambulates by pivoting over both crutches simultaneously. While this type of crutch walking pattern is the fastest crutch gait, it is the most energy consuming [28, 29]. Fatigue is one of the top hindrances in using crutches over longer distances, partially because crutch walking on level ground inherently carries a metabolic penalty 1.5 to 6 times that of normal walking[28].

Individuals with chronic impairments rely on their crutches for everyday ambulation, for example, lower limb amputation, spinal bifeda, cerebral palsy, muscular dystrophy, spinal cord injury, post-polio syndrome, osteoarthritis, or multiple sclerosis. Crutch ambulation for long-term lower-limb-impaired individuals offers partial preservation of lower-extremity function [27] . Many long-term crutch users rely on a more stable 4-point crutch walking style. When ambulating with this type of crutch gait, the crutch user always maintains three points of ground contact. They repeat a step pattern of alternating leg step, then crutch step. Stability is a prime concern in chronic crutch users, especially the progression down a decline, which can be dangerous. The loss of control during crutch walking down a decline can lead to unstable dynamics and falling in some cases. As a result, users descend slowly, diagonally, or avoid declines altogether because of a fear of falling [30, 31].

## III. The CAREN Virtual Reality System

### A. *Hardware*

The CAREN system (Computer Assisted Rehabilitation ENvironment) is a versatile, multisensory system for clinical analysis, rehabilitation, evaluation and registration of the human balance system (Figure 1). By means of unique software, MOTEK Medical integrates both existing and new technologies into research and medical solutions for orthopedic, neurological and rehabilitation use. The use of virtual reality (VR) enables researchers to assess the subject's behavior and includes sensory inputs like visual, auditory, vestibular and tactile. Inputs may be isolated or combined. The real-time feedback system registers and responds faster than human perception. The CAREN system is a unique integrated-reality environment capable of creating the highly realistic situation where researchers can investigate new ways and methods of encouraging patients. Based on the available sensor information, custom rehabilitation behaviors can be defined, utilizing the optimal treatment program.

### B. *Software*

The CAREN system's D-Flow software allows the multiple components to be combined into one real-time device. The user's actions are defined as input and the various CAREN components are defined as outputs. The software interface is modular in design with inputs and outputs going from module to module through connections. Each module has a user interface for its parameters to be altered.

Gait software is available from Motek Medical including the Human Body Model (HBM), Gait Real-time Analysis Interactive Lab (GRAIL), and Gait Offline Analysis Tool (GOAT). The CAREN System with Vicon motion tracking has the capabilities to collect spatiotemporal gait parameters such as stride length, mean walking speed, stance and swing time, kinematic parameters such as knee flexion angle, trunk tilt, ankle pronation, and kinetic parameters that include hip, knee and ankle moments continuously in a controlled simulated environment.

The HBM, a musculo-skeletal model, allows for both visualization and calculation of muscle forces, joint angles, moments and powers in real-time during CAREN sessions. The subject measurements, marker and force plate data are input into the model, and inverse dynamics are used to calculate the biomechanical outputs. The HBM (Figure 2) can be displayed on the screen to represent the patient in the virtual reality environment and as muscles are activated, the


Figure 1. The CAREN system

muscles will light up and change colors depending on the amount of force produced. GRAIL is gait analysis tool that provides real-time gait parameters and feedback to the patient and clinician, which allows for immediate adjustments to gait and balance during the training sessions. The GOAT provides a clinical gait report following sessions; including average gait parameters, standard deviations and graphs, as well as a comparison between the right and left sides, and to a set of normative data.

## IV. Assessing AMPUTEE GAIT

### *A. Evaluating Outcome Measures for Lower Limb Prostheses*

In a previous study conducted at USF's typical motion capture laboratory, the C-Leg and the Genium knee prostheses were compared on ramps and stairs instrumented with two force plates. This study showed that the Genium knee improves knee kinematics closer to non-amputee values as compared to C-Leg. While comparisons such as these are useful, the ultimate utility is limited. That is, we attempted to analyze our data to provide some psychometric analysis of the hill assessment index. We were able to assess reliability of the instrument [19]. Conversely, we were unable to compare step length from our motion analysis data. That is because subjects were targeting the force plates and altering their stepping pattern and thus confounding our attempts to conduct criterion validity analyses. Because the CAREN system has a kinetic instrumented treadmill that can tilt in the sagittal plane, this situation will be greatly improved and enable the validation analysis not possible with a conventional, static force plate instrumented motion analysis laboratory.

An initial testing protocol was approved by the University of South Florida's Institutional Review Board to collect data with the CAREN system while non-amputees and amputees walk on a treadmill in the mountain road scene at a self-selected speed on level ground, up-hill and downhill, side-hill on the intact side, side-hill on the prosthesis side. Preliminary data from two non-amputees has been collected and analyzed. Gait trials were collected for walking on level ground, 5 and 10 degrees uphill and downhill, and a 5-degree side hill.

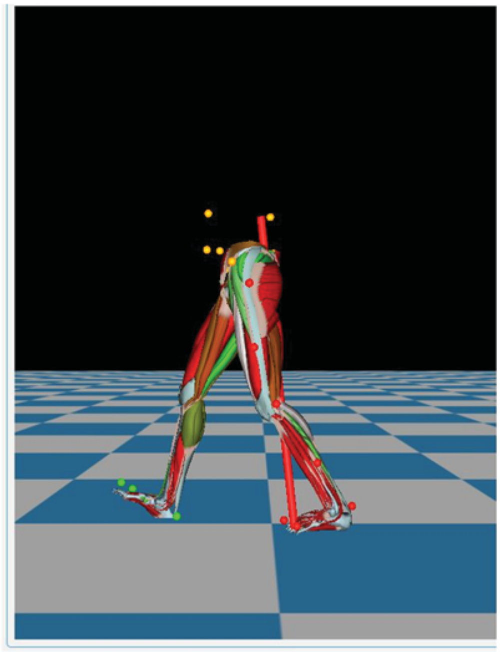

Figure 2. The Human Body Model (HBM) that can be displayed on the CAREN system screen

The kinematic analysis at each elevation, including the mean minimum and maximum angles and standard deviation for the five subjects, is presented below in Table 1. As would be expected the values differ at each elevation; however the +/- cross slopes are relatively similar as these were healthy subjects with no apparent gait asymmetries. A comparison amongst the elevations showed the maximum knee flexion occurred with decline gait, whereas the maximum hip and ankle flexion angles occurred with incline gait. The differences between the maximum at each elevation were approximately 5° for knee and ankle flexion; however, the difference in maximum hip flexion was about 15° between incline and decline. Knee, hip and ankle flexion at initial contact and throughout the stance phase were also significantly greater for incline gait. Figure 3 shows the average ankle dorsiflexion and plantar flexion of subjects walking on the CAREN system simulating various elevations. This analysis is consistent with other literature. Similar data from prosthetic users can be used to evaluate and prescribe lower limb prostheses.

This preliminary work will lead to the evaluation of existing outcome measures using the CAREN virtual reality system with motion tracking and create patient-centric assessment selection algorithms for clinicians to determine the optimal lower limb prosthetic prescription and function. The 6MWT, HAI, SEW and PEW will be the first conventional prosthetic outcome measures that will be

| Kinematics | Elevation | Min. Angle (Degrees) | Max. Angle (Degrees) | Std. Dev. (Degrees) |
|---|---|---|---|---|
| *Knee Flexion/Extension* | Level | 1.1 | 58.5 | 19.1 |
| | Incline | 3.9 | 56.5 | 15.9 |
| | Decline | 2.6 | 60.8 | 18.0 |
| | + Cross Slope | 3.3 | 57.9 | 18.1 |
| | - Cross Slope | 2.7 | 57.0 | 18.0 |
| *Hip Flexion/Extension* | Level | -6.3 | 33.5 | 14.1 |
| | Incline | -5.9 | 45.0 | 17.8 |
| | Decline | -4.7 | 29.9 | 12.5 |
| | + Cross Slope | -6.8 | 33.8 | 14.3 |
| | - Cross Slope | -6.3 | 33.7 | 14.6 |
| *Ankle Dorsi/Plantar Flexion* | Level | -7.5 | 21.0 | 7.4 |
| | Incline | -3.8 | 24.5 | 7.4 |
| | Decline | -3.3 | 22.7 | 7.2 |
| | + Cross Slope | -6.0 | 21.4 | 7.2 |
| | - Cross Slope | -6.0 | 20.8 | 7.1 |

Table 1. Kinematic analysis of five healthy subject walking on the CAREN system are various elevations

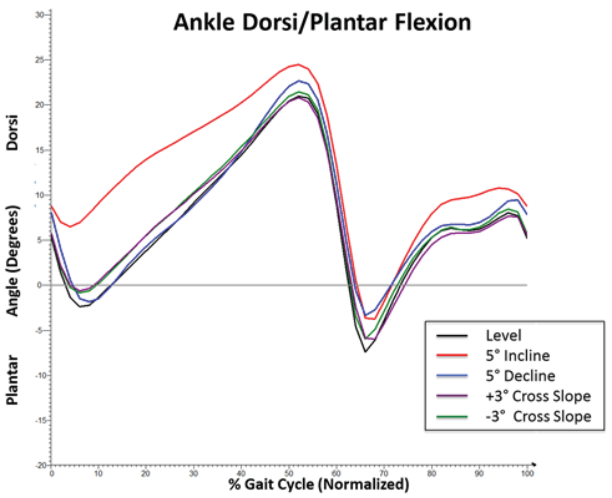


Figure 3. The average (n=5) ankle angles of subjects while walking on the CAREN system simulating level, uphill, downhill and side slope.

simulated and tested on the CAREN system. Based on the CAREN system's ability to provide continuous gait analysis, the ability to alter the visual and other sensory stimuli, the determination of key outcome measures needed to evaluate and classify lower limb amputees and prosthetic components will be completed. A testing protocol will be implemented for psychometric (i.e. reliability, repeatability, validity, sensitivity) analysis of outcome measures. An algorithm will be developed to improve the implementation of outcome measures for optimized amputee care.

## *B. Lower Limb Impairment Simulators*

Wearing a prosthesis affects gait in several ways, such as changing the passive dynamics of the prosthetic leg compared to the intact leg, changing the amount of propulsive force from each leg, and changing the stiffness of the joints. Each of these changes causes some asymmetric alteration in the gait. To understand how each of these factors affects the gait, we use a prosthetic simulator. The prosthesis simulator [22, 32] functions similar to existing passive prostheses, but fits over an intact knee. The difference is that non-amputees wearing the prosthesis simulator will have an extra mass from their shank that protrudes behind them. Similar dynamics with the large extra mass can be realized by shifting the moment of inertia of the prosthetic shank.

The prosthetic simulator was used in one set of experiments to examine the effect of prosthetic knee location on gait patterns. When wearing a transfemoral prosthesis, the mass and strength of the two legs are not equal, and there are fewer biomechanical reasons to keep the prosthetic knee location the same as the intact knee. The hypothesis is that moving the prosthetic knee location can beneficially affect the gait by balancing the motions and forces. The hypothesis is justified based on tests with a passive dynamic walker model that shows a prosthesis 40% lighter than the intact leg with a knee location moved down the leg by 15% can have symmetric step lengths [33] .

The experiments, described in detail by Ramakrishnan[22], had individuals walk on the prosthetic simulator with the prosthetic knee at different heights. These initial results, shown in Figure 4, show that the step length and swing time are more symmetric for lower (i.e., closer to ground) knees and worse as the knee approaches the contralateral knee location. This demonstrates that lower knees may be better in certain cases, but the mass distribution of the prosthetic leg is distinctly different in this case since the entire existing leg and the prosthetic simulator mass are affecting the gait.

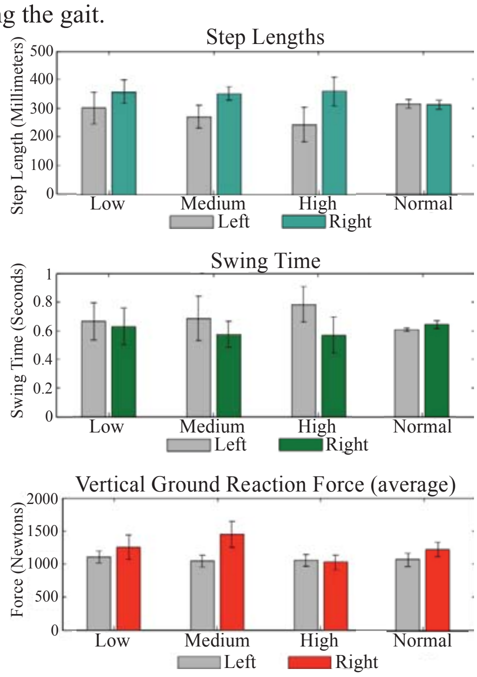


Figure 4. Results from walking on the prosthesis simulator (data adapted from Ramakrishnan, [22]. Low is 7 inches (19%) below standard knee height; medium is 5 (14%), high is 3 (8%), and normal has no simulator.

## V. EVALUATION OF CRUTCH DESIGN

The CAREN system was also used to evaluate new crutch tips that interface with the ground to provide assistance. The kinetic crutch tip (KCT) [34] uses a specially designed curve based on a kinetic shape [35] that converts the downward force from walking into an assistance force that helps to propel the user forward. One way to think about this assistance is that it moves the equilibrium point of a crutch from being straight up to being at an angle, so that the crutch will seemingly rotate against gravity (see Figure 5).

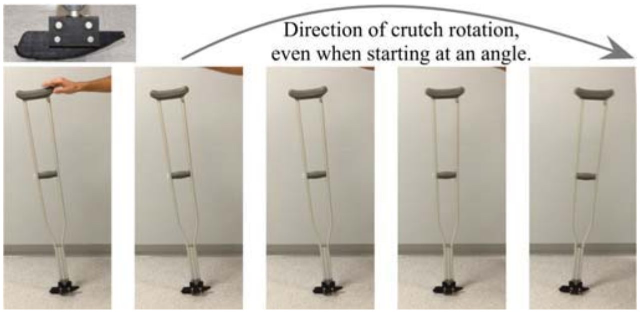


Figure 5. Crutch motion shown over one second. The Kinetic Crutch Tip changes the equilibrium point so that the user does not have to push off as hard to swing over the peak of the crutch, thus using less energy.

Moving the crutch equilibrium point provides an assistance force, which reduces the effort needed and hence reduces the fatigue and stress-related pain, which are two of the most common issues associated with crutch walking. The study by Capecci et al. [34] used the CAREN system to examine the forces and motion while walking on two different KCTs and compared the gait patterns to walking on standard crutch tips. They found that the horizontal ground reaction forces that were resisting forward motion were reduced by up to 74% compared to using a standard crutch tip. They also found that the peak vertical force of the heel strike was reduced by up to 27% using a different KCT. Future work on the crutch tips will examine different shapes and how the assistance can benefit gait when walking up and down hills (example shown in Figure 6).

Figure 6. Future experiments will use the CAREN to examine how the Kinetic Crutch Tip can assist a user to walk up and down slopes.

## VI. FUTURE DIRECTION

Quantitative assessments of gait enhancing technologies are necessary to properly evaluate and optimize them. The state of the art CAREN virtual reality system offers a repeatable systematic framework providing a quantitative way to aid researchers in rehabilitation and gait augmenting technology. To continue making scientific advances in gait rehabilitation that are repeatable and to make comparisons between studies easier, more standards should be established with consistent benchmarks across studies. Some benchmarks have been proposed [36], but the related scientific and industry communities need to jointly be behind them to make them effective.

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# User-Oriented Human-Robot Interaction for an Intelligent Walking Assistant Robotic Device

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***Abstract*— During the past decade, robotic technology has evolved considerably towards the development of cognitive robotic systems that enable close interaction with humans. Application fields of such novel robotic technologies are now wide spreading covering a variety of human assistance functionalities, aiming in particular at supporting the needs of human beings experiencing various forms of mobility or cognitive impairments. Mobility impairments are prevalent in the elderly population and constitute one of the main causes related to difficulties in performing Activities of Daily Living (ADLs) and consequent reduction of quality of life. This paper reports current research work related to the control of an intelligent robotic rollator aiming to provide user-adaptive and context-aware walking assistance. To achieve such targets, a large spectrum of multimodal sensory processing and interactive control modules need to be developed and seamlessly integrated, that can, on one side track and analyse human motions and actions, in order to detect pathological situations and estimate user needs, while predicting at the same time the user (short-term or long-range) intentions in order to adapt robot control actions and supportive behaviours accordingly. User-oriented human-robot interaction and control refers to the functionalities that couple the motions, the actions and, in more general terms, the behaviours of the assistive robotic device to the user in a *non-physical interaction* context.**

**In this context, this paper presents current advances in two directions, focusing towards the development of: 1) a user monitoring system that can enable tracking, analysis and classification of human gait patterns, based on non-intrusive laser rangefinder data, and 2) a control system that can support a 'user-following' behaviour; that is, enable the robotic rollator to follow and comply to the walking characteristics of the user without any physical interaction (i.e. without any force being applied on the handles of the Rollator) and remain in close vicinity to the user in case of need. This paper summarizes the theoretical framework and presents current experimental results obtained using real data both from patients (elderly subjects with mild to moderate walking impairments) and normal subjects. Results are promising demonstrating that such a framework can be used efficiently and effectively to provide user-adapted mobility assistance that can enhance the functionality of such robotic devices.**

## I. INTRODUCTION

Elder care constitutes a major issue for modern societies, as the elderly population constantly increases [1]. Mobility problems are common in seniors. As people age they have to cope with instability and lower walking speed [2]. It is well known that mobility impairments constitute a key factor impeding many activities of daily living important to independent living, having a strong impact in productive life, independence, physical exercise, and self-esteem [3], [4]. Most people with mobility issues, patients or elders, have to use walkers in their everyday activities and they need the constant supervision of a carer. The social and economic significance of solving these issue should not be underestimated. Robotics seems to fit naturally to the role of assistance since it can incorporate features such as posture support and stability enhancement, walking assistance, navigation and cognitive assistance in indoor and outdoor environments, health monitoring etc.

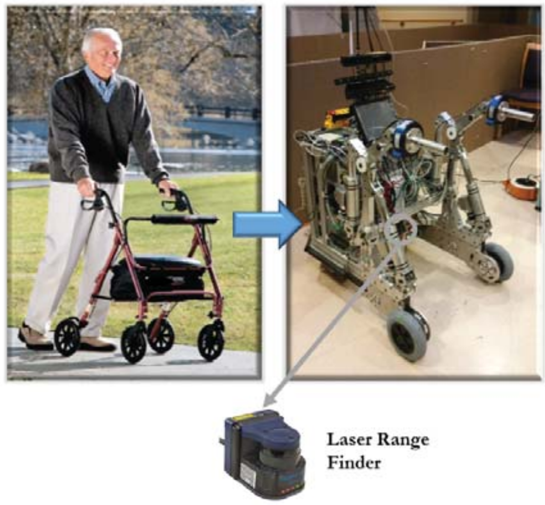


Fig. 1: Left: Typical passive assistive device for elderly. Right: The robotic platform based on the rollator prototype equipped with a Hokuyo Laser Sensor aiming to record user's gait data.

This paper reports research work conducted in the frames of an EU funded research project MOBOT, aiming to develop an intelligent robotic rollator aiming to provide user-adaptive and context-aware walking assistance (see Fig. 1). The main motivation behind this work derives from our vision of developing and advancing robotic technologies enabling the development and deployment of cognitive assistive devices that can monitor and understand specific forms of human walking activities in their workspace, in order to deduce the particular needs of a user regarding mobility and ambulation. The ultimate goal is to provide context-aware support [5],

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and intuitive, user-adapted assistance to users experiencing mild to moderate mobility and/or cognitive impairments in domestic environments. To achieve such targets, a large spectrum of multimodal sensory processing and interactive control modules need to be developed and seamlessly integrated, that can, on one side track and analyse human motions and actions, in order to detect pathological situations and estimate user needs, while predicting at the same time the user (short-term or long-range) intentions in order to adapt robot control actions and supportive behaviours accordingly. User-oriented human-robot interaction and control refers to the functionalities that couple the motions, the actions and, in more general terms, the behaviours of the assistive robotic device to the user in a *non-physical interaction* context.

In this paper, we summarise current research work, focusing on recent advances and challenges in two directions:

1) First of all, we address the challenge of developing a reliable pathological walking assessment system, that can operate on-line and in real-time enabling the robotic assistive device to continuously monitor and analyse the gait characteristics of the user in order to recognise walking patterns that can be classified as pathological requiring specific attention and handling by the system. The proposed system uses an onboard laser rangefinder sensor to detect and track user legs (a non-intrusive solution that does not interfere with human motion). A hidden Markov model (HMM) approach is used to perform statistical modeling of human gait. This paper presents the results of this gait modeling framework in terms of segmenting the gait cycle and recognising different gait phases, which can be subsequently used to extract gait parameters. This paper presents preliminary gait characterisation results for five patients, from a full-scale experimental study conducted at the premises of the Bethanien Hospital - Geriatric Centre of the University of Heidelberg, at the frames of the EU-funded FP7 research project MOBOT.

2) Secondly, we focus on the development of a control system that can support a 'user-following' behaviour; that is, enable the robotic rollator to follow and comply to the walking characteristics of the user without any physical interaction (i.e. without any force being applied on the handles of the Rollator) and remain in close vicinity to the user in case of need. This paper summarizes the theoretical framework and presents current experimental results obtained using real data both from patients (elderly subjects with mild to moderate walking impairments) and normal subjects. Results are promising demonstrating that such a framework can be used efficiently and effectively to provide user-adapted mobility assistance that can enhance the functionality of such robotic devices.

This paper summarizes the theoretical framework and presents current experimental results obtained using real data both from patients (elderly subjects with mild to moderate walking impairments) and normal subjects. With respect to gait analysis and assessment, as opposed to most of the literature available on the topic, the approach presented in this paper is completely non-intrusive based on the use of a typical non-wearable device. Instead of using complex


Fig. 2: Internal gait phases of human normal gait cycle.

models and motion tracking approaches that require expensive or bulky sensors and recording devices that interfere with human motion, the measured data used in this work is provided by a standard laser rangefinder sensor mounted on the prototype robotic rollator platform. In this paper, we perform an initial assessment of an HMM-based methodology used for the statistical modeling and classification of human gait patterns and for the extraction of clinically-relevant gait parameters.

This paper also summarizes the methodological framework enabling a user front-following behaviour for the robotic rollator. The current methodology implements a kinematic human-robot interaction control approach, essentially regulating a virtual pushing behavior. Experiments with real users have shown that even though this control behavior is successful, it inserts a cognitive load on the users who try to steer the robot on the optimal path they would have taken under normal conditions. As a result, the users deviate from their normal gait pattern in their effort to control the robot. Current research focuses on the development of a shared control user-assistance behaviour. Our approach considers user intent recognition by introducing the concept of dynamic undecidability, and employs a dynamic window method for local kinodynamic planning.

The experimental results presented in this paper are promising, demonstrating that such a framework can be used efficiently and effectively to provide user-adapted mobility assistance that can enhance the functionality of such robotic devices. The ultimate objective of this work is to design a reliable pathological walking assessment system (that embodies several walking morphologies, allowing inclusion of new patients with different mobility pathologies) and incorporate this tracking and monitoring system in a context-aware robot control framework enabling a cognitive mobility assistance robotic device to provide user-adaptive walking support actions and intuitive assistive behaviours.

The paper is organised as follows. Section II describes the proposed HMM-based gait analysis and characterisation framework, while Section III summarises the user front-following methodology adopted in current experiments. Section IV describes the experimental results achieved regarding both the gait analysis and the user-following control modules, while Section V presents conclusions and summarises future research work directions.

## II. HMM-BASED GAIT ANALYSIS

For gait recognition purposes we have used Hidden Markov models (HMMs). An HMM has well suited statistical properties, and it is able to capture the temporal state-transition nature of gait. In our previous work, we have proposed and analyzed extensively the properties of an HMM system and its applications for modelling normal human gait [6], as well as for pathological gait recognition [7]. The proposed model uses a seven-state representation that follows the typical definition of stance and swing phase events for normal human gait, which are depicted in Fig. 2.

This paper focuses on performing an initial assessment of this framework in terms of extracting clinically-relevant gait parameters that could be used for the characterisation and classification of specific pathological walking patterns. Gait Analysis literature uses specific gait parameters for the quantification of each gait cycle, commonly used for medical diagnosis, [8], [9]. In this work, we are using two temporal parameters: a. ***stride time***: the duration of each gait cycle, b. ***swing time***: the swing phase duration in a gait cycle, and, one spatial parameter: c. ***stride length***, i.e. the distance travelled by both feet in a gait cycle. The rest of this section summarises the methodological background of the proposed HMM framework for gait analysis and characterisation.

### A. User's legs Detection and Tracking

The raw laser data are processed by the detection and tracking system. Each time frame this system estimates the position and velocity of the user's legs with respect to the robotic platform motion. Thus, we mainly utilize K-means clustering and Kalman Filtering (KF) for the estimation of the central positions and velocities of the left and right leg of the user along the axes, [7].

Every time instant, a background extraction of the raw laser data is performed for deleting outliers and then a simple method for grouping laser points based on experimental thresholds is applied. When we end up with two groups, we perform the K-means clustering algorithm, in order to assign each laser group the left/right leg label. Circle Fitting is then used for computing the legs' centers. Those centers are the observation vector that enters a constant acceleration KF. The KF tracks the central positions of the limbs by stochastically estimating their position and velocity. We seed the next detection frame with the prior information of the predicted legs' position and variability. When one leg is occluded by the other while turning, we have a false detection case and we do not use the corresponding laser information for the observation vector. To overcome such situations, we only apply the prediction step of the KF, as we do not observe abrupt changes of the legs' velocity frame-by-frame. The estimated positions and velocities are the features used in the HMM recognition system.

### B. HMM Gait Cycle Recognition

The hidden states of the HMM are defined by the seven gait phases, Fig. 2. As observables, we utilize several quantities that represent the motion of the subjects' legs, (relative position w.r.t. the laser, velocities, etc.), which are estimated using sequential signals from a laser sensor. The state and observations at time $t$ are denoted as $s_t$ and $O_t$, respectively. The seven states at time $t = 1,2,...,T$, where $T$ is the total time, are expressed by the value of the (hidden) variable $s_t = i$, for $i = 1,\ldots,7$, where $1 \equiv IC/TW$, $2 \equiv LR$, $3 \equiv MS$, $4 \equiv TS$, $5 \equiv PW$, $6 \equiv IW$, and $7 \equiv MW$. The observations at time $t$, are represented by the vector $O_t = [o_t^1 \ldots o_t^k]^T$, for $k = 1,\ldots,9$, where $o_t^1 \equiv x^R$, $o_t^2 \equiv y^R$, $o_t^3 \equiv x^L$, $o_t^4 \equiv y^L$, $o_t^5 \equiv \upsilon_x^R$, $o_t^6 \equiv \upsilon_y^R$, $o_t^7 \equiv \upsilon_x^L$, $o_t^8 \equiv \upsilon_y^L$, and $o_t^9 \equiv Dlegs$. The quantities $(x^R, y^R, x^L, y^L)$ are the positions and $(\upsilon_x^R, \upsilon_y^R, \upsilon_x^L, \upsilon_y^L)$ are the velocities of the right and left leg along the axes, and $Dlegs$ is the distance between the legs. The observation data are modeled using a mixture of Gaussian distributions.

### C. Gait Parameters Computation

For the computation of the gait parameters from the laser data, we use the time segmentation given by the HMM recognition system. Each recognised gait cycle provides the stride time, while the swing time is the duration of the phases from **IW** to **MW**. The stride length is computed by summing the distances travelled by each leg in the direction towards the robotic platform.

## III. USER FRONT-FOLLOWING

The problem of following from the front can be divided into two general cases; following the human in free space i.e. in an obstacle-free space and, following the human in a structured environment e.g. in an office building, corridor etc. The two problems have different complexity with the former being substantially simpler than the latter. Specifically, in *free space following*, the problem can be cast as a control problem where the goal is to minimize some error measures e.g. minimize the distance and orientation errors between the human and the robot. This approach is singularly treated in the current literature. In the *structured environment* case, the task involves avoiding obstacles, either static of moving, as well as deciding where the human actually wants to go; a possibly undecidable problem. See for example Fig.1.

It is clear that the robot has no way of knowing where the human wants to turn by examining solely the human motion. This problem requires the addition of further information into the control loop by letting the human show the robot to turn left/right using some kind of feedback e.g. audio, posture, gestures etc. Thus, the human must also steer the robot and not just act as an observable for the robot. The control strategy for this problem is radically different from the *free space* following problem, and has received no attention in the literature.

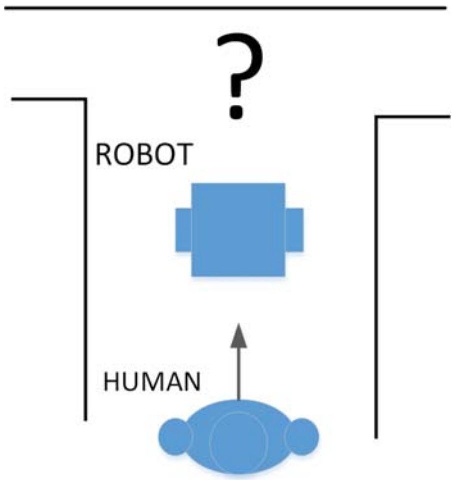


Fig. 3: Undecidability of the front-following problem in structured environments

The front-following problem has received scarce attention from the research community. Our survey has produced only three papers dealing with subject. All three deal with the free-space following problem. In [10] the authors use a Laser Range Finder (LRF) to scan the human torso, which serves as a more robust scanning target than the legs. Using a particle filter employing a constant velocity model, they track the pose of the human during motion. The control algorithm uses a *virtual target* based on the human and robot poses. The aim is for the robot to track the target, which lays in the approximate direction of the human velocity vector. [11] use an RGBD sensor (Microsoft Kinect) to track the human position relative to the robot. Following, they use the nonholonomic human model [12], [13] to calculate the humans orientation, combined with an Unscented Kalman Filter to provide a smooth estimate of the human orientation, linear velocity and angular velocity. The controller is an ad-hoc solution aiming to align the human-robot poses while putting the robot in front. [14] combine readings from a wearable IMU sensor on the human, along with LRF data of the legs in order to provide an estimate of the human pose and linear/angular velocities. They use an inverse kinematics controller to exponentially stabilize a position and orientation error between the human and the robot. In this setup, they perform experiments in straight line tracking, as well as in tracking the human along an 8-shaped path.

### A. Human pose estimation

The first step towards human following is the detection/estimation of the human pose. A basic assumption is that the human is detected by a LRF located on the robot, which scans the user legs. Furthermore, the kinematic controller only needs the position of the human, not the orientation and velocity. This simplifies the control and is more robust to estimation errors. To filter out environment artefacts and obstacles, we borrow the idea of a Human Interaction Zone (HIZ) from [14], which consists of a parallelogram of width 2m and length 2m, centered at the LRF. Based on the laser scans inside the HIZ, a *centroid* is calculated by taking the average in each *x,y* coordinates. Thus, if $k$ scans lay inside the HIZ, the centroid coordinates are,

$$\begin{bmatrix} x_H \\ y_H \end{bmatrix} = \begin{bmatrix} 1/k \sum_k x_L^i \\ 1/k \sum_k y_L^i \end{bmatrix} \tag{1}$$

To enable more valid detection results, in order to exclude false positives from walls, furniture etc. we have inserted an adaptive algorithm based on the previous valid centroid position. Specifically, in the beginning, the robot considers only scans inside an *initial window*, similar to the HIZ but with a width of 0.8m. This implies that the human who is intended to be followed, approaches the robot in a narrow region. Following, the algorithm estimates the centroid coordinates $[x_H^i, y_H^i]$ at loop $i$. In the next loop $i+1$, the algorithm scans inside a small *leg window*, of width 0.3m and height 0.2m. Thus the detection area is the rectangle$[x_H^i \pm 0.3, y_H^i \pm 0.2]$. In this way, the algorithm tracks the human as he/she moves inside the HIZ, and discards other unrelated objects.

### B. Kinematic controller

The proposed solution for the front-following problem, is a *virtual pushing* approach through a kinematic controller. We define an equilibrium distance $x_0$ where the system is at rest. If the human passes the equilibrium point and approaches the robot, then the robot starts to move depending on the human-robot distance.

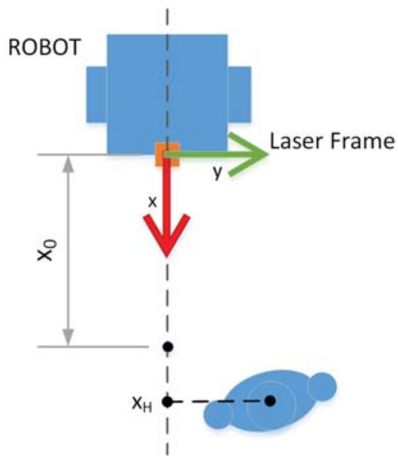


Fig. 4: Depiction of the Laser Frame and the Equilibrium distance $x_0$

The robot model used is the widely known Unicycle robot, controlled by the inputs $v_R, \omega_R$ (linear and angular velocities respectively). Rigidly attached to the robot is the *laser frame*, in which the user centroid $x_H, y_H$ is calculated. The robot's linear velocity is given by,

$$v_R = \lambda(y_H)v(x_H) \tag{2}$$

where,

$$v = \begin{cases} 0 & ,x_H > x_0 \\ k_1(x_H - x_0) & ,x_2 \le x_H \le x_0 \\ v_{walk} & ,x_1 \le x_H \le x_2 \\ v_{max} - k_2 x_H & ,0 \le x_H \le x_1 \end{cases} \tag{3}$$

$k_1 = \frac{v_{walk}}{x_2 - x_0}, k_2 = \frac{v_{max} - v_{walk}}{x_1}$

The term $\lambda$ is a velocity modulating term (see below for a more thorough analysis). Equation (3) defines a piece-wise linear velocity profile, consisting of three regions; the *approach region*, the *walking region* and the *collision region*.

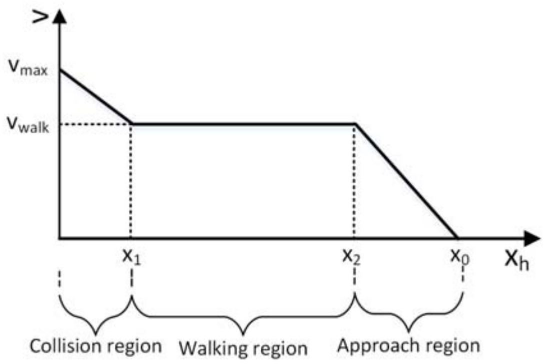

Fig. 5: Profile of the linear velocity input

The *walking region* is the set on the $x$-axis of the LRF frame, within which the robot has a constant velocity, namely the walking velocity $v_{walk}$. In this region the robot moves synchronously with the user. If the human moves very close to the robot, he/she enters into the *collision region*, in which the robot accelerates up to a maximum velocity $v_{max}$. Conversely, if the human falls behind (or enters the HIZ from a distance greater than the Equilibrium distance $x_0$), the *approach region* is considered, where the robot accelerates from halt up to the walking velocity. The second robot input, the angular velocity $\omega_R$, is described by the following equations,

$$\omega_R = \begin{cases} 0 & ,|y_H| < \varepsilon \\ k_\omega sgn(y_H)(|y_H| - \varepsilon_0) & ,|y_H| > \varepsilon \end{cases} \tag{4}$$

$k_\omega = \frac{\omega_{max}}{HIZ_w/2 - \varepsilon}$

Here $\omega_{max}$ the maximum angular velocity, $HIZ_w$ is the width of the HIZ and $\varepsilon$ is a deadband about the $x$-axis. The deadband is inserted in order to filter out natural gait oscillations during walking, as well as noise from the centroid estimator. In our experiments $\varepsilon$ was set to 10cm.

Using Eq. (4), the robot essentially turns in such a way as to always face the user. During experiments it was observed that in corners the users place themselves on the outer limits of the $y$-axis to make the robot turn fast enough. This oversteers the robot and in order to correct its heading, they must swiftly move on the other end of the axis. At the same time the robot is moving forward with a linear velocity, making the reaction time rather short and leading to unstable behaviors. To prevent this situation, we have inserted a velocity modulating term $\lambda(y_h)$ in Eq.(1). The term is given by,

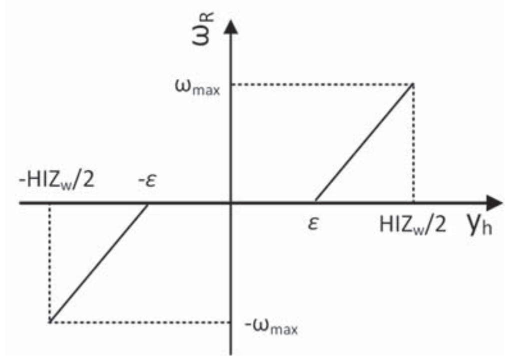

Fig. 6: Profile of the angular velocity input

$$\lambda = \begin{cases} 1 & ,|y_H| < y_a \\ \frac{y_b - |y_H|}{y_b - y_a} & ,y_a \le |y_H| \le y_b \\ 0 & ,y_b < |y_H| \end{cases} \tag{5}$$
$$y_b = \varepsilon + b(HIZ_w/2 - \varepsilon)$$
$$y_a = \varepsilon + a(HIZ_w/2 - \varepsilon)$$

The parameters *0 < a < b < 1* are percentages with respect to the deadband. A graphical depiction of $\lambda$ can be seen in below.

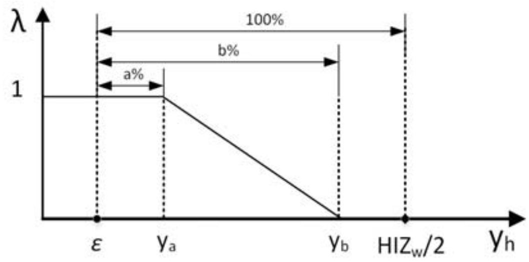

Fig. 7: Illustration of the $\lambda$ function

The $\lambda$ term reduces the linear velocity as the user increases his/hers lateral displacement. On the outer regions, the robot halts and turns on the spot to face the human. For our experiments the parameters were set to $a$=0.3 and $b$=0.6.

## IV. EXPERIMENTAL RESULTS

### A. Assessment of HMM-based gait characterisation

*1) Experimental setup and data description:* The experimental results presented in this section are based on data collected during a full-scale experimental study conducted at the premises of Agaplesion Bethanien Hospital - Geriatric Center (University of Heidelberg) at the frames of the EU-funded FP7 research project MOBOT. Patients with moderate to mild impairment, according to pre-specified clinical inclusion criteria, took part in this experiment. The

Fig. 8: Snapshots of a subject walking assisted by the robotic platform, during one stride.

| Subject | Stride Time [sec] | Swing Time [sec] | Stride Length [cm] |
|---|---|---|---|
| **1** | 1.02 $\pm$ 0.04 | 0.38 $\pm$ 0.03 | 74.6 $\pm$ 4.6 |
| **2** | 1.04 $\pm$ 0.02 | 0.39 $\pm$ 0.04 | 88.7 $\pm$ 2.9 |
| **3** | 1.06 $\pm$ 0.02 | 0.41 $\pm$ 0.04 | 73.7 $\pm$ 1.6 |
| **4** | 1.17 $\pm$ 0.06 | 0.45 $\pm$ 0.01 | 72.0 $\pm$ 1.1 |
| **5** | 1.17 $\pm$ 0.03 | 0.41 $\pm$ 0.03 | 59.6 $\pm$ 2.3 |

TABLE I: Gait parameters (means and standard deviations) computed by the proposed HMM-based methodology for five subjects.

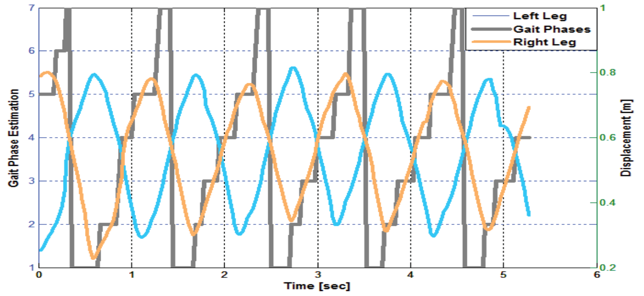


Fig. 9: Experimental Results: Example of an exact gait phase recognition sequence for Subject #2, as estimated by the HMM-based approach. The grey line (axis on the left) depicts the gait phase transition. The blue and orange lines (axis on the right) show the displacement of the left and right leg, respectively, on the sagittal plane.

patients were wearing their normal clothes (no need of specific clothing). We have used a Hokuyo Rapid URG laser sensor (UBG-04LX-F01 with mean sampling period of about 28msec), mounted on the robotic platform of Fig. 1 for the detection of the patients' legs (scanning was performed at a horizontal plane below knee level). A GAITRite system was also used to collect ground truth data, which will be used in future work for a formal clinical validation study. GAITRite provides measurements of the spatial and temporal gait parameters and is commonly used for medical diagnosis [15].

The study presented in this paper uses the data from five patients with moderate mobility impairment (aged over 65 years old). Each subject walked straight with physical support of the robotic rollator over a walkway. The HMM was trained by using the recorded data from twelve different patients. All patients performed the experimental scenarios under appropriate carer's supervision. The subjects were instructed to walk as normally as possible. This results in a different walking speed for each subject, and in different gait parameters.

Fig. 8 shows a sequence of snapshots of a subject performing the experimental scenario, captured by a Kinect camera that was also mounted on the robotic rollator (Fig. 1).

*2) HMM Results:* As discussed, the goal of the work presented in this paper is to perform an initial performance assessment of the HMM-based methodology regarding the extraction of gait parameters. We have first isolated the laser data corresponding to the strides performed by each subject on the walkway. These data were then processed to extract the gait parameters using the HMM methodology described in Section II.

Table I contains the statistics of the gait parameters computed as the outcome of the HMM-based gait segmentation and characterisation.

For better demonstrating and assessing the experimental results obtained, we present as an example the exact gait phase recognition sequence provided by the HMM-based approach for the full duration of the strides performed by one subject (Subject #2). These results are depicted in Fig. 9, where the blue and orange lines show the displacement of the left and right leg in the sagittal plane, respectively, during the five strides (axis on the right), while the grey line depicts the gait phase segmentation extracted by the HMM (axis on the left).

By analysing these results it can be concluded that the gait characterisation performed by the proposed HMM-based methodology manages to provide a reliable outcome in terms of clinically-relevant gait parameters, as can be deduced by the consistency in the extracted gait parameters between consecutive strides within each subject (also related to the standard deviation results). An initial evaluation with ground-truth data demonstrates that the HMM approach provides reliable and valid gait characterisation results, that could be eventually used for further classification of gait properties. Initial comparison with other approaches (e.g. a rule-based methodology based on raw data spatiotemporal filtering) also demonstrates that the added complexity of the HMM approach, w.r.t more basic tracking methodologies, is necessary for improved accuracy. These results are very promising clearly depicting the capacities of the proposed HMM-based methodology to successfully segment the gait cycle and recognize the specific gait phases, extracting comprehensive information about the specific action of each leg, which can be very useful for medical diagnosis. Nevertheless, the results demonstrate that there is significant space for increasing the accuracy of the system. Further comparative analysis and full-scale validation of this methodological framework constitutes one of the main objectives of current research work.

### B. User Following

The user front-following control scheme presented in the previous section, has been implemented on a Pioneer 3DX differential drive robot, with a Hokuyo UBG-04LX-F01 laser

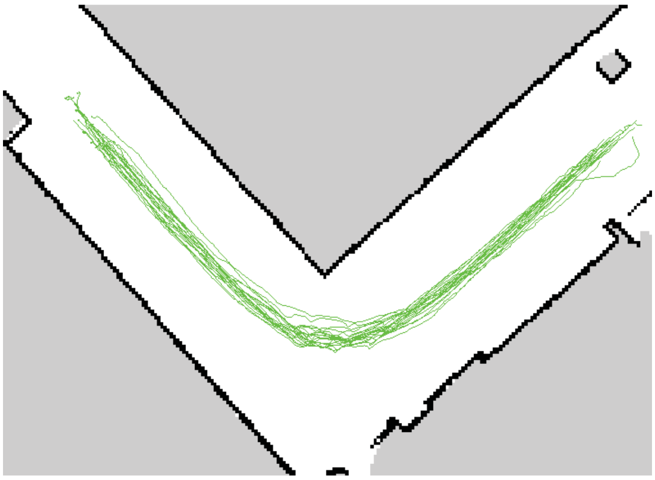

Fig. 10: Traces of the baseline experiments (green). The subjects started on the right and progressed to the left.

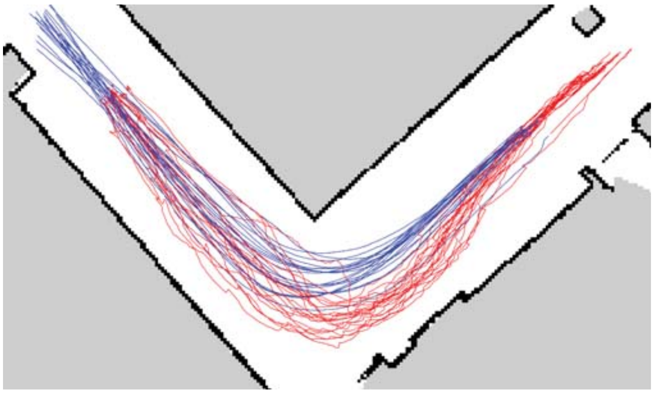

Fig. 11: Traces of the following experiments (Human-red, Robot-blue). The subjects started on the right and progressed to the left

range finder. The experiments considered here, aim to assess the gait pattern of the users with and without the robot following them from the front. Ten healthy subjects were asked to walk naturally from an initial predefined position, around a corner and stop at a designated target position. Each subject performed two runs, thus in total 20 paths were collected as a baseline. The subjects were tracked with the laser scanner on top of the robot, which in turn was placed statically at the head of the corner, overseeing the experimental field. In post processing, using the detection algorithm, the centroid traces were extracted, as seen in Figure10.

Following, the subjects were asked to perform the experiment again, but with the robot following them from the front. Each subject did two test runs in order to get acquainted with the robot behavior. Then, they performed the experiment twice. The total collected paths are again 20.

To analyze the paths, we have divided the plane into a grid of 48 $\times$ 26 square cells with an edge of 20 cm each. Then, for each path we collected the binary mask consisting of those cells that the path has traversed. By counting the

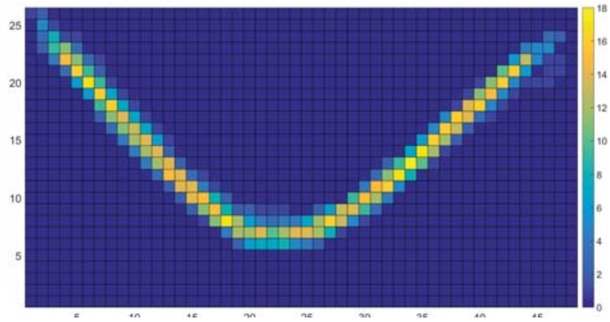

Fig. 12: Histogram of the baseline paths

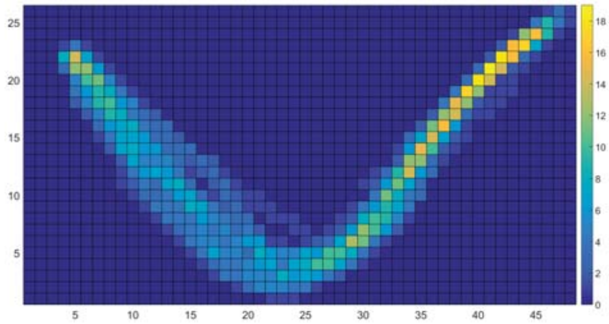

Fig. 13: Histogram of the users' paths (following)

number of masks each cell appears in, we have produced a 2D histogram of those masks. Apparently, since we have 20 paths in each case, the count of each cell goes from zero up to twenty. The three histograms are,

$$\begin{aligned} &H_B(i,j) : \text{Baseline paths} \\ &H_U(i,j) : \text{User paths} \\ &H_R(i,j) : \text{Robot paths} \\ &i \in [1,48], j \in [1,26] \end{aligned} \tag{6}$$

The histograms are presented in figures 12-14.

From the three histograms we can produce two new sets of distributions. By dividing the count of each cell with the total number of paths, we produce the probability of each cell being traversed by a path, viz.

$$\begin{aligned} T_B(i,j) &= H_B(i,j)/20 \\ T_U(i,j) &= H_U(i,j)/20 \\ T_R(i,j) &= H_R(i,j)/20 \end{aligned} \tag{7}$$

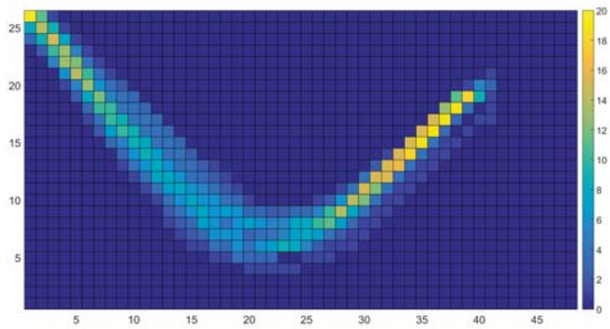

Fig. 14: Histogram of the robot paths (following)

TABLE II: Measure of the extent of the "User" and "Robot" groups with respect to the "Baseline" group

| | *Count()* | *% rel. diff.* |
|---|---|---|
| $T_B$ | 186 | - |
| $T_U$ | 318 | 70.96% |
| $T_R$ | 253 | 36.02% |

Thus a cell with high such a probability means that it is traversed by most of the paths. Note that these are not probability distributions as they don't sum up to one. Another set of distributions can be produced by dividing each cell with the total count of its respective histogram, i.e.

$$\begin{aligned} P_B(i,j) &= H_B(i,j)/\sum_{i,j} H_B(i,j) \\ P_U(i,j) &= H_U(i,j)/\sum_{i,j} H_U(i,j) \\ P_R(i,j) &= H_R(i,j)/\sum_{i,j} H_R(i,j) \end{aligned} \tag{8}$$

These express the probability of a user/robot being on a specific cell and are probability density functions. Equations (6),(7),(8) are similar up to a scaling factor (for each group "B", "U", "R"), thus all three have the same shape. To compare the three groups, we resort to the Hellinger distance which is a measure of statistical distance between two distributions P, Q given by,

$$H(p,q) = \frac{1}{\sqrt{2}} \sum_k (\sqrt{p_k} - \sqrt{q_k})^2$$

The Hellinger distance ranges from zero to one, with zero being identical distributions and one completely disjoint. The distances of $P_U$ to $P_B$ and $P_R$ to $P_B$ are,

$$H(P_U, P_B) = 0.6265, H(P_R, P_B) = 0.4907$$

We see that the Robot path distribution is more similar to the Baseline distribution than the User' distribution. This means that the users actually tend to "drive" the robot to the path they consider "optimal" i.e. the one that *they* would take under normal conditions (the baseline paths). Doing so, they deviate from their normal gait patterns. A measure of dispersion of the histograms is the relative differences between *count*($T_R$)-*count*($T_B$) and *count*($T_U$)-*count*($T_B$), since the count function measures the number of cells a distribution contains. Thus the relative difference is a measure of the extent of a group with respect to the baseline group.

From Table II we see that the users cover almost 71% more cells trying to steer the robot, than when walking normally, which is almost twice the cells the robot covers. This can be regarded as a measure of cognitive load since it shows that the users walk through a wider area.

*1) Current research direction:* Our current research efforts focus on extending the following behavior in unstructured environments. The control has been split into three tasks; *undecidability detection*, *intent identification* and *local planning*. As mentioned earlier, the robot can encounter areas in which there are more that one "distinct" directions e.g. in a T-junction. The robot must be able to discern these

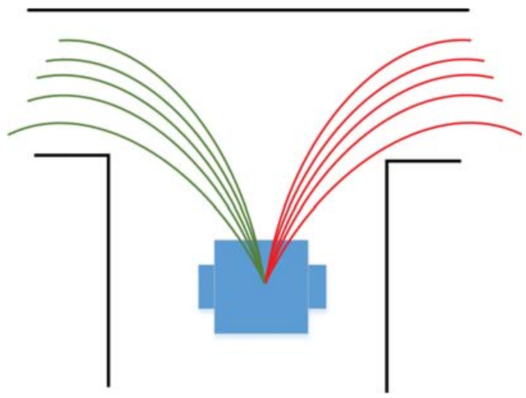

Fig. 15: Equivalence classes for path sets in a T-junction. Red is the "Right" class and Green is the "Left" class

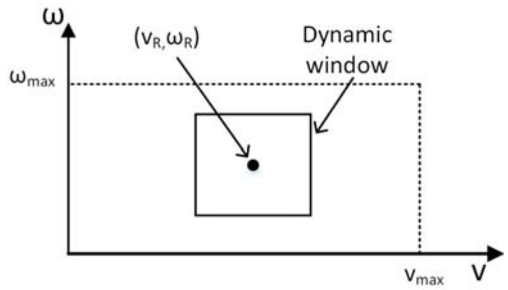


Fig. 16: Dynamic window of constrained input

cases and go into *intent identification* mode, in order to resolve the conundrum it is faced with. Knepper et al. [16], have presented an algorithm based on an extended notion of path-homotopy, in order to produce "equivalence classes" of feasible paths. Formally, two paths are homotopic is there is a continuous deformation which send the one to the other. Strictly speaking, the paths must have the same start and end points. By relaxing the definition, one can speak of "equivalent" paths, that is, paths that have the same starting point and can be continuously deformed to one another. In [16], the algorithm produces feasible paths of a certain length i.e. ones that satisfy the differential equations of the robot, with varying curvature $\kappa(s)$. The paths are checked for collision against a costmap and are grouped into classes based on their Hausdorff distance.

Our current approach is similar to [16], albeit simpler. Firstly, we introduce the notion of *dynamic undecidability*. This is based on the fact that, as the robot moves, the feasible paths are constrained by the kinodynamic bounds of the system. For example, if the robot is moving fast, as sharp turn might be unfeasible. Thus, in a T-Junction, it might be the case that only one direction is actually feasible. Following the widely used *Dynamic Window Approach* in local planning, we produce paths of *constant* curvature, sampling from a dynamic window of the input space $(v, \omega)$.

The curvatures are checked for collision against a moving costmap centered around the robot, which is created by laser range scans. Following the free paths are clustered together based on their curvature separation (simple 1D clustering).

Given the available clusters, if there is more that one available directions, the robot enters into the *intent identification* mode, slowing down and observing the human. It uses the kinematic controller and produces a set of control inputs $(v_H, \omega_H)$, resulting to a curvature $\kappa_H$. When the human gets close to robot, under a predefined distance, the controller selects the closest cluster to $\kappa_H$, and and feeds the median free path to a local planner, as a "global path". This ensures a collision-free trajectory of the robot, which moves towards the human direction.

## V. CONCLUSION AND FUTURE WORK

This paper presents current research work that aims at the development of an intelligent robotic rollator to provide user-adaptive and context-aware walking assistance. To achieve such targets, a large spectrum of multimodal sensory processing and interactive control modules need to be developed and seamlessly integrated. This paper focuses on user-oriented human-robot interaction and control, by which we refer to the functionalities that couple the motions, the actions and, in more general terms, the behaviours of the assistive robotic device to the user in a *non-physical interaction* context. The paper summarizes recent research advances and scientific challenges aiming towards two complementary directions: 1) the first one addresses the development of a reliable gait tracking and classification system, for which we propose an approach based on HMMs, which can operate online by processing raw sensorial data provided by an onboard laser rangefinder sensor, and 2) the second one regards the development of a control system that can support a 'user-following' behaviour, that is, enable the robotic rollator to follow and comply to the walking characteristics of the user without any physical interaction (i.e. without any force being applied on the handles of the Rollator) and remain in close vicinity to the user in case of need.

This paper summarizes the theoretical framework and presents current experimental results obtained using real data both from patients (elderly subjects with mild to moderate walking impairments) and normal subjects. In particular, we perform an initial assessment of the gait characterisation performance achieved by the proposed HMM-based methodology, and demonstrate that this approach manages to provide a reliable outcome in terms of extracting clinically-relevant gait parameters. These results are very promising clearly depicting the capacities of the proposed HMM-based methodology to successfully segment the gait cycle and recognize the specific gait phases, extracting comprehensive information about the specific action of each leg, which can be very useful for medical diagnosis. Nevertheless, the results demonstrate that there is significant space for increasing the accuracy of the system. Further comparative analysis and full-scale validation of this methodological framework constitutes one of the main objectives of current research work. Furthermore, we demonstrate the applicability of a user front-following interactive control behaviour based on a virtual force field that enables the robotic rollator to provide adaptive assistance to the walking user. The main scientific challenge here is to detect the user intention and develop a shared control framework that can provide intuitive mobility assistance while reducing the cognitive load of the user.

Combining work in all these research directions, our ultimate goal is to develop assistive robotic technologies that can both monitor user actions (in order for instance to detect in real time specific gait pathologies and automatically classify the patient status or the rehabilitation progress) and provide effective, user-adaptive and context-aware, active mobility support.

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# Intention reading and intuitive shared control for mobility assistive devices

Etienne Burdet

***Abstract*—My talk will first examine conditions for efficient and intuitive interfaces to control mobility assistive devices. How observation of human sensorimotor behaviour can be used to design such interfaces, will be then illustrated in two examples: (i) intuitive shared control, in a collaborative robotic wheelchair that has been tested on healthy and impaired individuals, and (ii) a system to detect turning intention for controlling the movement direction in a lower limb exoskeleton.**

## I. Principles for the interaction with mobility assistive devices

Intelligent mobility assistive devices such as robotic wheelchairs and lower limb exoskeletons have been intensively developed in recent years. The mature mobile robots technology and the well developed field robotics promise robotic wheelchairs able to move safely in various terrains. However, to our knowledge there is no commercially available smart wheelchair, and only sparse literature describing experiments with end users. I claim that one major reason for the very limited use of robotic technology in wheelchairs lies in unsuitable human-machine interaction strategies to control them.

On the other hand, the mechatronic design of a light but powerful lower-limb exoskeleton to enable neurologically impaired individuals to walk involves various difficult problems, and it is not yet a mature technology. However extensive efforts, such as the recent European projects MINDWALKER, BETTER, BALANCE, SYMBITRON, BIOMOT, H2R, are producing rapid advances in this area. It is no longer fanciful to pretend that individuals affected by spinal cord injury will be able to walk again with an exoskeleton. However, a mechatronically perfect exoskeleton will not be a big help to impaired users if it is not able understand their intention.

So, what factors should be considered to design an interface that enables human users to control a mobility assistive device efficiently and comfortably? A *first principle is that the device should let the user as much as possible in charge of the control*. This is critical because impaired individuals, like able ones, want to decide and carry their actions independently. For instance, autonomous mobile robots used as wheelchairs are not appreciated by users, who do not want to be driven but only helped to drive themselves. Conversely, it is important to use minimal assistance as humans naturally tend to minimise effort, thus will tend to depend more and more on it [1].

As a consequence of this principle, assistance of able subjects will gradually decrease and eventually disappear. In fact, the device should be usable by various kinds of users and *it should not disturb healthy subjects*. In fact unimpaired users should not notice the device, i.e. it should be *transparent* to them. While this principle seems to be trivial, it is in fact difficult to obtain this from an assistive device: robotic wheelchairs often disturb users as they impose a command even when a user would be able to maneuver well without it, and current exoskeletons can hardly be controlled in a transparent way.

A *second principle to control an assistive device is that it should obey natural motion intention*. This has two favourable consequences: Users will be able to use the device efficiently, because they can control their movements well, and they will need little cognitive effort. In order to implement this strategy, it is necessary to examine natural behaviours and identify how these could be used in order to elicits suitable commands of the assistive device.

## II. Collaborative wheelchair

The concept at the heart of our *collaborative wheelchair assistant* (CWA) [2] is to rely on the users motion planning skills while assisting the maneuvering with flexible path guidance. The user decides where to go and controls the speed (including start and stop), while the system guides the wheelchair along software-defined guide paths. An intuitive path editor allows the user to avoid dangers or obstacles online and to modify the guide paths at will. By using the human sensory and planning systems, no complex sensor processing or artificial decision system is needed, making the system safe, simple, and low-cost.

This system fulfils the first principle as it will guide individuals who cannot control the wheelchair, while still letting them in charge of speed control. For instance, they can start to move when they want (not just when the robot starts) and stop to observe a butterfly or discuss with a friend along the way. Human-like [3], [4] adaptive guidance stiffness yields automatic adaptation of the path elasticity so that assistance disappears for able subjects. The second principle is fulfilled as the joystick command is not modified, just filtered on the lateral motion.

Trials on individuals affected by cerebral palsy or traumatic brain injury who could initially not use a motorised wheelchair demonstrated that the CWA enabled them to drive safely safely and efficiently in an environment with obstacles and narrow passageways. The CWA enabled these subjects to drastically reduce their effort and intervention level without compromising performance. Some subjects improved their control to the point that the guidance assistance automatically disappeared, and they did not notice the gradual change.

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## III. Detection of turning intention

Control systems of exoskeletons for walking assistance should provide sufficient performance, be safe for users and enable intuitive and natural human-machine interaction. In cases of neurological injury such as stroke and spinal cord injury, patients are unable to control their lower body but often have better control of the upper body including the head and trunk.

During locomotion in humans, upper body movements generally precede the actual turn: it has been shown that the head and gaze react first during locomotion and turning by steering the eyes and head towards the turning direction. We propose to use these natural synergies, and detect the intention to turn from the head and trunk in order to control a gait assistance exoskeleton.

An experiment with able bodied subjects showed that head and pelvis yaw measurements can be used to detect turning action before the movement actually occurs. This method may be used as an intuitive way of controlling the steering of exoskeletons by using the natural anticipatory behaviour of the upper body during locomotion. This method based on natural movements thus fulfils the second principle; in turn the system will assist minimally as is required by the first principle.

Future experiments with impaired individuals will test whether this modality can be used to command a mobility assistive device. We believe that even if impaired individuals may initially not use head movements during mobility with an exoskeleton, because they did not move for a long time, it will be relatively easy for them to learn using this modality based on natural synergies.

## Acknowledgment

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# Promoting Independent Mobility

## -Assistance mobility and evaluation technology in robotic wheelchair-

Naohisa Hashimoto, *Member, IEEE*, Ali Boyali, Masashi Yokozuka, and Osamu Matsumoto

***Abstract*— A rapid population increase of elderly people has caused several issues including the need for eco-friendly and comfortable mobility. In this paper, on-going projects related to mobility technology for elderly people are discussed. We propose robotic autonomous wheelchairs to aid in resolving mobility problems for the elderly. When using an autonomous wheelchair, the rider does not need to control the wheelchair. However, there are several challenges associated with the use of an autonomous system. One of the most difficult challenges to overcome is the purchase price. Normally, an autonomous wheelchair is costly because of several expensive sensors that are required for full autonomous functionality. Thus, it is difficult for elderly people to own an autonomous wheelchair.**

**We introduce three projects including an assistance cart, and two other projects related to autonomous wheelchairs. The cart supports elderly people during walking and enables travel for greater distances without full autonomous features. The autonomous robotic wheelchairs have GPS, laser scanner sensors (LIDAR), and gyro sensors. We are researching positioning techniques, obstacle avoidance methods, rider usability, and a human machine interface to further expand the usage of autonomous wheelchairs. In addition, experimental results on usability and gesture recognition interface are discussed in this paper.**

## I. Introduction

In Japan, a greater proportion of elderly people (over 65 years old) are involved in road fatalities than people of any other age group, as shown in Fig. 1 [1]. Because of the advancement of science and inherent adaptability of humankind to changing life conditions, average life expectancy has increased. This leads to an increasing population of aged and disabled people in need of mobility aid. Current figures indicate that nearly 15% of the population, which corresponds to approximately one billion in the world, has some form of physical disability or impairment [2]. Additionally, according to studies [3, 4] the household rate of people in the US using wheelchairs doubled from 1.5% to 3% from 1990 to 2010 with a majority of these being elderly people. Automobiles are the optimal means of transportation for the elderly since automobiles permit door-to-door transportation [5, 6]. However, to address traffic problems related to air pollution in city areas, a shift in use from individual automobiles to public transportation is needed. This change will be less than ideal for elderly people. To resolve this conflict, useful and eco-friendly transportation must be provided. Public transportation is useful and eco-friendly; however, the last-mile problem remains, especially for elderly people [7, 8]. Convenient, comfortable, and eco-friendly mobility is considered one of the options for solving this problem of the last mile.

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We proposed robotic autonomous wheelchairs to solve mobility issues. With an autonomous wheelchair, the rider is not required to control the chair. However, there are several challenges associated with the use of an autonomous system, the most difficult being cost. Several expensive sensors are necessary for a wheelchair to achieve complete autonomous functionality. These sensors increase the cost of an autonomous wheelchair, making it difficult for elderly people to purchase an autonomous wheelchair. We introduce three projects in this paper regarding autonomous or assisted wheelchairs and how they will aid the elderly.

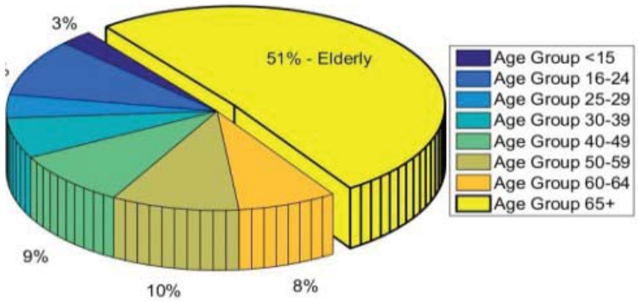


Figure 1. Number of traffic accident fatalities by age group [1]

## II. Assistant Mobility Device

In the automobile field, there are numerous on-going research projects regarding automated vehicles for use on public roads; however, there are still challenging issues such as the overall cost that require resolution [9-12]. While the cost of autonomous functionality within an automobile is relatively small compared to the cost of a vehicle, the overall high cost of an autonomous vehicle can be a serious problem for the elderly. National Institute of Advanced Industrial Science and Technology (AIST) is studying not only options for autonomous mobility but also assistance mobility for elderly people. This paper explains three assistance levels of mobility devices for elderly people.

### *A. Autonomous Robotic Wheelchair*

Autonomous wheelchairs for assisting elderly and disabled people are proposed to assist in their daily activities [13-15] and are shown in Fig. 2. These wheelchairs can seamlessly travel in both indoor and outdoor environments through self-positioning and route planning. A localization method determines the wheelchair's own position using a 3D laser range scanner sensor attached to the wheelchair in conjunction with 3D maps. To avoid collisions, the system uses short-term and long-term planning methods. The short-term method, which is used within obstacle sensor area, finds a safe travel pattern through map simulations of every conceivable pattern. The long-term method generates a feasible route to the desired destination. If the route generated by the long-term method presents obstacle or collision hazards, the wheelchair uses the short term planning to avoid the hazard. The localization and the planning systems enabled our wheelchair to travel in public spaces autonomously. We are now researching methods to reduce the cost of this autonomous wheelchair system.

Figure 2. Two Robotic Wheelchairs

### *B. Experiment of Human Factors on Robotic Wheelchair*

It is difficult to develop a completely autonomous wheelchair that functions in public areas. Multiple users of public space, including pedestrians and bicycles, create a challenging environment for an autonomous wheelchair. Therefore, it is necessary to include surveillance equipment for emergency or any robot unstable conditions into the design of mobile autonomous systems. Experimental studies of surveillance equipment, using real life conditions, are required to provide accurate data.

We studied human factors regarding the acceptability and capability of surveillance equipment, including the age of the user and duration of use. We created experimental scenarios to test the wheelchair in public areas, as shown in Fig. 3, to estimate a user's surveillance capability. The experimental results indicated differences in each ride.

Figure 3. Experimental scenes

### *C. Proposed Interfaces of Gesture Recognition for Robotic Wheelchair*

A joystick is typically used as an interface for control of a wheelchair. The joystick controller is useful and simple to operate. However, the normal joystick has only four types of inputs. Additionally, some elderly people have challenges using a standard joystick. Alternatively, there are new interface tools available in the marketplace [16-18]. These smart interfaces pave the way for Human Machine Interfaces that aim to decrease the physical and cognitive loads of the users. The smart systems, however, are difficult to use for those who are handicapped or have some form of physical disabilities. This study is the first step toward developing a wheelchair control interface that will allow people having severe mobility impairments to use gestures and postures to control a wheelchair. This method of control is accomplished by using state of the art sensors, such as a pressure distribution sensor or the gesture armband from Microsoft.

A gesture and posture recognition algorithm was proposed for a robotic wheelchair as a replacement for a conventional joystick control [19]. For our experiments, we employed a Leap Motion sensor to capture the positions of the left hand, as shown in Fig. 4. The Leap Motion sensor reports the palm position, hand velocity, and orientation values at sub-millimeter accuracies.

A critical issue in recognizing real time signal patterns of the user's hand motion is the determination of the signal patterns without definite starting and stopping points. The problem of finding the most representative signal patterns was solved by employing subspace clustering methods. The use of subspace clustering, including the necessary algorithms, constitutes the framework used for different classification tasks. Further, we also implemented spectral variants of the Collaborative Representation based Classification as presented with MYO arm band [20, 21], shown in Fig.5

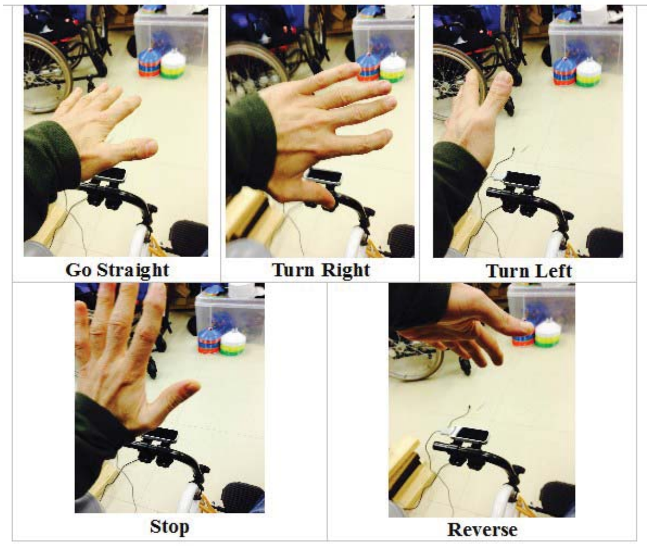


Figure 4. Hand gestures using Leap Motion: 1-Go Straight; 2-Turn Right; 3-Turn Left; 4-Stop; 5-Reverse


Figure 5. MYO armband and hand gestures, 1-Fist, 2-Hand relax, 3-Fingers spread, 4-Wave in, 5-Wave out, 6-Double tap conclusion

### D. *Robotic Assist Walker*

The Ministry of Economy Trade and Industry organized the Development and Introduction of Robotic Devices for Nursing Care [22]. The objectives of the project are as follows [22]:

- To perform research and development into the introduction and promotion of robotic devices for nursing care facilities, thereby contributing to the independence of elderly people,
- To formulate and evaluate standards that are necessary to commercialize robotic devices for nursing care facilities,
- To provide financial support to enterprises that develop robotic devices for nursing care that fulfill criteria categorized in the government's "Priority Areas to Which Robot Technology is to be Introduced in Nursing Care of the Elderly".

Through this project, the Walking Assist Cart has been produced by The RT. WORKS Co., LTD., as shown in Fig. 6 [23]. The cart has an assistance function; however, it does not function autonomously. The objective of this cart is to provide support for elderly people and enable them to travel greater distances. It is a simple and low-maintenance cart that provides features developed for elderly people. Experiments were performed with elderly people, which provided feedback to improve the design of the cart. The cart is not an expensive system and has an effective technology to address mobility concerns of elderly people.

Figure 6. Walking Assist Cart

## III. Summary

This paper introduces mobility devices being developed at AIST and manufactured by a private company. The concept, system configuration, and experimental summaries are explained in this report. As the number of elderly people increase, personal mobility devices, including wheelchairs, become necessary for maintaining a high quality of life.

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# MULTIMODAL SENSORY PROCESSING FOR HUMAN ACTION RECOGNITION IN MOBILITY ASSISTIVE ROBOTICS

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## 1. INTRODUCTION

One of the main objectives of the EU project MOBOT [1], which generally aims at the development of an intelligent active mobility assistance robot, is to provide multimodal sensory processing capabilities for human action recognition. Specifically, a reliable multimodal information processing and action recognition system needs to be developed, that will detect, analyze and recognize the human user actions based on the captured multimodal sensory signals and with a reasonable level of accuracy and detail within the context of the MOBOT framework for intelligent assistive robotics. Different sensory modalities need to be combined into an integrated human action recognition system. One of the main thrusts in the above effort is the development of robust and effective computer vision techniques to achieve the visual processing goals based on multiple cues such as spatio-temporal RGB appearance data as well as depth data from Kinect sensors. Another major challenge is the integration of recognizing specific verbal and gestural commands in the considered human-robot interaction context.

In this presentation we summarize advancements in three tasks of the above multimodal processing system for human-robot interaction (HRI): action recognition, gesture recognition and spoken command recognition.

## 2. ACTION RECOGNITION

Our approach to detect and classify human actions from continuous RGB-D video streams, captured by visual sensors on the MOBOT robotic platform, consists of the following main steps: visual feature extraction, feature pre-processing and encoding, and the classification. An initial baseline version of our system was based on detecting space-time interest points, computing descriptors in a neighborhood around these points [e.g. Histogram Of Gradient (HOG) [3], Histogram of Flow (HOF), and HOG3D], using the Bag-of-Features (BoF) representation of the videos, and classification with Support Vector Machines (SVMs); such systems have exhibited promising performance in movie action classification [6]. Subsequently, we have enriched several sub-components of this pipeline by developing state-of-the-art approaches, as explained in [2]. Specifically, for the visual features we employ approaches such as spatio-temporal interest points by computing spatio-temporal energies via our multiscale Gabor 3D detector [7] on the RGB or Depth visual streams, as well as dense trajectories [10]. Then several descriptors capture appearance and motion information. State-of-the-art encoding methods employed include i) vector quantization and ii) vector of locally aggregated descriptors [4]. After feature encoding we train discriminative classifiers, such as SVMs, and classify a video segment containing a single action instance by employing different state-of-the-art variants of the widely used bag of visual words framework. In our set of tools employed (either in post-processing or in gesture recognition), we also combine SVMs with Hidden Markov Models (HMMs) and related algorithms. Overall, our system automatically detects human activity, classifies detected actions and localizes them in time; see Figure 1 for an overview of the system's pipeline. All the above have been evaluated on both the MOBOT dataset as well as on known datasets found in the literature. Our recognition results reach 86% on the MOBOT dataset and 93% on the KTH dataset. Details can be found in [2].

## 3. GESTURE RECOGNITION

Gesture recognition concerns the communication of the elderly subjects with the platform via a predefined set of gestural commands. There are several challenges faced during our work with the MOBOT dataset. For instance, it is usual to have alternative pronunciations of the same gesture among performances by different users. Further, in the MOBOT case, mobility disabilities seriously impede the performance ability of a gesture for some users, and therefore, alternative pronunciations are more frequent. Our gesture recognition systems shares some methodologies with the visual action recognition system. Initially, for the visual processing we used the RGB video stream, combined with pose information that became available after pose annotation. The extracted features included either handshape or movement information. For handshape features we focused on a neighbourhood of

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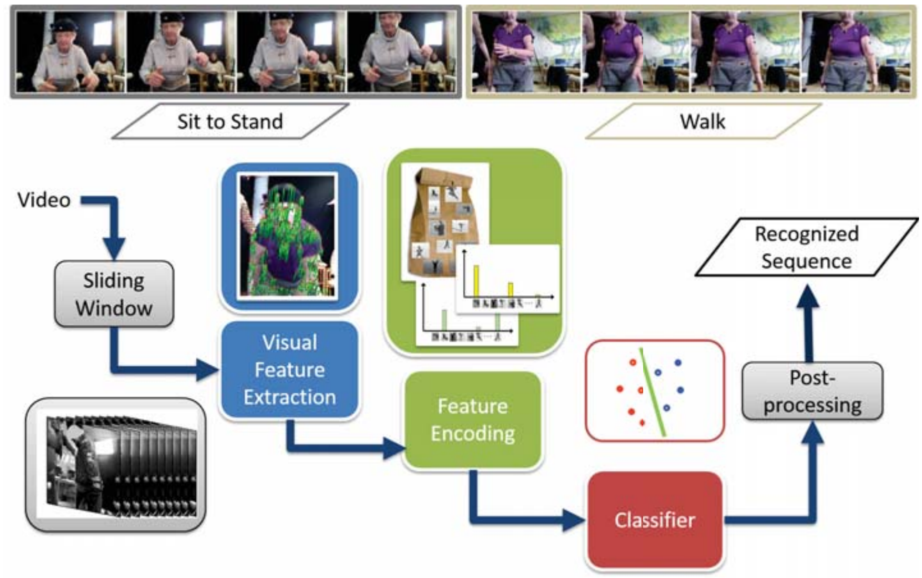

**Fig. 1**: Visual action recognition system overview. Top: Actions performed by patients in the MOBOT dataset. Bottom: Action localization and classification pipeline.

the hand centroid, so that we can use local descriptors such as HOG to extract features on the handshape. For movement-position features we used the available pose annotation to compute characteristics about position and motion of the arms (positions, velocities, accelerations of hands and elbows mostly). We have evaluated the complete framework of feature extraction and gesture learning based on HMMs for the statistical modeling. Our experimental results on the 2013 ACM Gesture Challenge dataset can found in [8] and preliminary results for the MOBOT data set can be found in [2]. More recently, in an effort to view gestures as refined visual actions, we have developed a visual front-end for gesture recognition that is based on the same approach used for action recognition, i.e. dense trajectories, feature encoding, and SVMs. This newer approach on gesture data showed that we can get roughly similar results to the ones obtained with our previous system, but without employing any manual (human provided) pose annotations. Our current gesture recognition systems has an average performance of about 70% on the MOBOT dataset, by using only motion-appearance features extracted from the RGB data. Our ongoing plans include the incorporation of an automatic pose annotation system.

## 4. SPOKEN COMMAND RECOGNITION

In the context of multimodal processing for human action recognition, we have developed a first version of an online system for always-listening spoken command recognition in German that is integrated on the ROS-based robotic platform and operates with an 8-channel MEMS microphone array. Based on the multichannel input, the module is designed to detect and recognize the user's intention to execute a specific operation of the robotic assistant. For instance, the elderly user may call the system by uttering a keyword like "MOBOT" and then provide a voice command from a predefined set of commands that are included on the recognition grammar, e.g, "MOBOT, turn right". The detection and recognition tasks are expected to be challenging due to the distant speaking configuration which is prone to noise and reverberation effects depending on the acoustic environment in which the session is taking place. Additional challenges may be introduced due to the existence of background speech and non-speech events possibly overlapping with the keyword and command segments to be detected and recognized. An overview of the implemented multichannel speech processing pipeline is depicted in Fig. 3. To support always-listening operation, the pipeline is built on the widely used cascade of three speech processing stages: a) voice activity detection, to separate speech from non-speech events, b) key-phrase detection based on the keyword-filler approach, to identify a predefined system activation phrase, and c) grammar-based automatic speech recognition, to recognize the issued command. All stages are applied to the denoised signal derived after delay and sum beamforming of the MEMS channels. Context-dependent German triphones have been trained on 55 hours of publicly available read speech and used for keyword spotting and recognition. Promising results were obtained after testing the system on MOBOT data. Two tests were conducted: i) the first on 8 patients seated approximately two meters in front of the robotic platform providing verbal and non-verbal (gestural) commands and ii) the second on 10 normal German-speaking users which held and followed the platform operat-

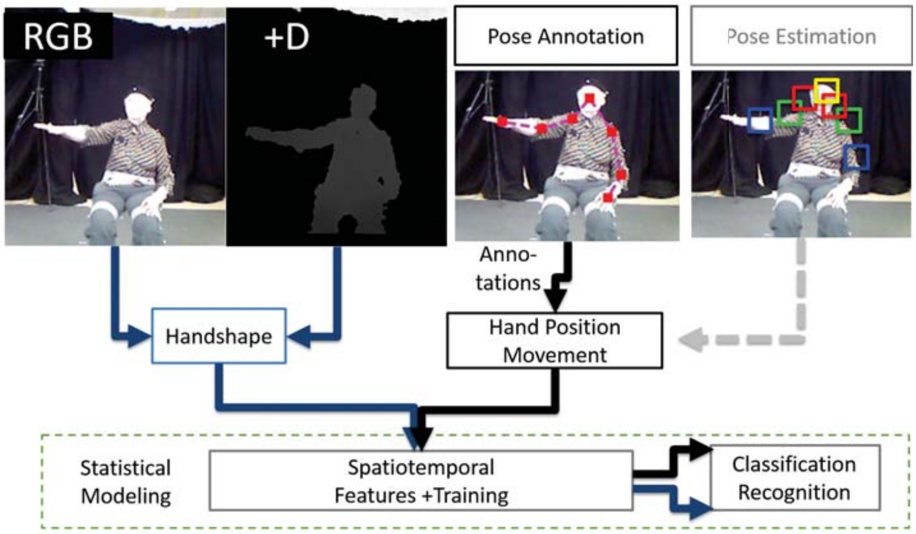


**Fig. 2**: Overview: Visual gesture recognition. Multiple information channels are combined within a common framework.

ing in a "following mode". The achieved average word accuracies of 73% and 85% on leave-one-out experiments (testing on one speaker after global MLLR adaptation of the acoustic models to the other speakers) renders the system usable as stand-alone or combined with the other modalities. More details about the employed methods for key-word spotting and recognition can be found in our previous work [5].

## 5. MULTIMODAL SENSOR FUSION

Within the MOBOT objective of multisensory processing for HRI, we have also been working with the design and experimentation of fusion algorithms for the integration of gestural and spoken command recognition. Such a cross-modal integration can significantly increase performance. Our first experimental system was based on a multimodal sensor fusion for audio-visual gesture recognition that exploited the color, depth and audio information captured by a Kinect sensor. Recognition of a time sequence of audio-visual gesture commands was based on an optimized fusion of all different cues and modalities (audio, movement-position, handshape). Our system [8, 9] was evaluated on the ACM 2013 Gesture Challenge dataset where it outperformed all other competing published approaches and achieved a 93% accuracy. We are currently adapting this multimodal action-gesture-speech recognition system for the MOBOT dataset and are developing a real-time version on the ROS robotic platform.

**Acknowledgement:** We wish to thank Kevis Maninis and George Pavlakos for their contributions to action recognition and gesture recognition while working at the NTUA IRAL, and Antonis Arvanitakis for his help with the ROS platform.

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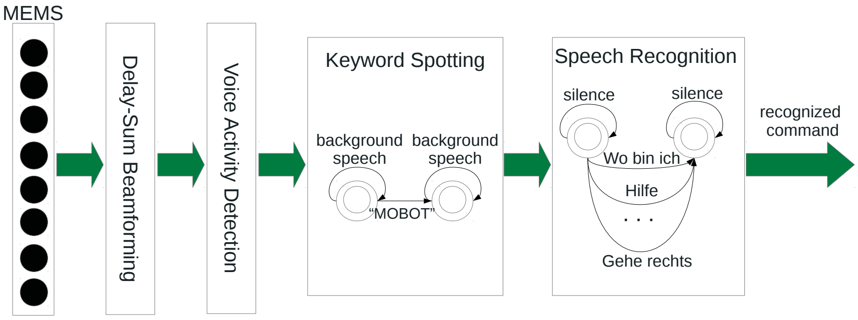


**Fig. 3**: An overview of the always-listening spoken command recognition pipeline with finite-state-automaton (FSA) representations of the finite state grammars employed for keyword spotting and recognition.


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# Measuring Human movements in the wild for HRI Contexts

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***Abstract*—Body movements are one of the main cues used in HRI. Despite the fact that body movements have a mechanist part, measuring it cannot be achieved as objectively as expected. Inherent variability (inter and intra personal variability, cultural meaning dependency, etc.) is hard to model and needs data driven approaches. We give some examples about our works in gestures analysis in developing an effective gesture-based robot controller.**

***Keywords—human behavior; HRI; gestures; physiology; model driven analysis, data driven analysis***

## I. INTRODUCTION

Human Robots Interactions (HRI) is a hybrid filed mixing many domains including engineering, physics, social sciences, neurosciences, etc. As such, research in HRI rely simultaneously on exact models and experimental approaches in developing interaction frameworks, theories and practical systems. Indeed and for the "R" part in HRI, measurements and procedures are known to be exact and objective. Models in these fields are enough known allowing quantitative accurate observations that can be measured repeatedly supporting the original models. Robots are controllable (most of the time) and observable agents. Their dynamics can be derived analytically allowing close form descriptions, i.e. the system can be described by equations. In psychology and social sciences the situation is different: the object of studies, namely humans, is much less known. Scientists in these areas are lacking in terms of accurate models compared physicists and engineers. Indeed, humans can be seen as high dimension multivariate systems, with complex dynamics, preventing from having complete explanatory models. This leads to qualitative approaches, where only isolated aspects (and most of the time related indirectly to the object of investigations) are considered.

The lack of knowledge combined with the poorness of analysis tools in human behavior analysis sounds like 'egg-chicken' problem. This situation is even worst when experiments are performed in real life conditions. Indeed, to obtain realistic observations, experiments in real world are needed; unfortunately, the control of experimental conditions is almost impossible out of laboratories, leading to higher difficulty and complexity in analysis and understanding.

In the recent years, more powerful and more adapted statistical methods have been introduced in behavioral sciences. Unsupervised analysis, latent modeling or data driven approaches for instance, have shown good properties in supporting more complexity allowing delivering more quantitative insights.

In our recent works about body movements' analysis, we focused on the "mechanist" part of behavior. This was supposed to be the easiest part as it is observable directly, it is of low dimensionality and thus, to some extent, objectively measurable. We showed how advanced statistical modeling could help in developing effective interfaces and also to give new insights about body movements/physiology relationships. We started with developing iconic gestures-based interface to control mobile robots. We showed that the main issues in such interfaces are related to:

1- Inter and intra personal variability,

2- Gestures segmentation

We solved the first issue using classical supervised machine learning tools, namely SVMs. For the second issue, we moved towards data driven and unsupervised techniques (change point model detection) in order to extract meaningful gestures present among inconsistent body movements (gesticulations). Another use of specific statistical tools was done to understand the relationships between body movements and some physiological signals. Here as well, our data driven approach allowed us to find out objectively how electro-dermal activity can predict movements.

In the following, we give the headlines of our approaches and more importantly, we discuss the difficulties we faced and the ways we circumvent it. We give also our recent line of research, which introduces some a priori "mechanist" knowledge to master the interpretation space.

## II. GESTURES, GESTICULATIONS AND BODY MOVEMENTS IN THE WILD

### *A. Model driven data analysis*

A large part of communication among humans and behaviors humans can exhibit are conveyed through nonverbal channels. Typically, facial expressions, body postures and gestures are considered complementary information to make speech messages more effective. Even if this assertion is still under debate, in HRI and with the lack of efficient speech recognition and understanding systems, gestures the usual candidates allowing naïve users to control robots through iconic gestures. The later are studied since the 40's under different aspects. Indeed, David Efron has initiated the analysis and classification of gestures for ethnography purposes. He postulated four main features to describe gestures: 1) spatio-temporal aspects, 2) the topographical relationships between the interacting persons, 3) The linguistic content and 4) gesticulations.

In our research, we focused on a class of gestures, namely, Emblematic/autonomous/symbolic gestures. These arm movements arm are usually accepted as face-to-face social gestures conveying self-contained semantic meanings. In other words, they do not need any additional information to be understood. These gestures are known to be structured and can be described through arm motion (joints position). The sequences have three main phases (pre-stroke, stroke and post-stroke), corresponding respectively to the preparation of the gesture; its execution and the return back to a rest position. On the basis of this structure, we developed a recognition system [1,2]. For this system, we made the assumption that the iconic gestures are segments that can be isolated, i.e., the pre-stroke and the post-stroke can be extracted. Accordingly, we developed a segmentation routine based on this assumption. We showed that controlling a robot using iconic gestures is feasible using a simple SVM to classify accurately a set of five iconic gestures. The system worked well in lab conditions, where people were instructed to be careful in performing the gestures. Unfortunately, the system failed in real life conditions: the robot was unable to extract meaningful gestures when other body movements were performed (gesticulations for instance).

### B. *Segmenting human gestures*

To separate between iconic gestures and gesticulations (respectively structured movements and chaotic ones), we considered arm movements are multivariate time series. According to our initial hypotheses (structured *vs* unstructured), we hypothesized statistical structure changes between gesticulations and gestures. That is to say, we considered gesticulations and iconic gestures as random variables drawn from different distributions. Following this hypothesis, we quantized the multivariate time series and we applied a T-test CPM (change point model) technique.

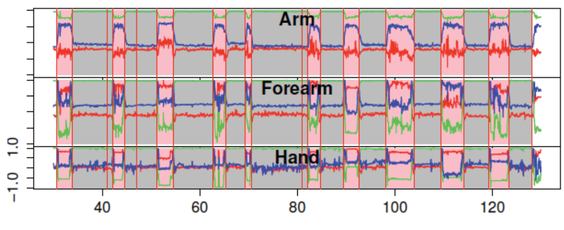


Fig. 1. Right arm movements segmentation

The developed technique [3] allowed us a high accuracy in segmenting upper body movements and thus good rates in recognizing robot controls. Through this work, we showed that a simple discrimination based on a weak hypothesis (distribution difference) is enough to perform meaningful segmentation.

## III. Physiciological signals in the wild: what we can learn from Electrodermal activity

Electro-dermal activity (EDA) or equivalently the skin conductance (SCR) are known as good candidate features to measure the stress when performing interactions or experiencing stressful situations. Unfortunately, EDA is observed also when physical efforts are performed: moving arms, walking or just standing induces EDA, which has to be considered as artifacts. Following that, it has been highly recommended to measure EDA-SCR in static situations, mainly with fixed arms as the sensors were placed on the wrist, the hand palm or on feet. In real life situations, humans are moving, if not continuously (walking or discussing), at least the static position does not last for long times. Limiting studies to just static situations seems to be too strong and prevents from observing realistic behaviors. The second point deals with stimulations. Except with movies, most of research uses predetermined stimulus. That is to say, photos, sounds or other physical activities that produce high-level emotions. These lab conditions cannot be applied to real life. In our work, we aimed at understanding the relationships between EDA and movements in real stressful conditions: PhD students' public defenses were recorded and analyzed using the extreme values theory (EVT). We confirmed the existence of EDA/movement artifacts. More important, we found out that EDA can predict movements: people perform movements after EDA increases (likely to lower the stress). In this work [4], we didn't use any model except the fact that EDA peaks are rare events with a tail-shaped statistics. The data showed us a phenomenon no observed before.

## IV. Conclusions and Recommendations

In our work concerning human movements analysis, we showed that classical approaches cannot be applied to real life conditions and data driven techniques are more suitable to perform recognition tasks and more. We are pursuing this trend with the inclusion of minimalistic mechanist hypothesis: namely, we consider the movement as originated by latent forces, themselves issued by compact neuro-controllers.

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# Identification of human body dynamics for evaluating assistive devices

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***Abstract*— Human assistive devices are expected to support daily life in several nations, and are studied and developed intensively. In order to promote the industrial expansion in this field, the quantitative evaluation about their effect on humans will have a great role. Though human motion capturing can estimate the joint trajectories and torques of each person when using a device, the measurement or estimation of his/her subject-specific parameters is essential for the accurate evaluation. This paper presents our work about the identification of whole-body geometric and inertial parameters by using motion capture system and force plates.**

## I. Introduction

Recent development of human assistive devices have been gathering attention in several nations entering the super-aged society. They are expected to support both the daily life of elderly people and to relieve the burden on nursing-care workers. However, the difficulty of evaluation often leads the slow development and implementation of the devices. The reliable evaluation framework of the devices, especially for the assistive performance on human body, needs to be developed for industrial growth, and has recently been studied and investigated [1], [2].

Human motion capturing also has an important role to estimate human joint trajectories and torques during when using an assistive device. Inverse kinematics and dynamics analysis of human motion [3] often need each human model whose inertial and geometric properties are known. The accurate motion analysis of each human subject requires the measurement or estimation of his/her parameters, and those techniques have been studied and developed [4], [5], [6], [7], [8], [9]. Non-invasive and simple technique becomes important for such a subject-specific analysis; on the other hand, a lot of properties of whole body segments also need to be obtained for the whole body analysis. Most techniques are difficult to satisfy both requirements.

In the field of robotics, the identification methods of a robot including a humanoid robot has been developed [10], [11], [12]. Based on the robotics technologies, the identification of human subject specific parameters has been studied [13], [14]. This paper presents the method to identify the geometric and inertial parameters of whole body segments by using motion capture system and force plates.

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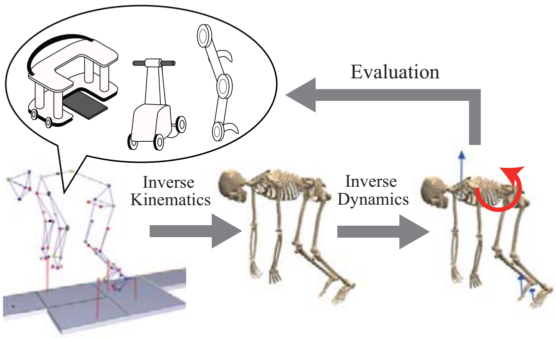


Fig. 1. Flow of the human motion analysis by using motion capture.

## II. Inverse kinematics and dynamics analysis

Robotics computation theories are applied for human motion capturing in recent days [3]. Inverse kinematics computes the human joint trajectories from human motion capture data. Inverse dynamics can calculate the joint torques from joint trajectories and external forces from the ground and the contact objects. Fig.1 shows the flow of the analysis. They are introduced in this section.

### A. Inverse kinematics

Let us model human skeletal system as a multi-body system. The system consists of $N_L$ rigid bodies. It has a floating base-link whose generalized coordinates is represented by $\boldsymbol{q}_O \in SE(3)$. Each joint connecting bone is considered to be a mechanical one such as a rotational or spherical joint. Let $N_J$ be the number of DOF of the system, and $\boldsymbol{q}_C \in \mathbb{R}^{N_J}$ be the joint angles. We now define $\boldsymbol{q} \triangleq [\boldsymbol{q}_O{}^T \ \boldsymbol{q}_C{}^T]^T$ as the whole generalized coordinates of the system.

Typical motion capture measures the position of the markers located on an object. Let $N_M$ be the number of markers, $\boldsymbol{p}_i(\boldsymbol{q}) \in \mathbb{R}^3$ is the position of markers in the space, and $\widehat{\boldsymbol{p}}_i \in \mathbb{R}^3$ is the measured position of each marker. The inverse kinematics solves the nonlinear optimization problem to minimize the following cost function.

$$\min_{\boldsymbol{q}} \ \frac{1}{2} \sum_{i=1}^{N_M} \sigma_i ||\boldsymbol{p}_i(\boldsymbol{q}) - \widehat{\boldsymbol{p}}_i||^2 \qquad (1)$$

where, $\sigma_i(> 0)$ is the weighting factor of the measurement error of each marker. There are several algorisms to solve the nonlinear optimization problem [15], and the efficient method for large-scale human musculoskeletal system has also been proposed [16].

### B. Inverse dynamics

The equations of motion of legged systems are given by Eq.(2).

$$\begin{bmatrix} \boldsymbol{H}_{OO} \, \boldsymbol{H}_{OC} \\ \boldsymbol{H}_{CO} \, \boldsymbol{H}_{CC} \end{bmatrix} \begin{bmatrix} \ddot{\boldsymbol{q}}_O \\ \ddot{\boldsymbol{q}}_C \end{bmatrix} + \begin{bmatrix} \boldsymbol{b}_O \\ \boldsymbol{b}_C \end{bmatrix} = \begin{bmatrix} \boldsymbol{0} \\ \boldsymbol{\tau} \end{bmatrix} + \sum_{k=1}^{N_c} \begin{bmatrix} \boldsymbol{J}_{Ok}{}^T \\ \boldsymbol{J}_{Ck}{}^T \end{bmatrix} \boldsymbol{F}_k^{ext} \tag{2}$$

where, $\boldsymbol{H}_{ij}(i,\ j = O,\ C)$ is the inertia matrix, $\boldsymbol{b}_i$ is the bias force vector including centrifugal, Coriolis and gravity forces, $\boldsymbol{\tau}$ is the vector of joint torques, $N_c$ is the number of contact points with the ground or the devices attached on the human body, $\boldsymbol{F}_k^{ext} \in \mathbb{R}^6$ is the vector of external forces exerted to the system at contact $k$, $\boldsymbol{J}_k \triangleq [\boldsymbol{J}_{Ok} \ \ \boldsymbol{J}_{Ck}]$ is the basic Jacobian matrix associated to contact $k$.

In order to compute the joint torques from Eq.(2), we need to compute the other variables in Eq.(2). Inverse kinematics computes $\boldsymbol{q}_O$ and $\boldsymbol{q}_C$ from the position of markers. We can compute the numerical derivatives of them, and then obtain $\boldsymbol{H}_{ij}$ and $\boldsymbol{b}_i$. When the contact situation is known, $\boldsymbol{J}_k$ can be also computed. Contact forces $\boldsymbol{F}_k$ can be directly measured by force plates or force sensors. When evaluating the human motion using assistive devices, if the simulation model of the device is known or identified, $\boldsymbol{F}_k$ can be also estimated from the model [2]. In the case of multiple contact situation, $\boldsymbol{F}_k$ can be estimated by solving optimization problem [3].

## III. Identification of Human Geometric Parameters

Inverse kinematics problem Eq.(1) requires the geometric parameters of the skeletal model. This section presents an identification method of the geometric parameters [13].

Let $N_\xi$ be the number of the geometric parameters, $\boldsymbol{\xi} \in \mathbb{R}^{N_\xi}$ be the constant geometric parameters. Marker position $\boldsymbol{p}_i(\boldsymbol{q}, \boldsymbol{\xi})$ is regarded as the function of not only $\boldsymbol{q}$ but also $\boldsymbol{\xi}$. Let us define $N_T$ as the number of time samples, $t_1, t_2, \cdots, t_{N_T}$ as a time sequence of motion, $\widehat{\boldsymbol{p}}_i^{(t)}$ $(1 \leq t \leq N_T)$ as the measured positions of marker $i$ at time instance $t$, and $\boldsymbol{q}^{(t)}$ $(1 \leq t \leq N_T)$ as the generalized coordinates at time instance $t$. Given $\widehat{\boldsymbol{p}}_i^{(t)}$ at all the time instances, let us solve the following problem.

$$\min_{\boldsymbol{q}^{(1)}, \cdots \boldsymbol{q}^{(N_T)}, \boldsymbol{\xi}} \quad \frac{1}{2} \sum_{t=1}^{N_T} \sum_{i=1}^{N_M} \sigma_i ||\boldsymbol{p}_i(\boldsymbol{q}^{(t)}, \boldsymbol{\xi}) - \widehat{\boldsymbol{p}}_i^{(t)}||^2 \tag{3}$$

Now, let us represent $\boldsymbol{\xi}$ as the generalized coordinates of virtual mechanical joints. For example, the length between two joints can be represented as a coordinate of one translational joint. With the generalized coordinates of virtual joints, the inverse problem to compute $\boldsymbol{\xi}$ can be also regarded as robotic inverse kinematics. Therefore, Eq.(3) means that the large-scale inverse kinematics problem to compute simultaneously the generalized coordinates $\boldsymbol{q}^{(t)}$ at all the time instances and the virtual coordinates $\boldsymbol{\xi}$ that is time-invariant through all the instances. Hence, the solution can be obtained by applying straightforwardly the recent large-scale inverse kinematics technique [16].

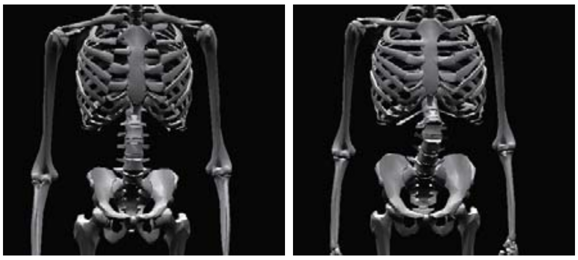

Fig. 2. Comparison of the inverse kinematic results between the two models: the identified model (Left), the template model scaled by the body height of a subject (Right).

The similar formula is found in the methodology used in the calibration of serial robot chains, where both the kinematics parameters and constant joint offsets [10]. The critical difference between the calibration of robots and humans is whether or not the joint angles can be measured directly, for example, by encoders. Therefore, the human joint angle trajectories and the geometric parameters generally have to be identified simultaneously.

The method was applied to obtain a subject-specific parameters of the human musculoskeletal model shown in [3]. The exercise motion of the whole body was recorded for the identification. In the only identification process, the low-dimensional model was used; some bones were grouped in order to avoid the identifiability problem. After the identification, the walking motions were also recorded by the motion capture system. For the validation, the two models were used for the inverse kinematics; (A). the identified model, and (B). the template model simply scaled by the body height of a subject. Fig.2 shows the comparison of the inverse kinematic results between the two models at a certain time instance during the walking motion. In the figure, the muscles are not drawn for illustrative purposes. In the case of the scaled template model, the spine was bent awkwardly because the model is not fitting to a subject. Therefore, the muscle lengths around the spine contained the significant errors. Such kind of a situation often happens, when the ratio of the length of body segments of a subject is different to some extent from that of the template model. The proposed method can obtain a subject-specific human model, which can enhance the accuracy of musculoskeletal analysis.

## IV. Identification of Human Inertial Parameters

When computing the joint torque from inverse dynamics model Eq.(2), not only the geometric parameters but also the inertial parameters assume to be known. This section shows the identification method of the inertial parameters.

The equations of motion of multi-body systems can be written in a linear form with respect to the inertial parameters [17], [11], and Eq.(2) can be transformed to as followings:

$$\begin{bmatrix} \boldsymbol{Y}_O \\ \boldsymbol{Y}_C \end{bmatrix} \boldsymbol{\phi} = \begin{bmatrix} \boldsymbol{F}_O \\ \boldsymbol{F}_C \end{bmatrix} \triangleq \begin{bmatrix} \boldsymbol{0} \\ \boldsymbol{\tau} \end{bmatrix} + \sum_{k=1}^{N_c} \begin{bmatrix} \boldsymbol{J}_{Ok}{}^T \\ \boldsymbol{J}_{Ck}{}^T \end{bmatrix} \boldsymbol{F}_k^{ext} \tag{4}$$

where, $\boldsymbol{\phi} \in \mathbb{R}^{10N_L}$ is the vector of the inertial parameters of whole body segments. Each body segment has 10 parameters:

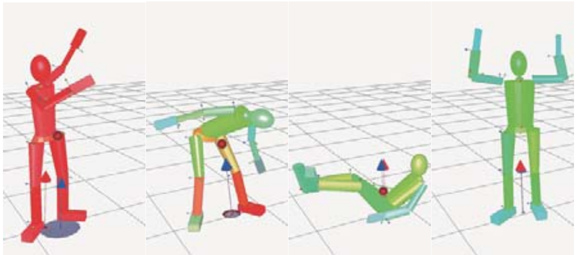

Fig. 3. The visualization interface to display the results of real-time identification. The color of each link shows the degree of progress of identification: red parts are not yet estimated, and green parts are successfully identified. Red arrow is the force plate measurement of contact force, blue arrow is the reconstructed contact force from identified dynamics. The red ball is the total center of mass computed from identified parameters.

mass, center of mass, and inertia tensors [11]. Coefficient matrices $\boldsymbol{Y}_{BO}$ and $\boldsymbol{Y}_{BC}$ are called regressor matrices.

Most common identification methods in the robotics field utilize liner form Eq.(4), and need to know all the variables except $\boldsymbol{\phi}$. However, it is difficult to measure human joint torques directly. Inverse dynamics Eq.(2) also cannot be computed because $\boldsymbol{\phi}$ is unknown. Now, let us formulate the following least squares problem:

$$\min_{\boldsymbol{\phi}} \ \omega_1 \sum_{t}^{N_T} ||\boldsymbol{Y}_O{}^{(t)}\boldsymbol{\phi} - \boldsymbol{F}_O{}^{(t)}||^2 + \omega_2||\boldsymbol{\phi} - \widehat{\boldsymbol{\phi}}||^2 \quad (5)$$

The first term of Eq.(5) evaluates the error about only the upper part of Eq.(4): the equations of the base-link, which does not contain $\boldsymbol{\tau}$. It has been proven that the number of the structural identifiable parameters from the base-link dynamics is the same when using the whole equations [12]. Therefore, in principle, we can perform the identification even without torque measurement. The second term of evaluates the error from a-priori knowledge $\widehat{\boldsymbol{\phi}}$ about the inertial parameters which can be obtained from literatures and databases. Some set of inertial parameters have no effect on the equation of motions. It is known that they cannot be structurally identified [11]. The performance of identification also depends on the motion trajectory used for the identification [11]. A-priori parameters $\widehat{\boldsymbol{\phi}}$ is used for those unidentifiable or less identifiable parameters.

Since the problem Eq.(5) can be solved iteratively, the real-time identification can be realized during motion capturing. One useful application of the real-time identification is the visualization of the identification result [14]. The outline of the visualization is shown in Fig.3; the color of each link changed gradually with the progress of the identification procedure. The human subject can immediately check the body segments yet to be identified, and intuitively know which body part should be moved. Since the performance of identification depends on the motion trajectory, the visualization can improve the quality of identification results. Fig.3 also shows that the estimated contact forces from the identified results (blue arrow) were gradually converged to the measured forces (red arrow). Hence, the method is expected to enhance the accuracy of inverse dynamics analysis.

## V. Conclusion

The paper presents the method to identify the human geometric and inertial parameters for subject-specific modeling. When evaluating assistive devices, the estimation of human joint trajectories and torques has an important role. The inverse kinematics and dynamics analysis by motion capturing require the geometric and inertial parameters of the human model. Our approach can identify the whole-body parameters non-invasively by using standard motion capture system and force plates, which is expected to lead the accurate evaluation of the assistive effects on human bodies.

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# Towards a Low-Cost Autonomous Wheelchair Navigation System Using COTS Components

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## I. Overview

Electric wheelchairs are often prescribed to individuals with mobility challenges. For a subset of users who have upper-body fine motor control impairments due to, for example, spinal cord injury, it is impossible to operate an electric wheelchair using the standard joystick interface. Such individuals must instead rely on other types of assistive control devices (e.g., sip-and-puff switches), which are typically extremely difficult to use. This results in degraded mobility and a substantially deteriorated quality of life.

A robotic navigation system for electric wheelchairs, which would allow the chairs to self-navigate in home and workplace environments, would dramatically improve users' mobility. However, at present, no widely available navigation system for wheelchairs exists, although the problem has been explored since the early 1980s [1]. Part of the reason is cost—much of the research to date has focused on the use of specialized sensing hardware. The prohibitive expense of such hardware makes the near-term, commercial deployment of a viable system unlikely.

Given significant recent advances in (inexpensive) navigation sensor technology and the continued maturation of open source robotics software, our research group recently asked the question: is it possible to build a reliable and low-cost autonomous or semi-autonomous wheelchair navigation platform using commercial-off-the-shelf (COTS) hardware and open source software only? In this extended abstract, we report on our initial progress towards answering this question by developing a prototype wheelchair navigation system with our industrial partners, Cyberworks Robotics, Inc., and Simcoe Habilitation Services, Inc.

## II. System Description and Capabilities

Our prototype navigation system (shown in Figure 1) is based on a standard commercial electric wheelchair, to which we have retrofitted a Kinect 2 sensor and related computing equipment. While previous research has focused on varying aspects of autonomy, including doorway traversal, wall following, and obstacle avoidance [2], modern simultaneous localization and mapping (SLAM) software enables the unification of these functions within a common navigation framework. We currently use the libfreenect2 open source library to acquire data from the Kinect 2. The second-generation Kinect has a $512 \times 424$ pixel time-of-flight depth sensor and a wide field of view HD video camera. We also use wheel odometry to aid in localization and mapping. All processing is carried out on a commodity laptop powered by an Intel i7 processor.

At present, we have implemented three main software capabilities: large-scale mapping, autonomous map-based navigation, and dynamic obstacle avoidance. We currently use the open source RTAB-Map as our SLAM package (running under ROS, the Robot Operating System) to build and maintain large maps in semi-dynamic environments [3]. An initial map can be built by an operator in real-time, by manually guiding the wheelchair to visit all locations where the platform will be expected to drive. During the mapping process, the SLAM software relies on odometry information to assemble successive point clouds captured by the depth sensor into a 3D map (see Figure 2), and also renders this map into a 2D floor plan. This floor plan must then be validated by the operator and corrected, if necessary, using an interface tool currently in development. RTAB-Map also continually captures RGB images from the Kinect and extracts visual features ('words') that are stored for future lookup to aid in localization and loop closure.

Fig. 1. A commercial electric power wheelchair with the Kinect 2 sensor mounted above the backrest, ensuring a wide field of view.

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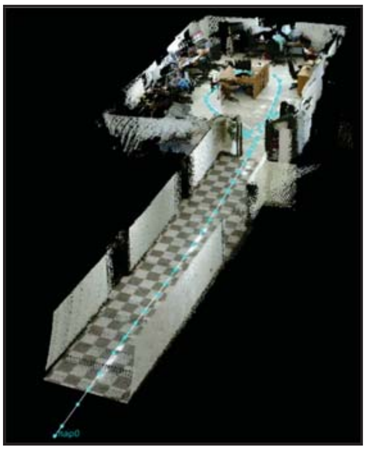

Fig. 2. Three-dimensional map of an office environment generated by RTAB-Map and the ROS Navigation Stack.

For autonomous navigation and obstacle avoidance, we employ the standard ROS navigation stack. The stack ships with a capable global path planner, which uses the 2D floor plan produced by RTAB-Map to compute an obstacle-free path from its current location to a selected goal. The system localizes itself primarily using dead-reckoning odometry. Concurrently, RTAB-Map processes RGB data to correct accumulated dead-reckoning errors by calculating updated pose estimates using recognized visual features.

The global path is then passed to a small-scale planner which builds a real-time map of the immediate vicinity of the wheelchair using live depth data, and adjusts the path to avoid any detected obstacles. A custom filter removes spurious measurements from the raw depth image and then exports a 2D cost map (in which obstacles accrue higher cost). The planner selects the path with the least cost through the navigation space. At present, the control loop operates reliably at 10 Hz, with depth information updated at 3 Hz.

The system is capable of reliably negotiating doorways and other narrow passages while following a smooth and predictable path to its destination. We have found that the system also operates well in complex environments with diverse geometries and scales.

## III. Research Challenges

While we have developed an initial prototype that performs reasonably well in many situations, the general problem of robust autonomous navigation is far from solved (of course). We are now investigating a variety of corner cases and failure modes, which we discuss briefly below.

As with any sensor, the Kinect 2 has some critical limitations. In particular, the unit can have difficulty registering accurate depth information in certain environments. Highly reflective surfaces may return false depth data and light-absorbent materials may produce a very low return signal. Transparent and translucent materials also produce erratic results. These issues could be mitigated by augmenting the infrared depth sensor with other sensors types, although cost would increase.

Due to RTAB-Map's reliance on visual features, localization is difficult in feature-sparse or highly repetitive environments. Importantly, highly repetitive environments may cause aliasing, that is, the false recognition of new environments as previously visited locations. Erroneous loop closure under this circumstance can result in significant mapping errors. A possible solution may be to combine the RGB and depth data to extract more distinct feature signatures.

As implemented, the ROS navigation stack obstacle detection algorithms do not account for floor gaps or other hazardous ground geometry. Also, the system cannot safely reverse because we have no rear-facing sensor.

The frequency and latency of the sensing and control loops necessitate limiting the wheelchair velocity to a modest walking pace, to ensure sufficient time to respond to dynamic obstacles. An upgrade to our on-board computer would partially solve this issue, although we hope to keep power consumption below 150 W (approximately 10% of the capacity of the existing wheelchair power subsystem). A further challenge is that the computer must stably operate at high loads for extended periods of time, without reaching the thermal limits of any of its components, even in high ambient temperatures.

Perhaps the most critical research challenge, that we have yet to address, is to determine how a user will interact with and command the system. There are a myriad of human-robot and human-computer interaction issues to explore. Thus far, we have focussed primarily on navigation performance only.

## IV. Conclusions and Ongoing Work

Over the 6-month duration of the project, we have been encouraged by the progress made towards realizing our goal. The ROS software components that drive the system have largely been used 'out of the box', without the need to write significant amounts of custom code. Our opinion is that the development of a viable, cost-effective COTS-based wheelchair navigation system may soon be within reach.

We hope to address the issues mentioned in Section III in the future, and to further improve the robustness and capabilities of the system. Full navigational autonomy has the potential to improve the safety of users and those around them, while greatly reducing operator fatigue.

We are also planning to begin testing our development platforms in busy home, office, and retail environments, in order to assess and validate its real-world performance. This testing will be carried out under the guidance of occupational therapist, ensuring that we meet the needs of the target community.

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# I-SUPPORT: ICT Supported Bath Robot

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***Abstract*—This paper presents the concept and the architecture of the I-SUPPORT service robotics system and a preliminary discussion on its market potential. The goal of the I-SUPPORT system is to support and enhance older adults mobility, manipulation and force exertion abilities and assist them in successfully, safely and independently completing the entire sequence of showering tasks, such as properly washing their back, their upper parts, their lower limbs, their buttocks and groin, and to effectively use the towel for drying purposes. Adaptation and integration of state-of-the-art, cost-effective, soft-robotic arms will provide the hardware constituents, which, together with advanced human-robot force/compliance control will form the basis for a safe physical human-robot interaction that complies with the most up-to-date safety standards. Human behavioural, sociological, safety, ethical and acceptability aspects, as well as financial factors related to the proposed service robotics system will be thoroughly investigated and evaluated so that the I-SUPPORT end result is a close-to-market prototype, applicable to realistic living settings.**

## I. Introduction

One important measure of morbidity and quality of life is a persons ability to perform Activities of Daily Living (ADLs) such as washing the body, dressing, transferring, toileting and feeding [2], [1]. When people are unable to perform even one of these basic personal care tasks, they become dependent on help from either informal or formal caregivers. As a result, difficulties in performing ADLs are a significant predictor of nursing care home use, significant family financial burden, use of hospital services, use of physician services, and mortality [2], [1].

A number of studies have assessed the extent to which loss of function across ADLs progresses hierarchically and it has been shown that just as there is an orderly pattern of development of function in the child, there is an ordered regression as part of the natural process of aging [2] and quite often the order of the later is the reverse of the order of the former. Loss of function typically begins with those ADLs, which are most complex and least basic, while these functions that are most basic and least complex can be retained to the last. Washing the body (either showering or bathing) is one of the most complex and least basic activities and, thus, is among the first that are lost. In addition it is among the last that are regained during post-surgery recovery. Furthermore, older adults showering is reported as one of the first ADLs that residents of a nursing home population lost the ability to perform [2]. This clearly suggests that support in shower and bathing activities, as an early marker of ADL disability, will foster independent living for persons prone to loss of autonomy and relieve the caring and nursing burden of the family, domiciliary services, medical centers and other assisted living environments.

Although washing the body is one of the high risk activities regarding the ageing population and one of the first ADLs that demand assistance, there has been relatively little work on developing robots that provide hygiene and/or bathing assistance. There have been research efforts towards a robotic bed-bath solution, which applies mostly to immobilised patients and not to the frail older adults group, and there have been research efforts in Japan for the development of a robotic head washer but not of any other part of the body [3]. Hence, there is an unmet need for an ICT-supported service robotics system that will assist the frail older adults in their hygiene tasks by compensating for their loss of strength and flexibility in performing these tasks.

This paper presents the concept of the I-SUPPORT service robotics system, which will be developed in the context of the EU Horizon2020 Project I-SUPPORT. The proposed service robotics system envisions the development and integration of an innovative, modular, ICT-Supported service robotics system that supports and enhances frail older adults' motion and force abilities and assists them in successfully, safely and independently completing the entire sequence of showering tasks, such as properly washing their back their, upper parts, their lower limbs their buttocks and groin, and to effectively use the towel for drying purposes. The I-SUPPORT concept once developed can be readily transferred to the bath environment too.

The structure of the paper is as follows: Section II presents the target group and the system requirements. The overall I-SUPPORT concept, the technological approach and all critical subsystems are described in Section III. The evaluation approach of the proposed service robotics system is presented in Section IV. The market perspectives are discussed in Section V. The conclusions are presented in Section VI.

## II. Target Group and System Requirements

The bathing process involves many functional challenges for the aged population [4], [5], [6]. For example, frail senior citizens often do not have the physical strength to enter the shower space or the bathtub, to perform stand-to-sit and sit-to-stand actions in the shower, or to properly rub their body parts especially those that are in constant contact with the seat. Furthermore, in some cases, they do not have the flexibility (stretching hands, bending, reaching extremities) to guide the showerhead or to efficiently use the cleaning-sponge or towel. For the same reasons, it is difficult for them to properly dry their hair and wipe themselves. According to the aforementioned needs we consider a primary group of users alongside with two additional groups that can potentially have benefits from the development of I-SUPPORT service robotics system.

### A. Primary target group

The primary target group includes senior citizens starting to get increasingly frail, who are able to live independently but experience mild or medium functional disabilities (notably, decline in physical strength and flexibility) and increasing difficulty in their ability to perform ADL, notably showering and bathing activities [4]. In fact this population has been defined by [7] as the presence at least of one on the physical frail indicators among mobility, muscle strength, nutritional intake, weight change, balance, endurance, fatigue, and physical activity. Furthermore, the proposed I-SUPPORT system would benefit all individuals, regardless of their age, suffering from functional impairments, including persons with neurological diseases resulting in muscle weakness or balance problems, as the result of an acute clinical event (e.g. stroke), or a consequence of neurodegenerative progressive disorders (e.g. Parkinson Disease, multiple sclerosis), which can cause deficits of strength in one arm or leg or deficits of balance that results in varying degrees of difficulty in performing bathing activities.

*Secondary target group:* Secondary users are formal and informal carers of primary users, including medical staff of all kinds, nurses, next-of-kin, etc.

### B. Requirements

The major requirements of I-SUPPORT system include safety, reliability, acceptability by users, adaptability to users actions, intentions, cognitive and mobility needs and capabilities. Furthermore, given the sensitive nature of the shower activity, such a system must take into account ethical, sociological and gender considerations. As the ultimate goal is to reach application in real life settings, it should be modular, flexible and cost-effective, requiring minimum interventions to the users bathroom environment.

## III. I-SUPPORT SYSTEM DESCRIPTION

Under the scope of the aimed functionality the showering tasks are classified into: (i) transfer activities: sit-to-stand and stand-to-sit in the bathing space, and (ii) washing activities: pouring water, soaping, scrubbing body parts, rinsing and drying. The service robotics system should accomplish these showering tasks in a semiautonomous mode where the goal of the automation is to fill a gap left by the sensory/motor weakness or impairment of the frail senior citizen and the degree of autonomy will depend on the user abilities and preferences. The system components and the system architecture for realising the semiautonomous I-SUPPORT service robotics system are presented in a concept level in the following paragraphs.


Fig. 1. Concept of the two robotic devices: (i) robotic hose and (i) robotic washing arm. The length of the robotic arm can vary depending the shower space and the ergonomic design. The concept is modular, self contained and easily interfaced with a conventional tab shower infrastructure.

### A. Robotic devices

I-SUPPORT system will accomplish these tasks by integrating three devices which will meet the motion and force requirements of the showering tasks:

- A motorized shower chair: a motorized chair dedicated to the provision of the stand-to-sit and sit-to-stand functionality.
- A robotic shower hose: a soft robotic arm dedicated to the provision of pouring water, soaping etc.
- A robotic washer/wiper: a soft robotic arm dedicated to the provision of scrubbing wiping, drying etc. functionality.

The proposed service robotics devices entail high degree of human-robot interaction since they involve frequent physical interaction. Due to this close coupling of the system with the user, safety is of major concern and is among the highest priority requirements of the service robotics design. This is the reason why the I-SUPPORT consortium opts for a soft robotic arm as part of the proposed service robotics system as shown in Fig. 1.

Their distributed compliance (i.e. the entire structure of the robotic arm is soft) in combination with the soft material (silicon, rubber, etc.) generates little resistance to compressive forces and produces small impacts during contact with humans, which makes them ideal for applications such as personal service robots that interact with people [8], [9]. Moreover, if the soft-robotic arm has adjustable stiffness, then arm sections that interact with the user will exhibit low stiffness while sections responsible for supporting the payload (i.e. lifting a sponge, a folded towel, or simply the rest of the soft-robotic arm structure) will exhibit high stiffness. To this end, the robotic shower hose and the robotic washer/wipe is a continuum robot of tubular shape (resembling a hose), with intrinsic compliant characteristics (i.e. built with soft materials and are deformable and intrinsically safe). Its soft structure is composed of soft lightweight materials and actuators (electromagnetic and/or pneumatic).

### B. Human robot interfaces

The interface of the human with this devices will be accomplished in two ways:

*1) A direct natural haptic interaction:* Human-robot interaction can be provided in a robot passive control operation mode by natural haptic interaction. During this operation mode, the soft robot(s) are guided to the appropriate position by the user, through direct physical (haptic) interaction. In this case, the controller is in charge of actively adapting the apparent mechanical properties of the robot arm, to ameliorate the haptic feeling this interaction creates to the elderly population. The robot performs gravity and friction compensation and this way holding and moving the soft-robot arm becomes transparent to the user in the sense that he/she does not feel the weight and the friction of the manipulator and improve its manoeuvrability.

*2) Remote control / Sensor bar:* Human-robot interaction can be provided by tele-manipulation of the soft robots (robotic shower hose or washer/wipe). The user using a remote controller, i.e. a lightweight remote controller similar to those used in video games (e.g. Wiimote [10]), will guide the soft-robotic arms. It is envisaged that the senior citizen seated on the shower chair, would be able to grasp the remote controller and perform small smooth motion patterns, as she/he would do for washing her/himself. These motion patterns would not need to be accurate and detailed as they will be intelligently translated into actuator commands and robotic motions in a master/slave mode (user/robot). Thus, simple, not accurate, weak (no need to apply force) and most importantly natural motions (all users are familiar to those) of the user's hand would provide the data required (through the sensors within the sensors bar) and interpreted to robots actions that would perform tasks like rinsing, soaping and scrubbing (depending on the object that the end-effector e.g. sponge, towel etc).

### C. Robotic cognition system

The goal is the development of integrated service robotics system that are responsive to the user's needs and are fully adaptable to the users behaviour and abilities, in particular to his/her manipulation and force exertion abilities. For this purpose the I-SUPPORT service robotics system will integrate robot cognition which will be based upon:

*1) Action and gesture recognition:* To be able to give the appropriate aid to frail senior citizens, it is necessary for the I-SUPPORT system to successfully interpret the users intent and adapt to his/her capabilities on-line and real-time (i.e. while the person is performing showering activities). Therefore, pivotal role in the I-SUPPPORT concept plays the design and development of cognitive robotic and learning algorithms for real time gesture and intention recognition, which based on a set of control primitives (very basic control commands whose combination yields complex motion patterns) generated during a preliminary learning process, are responsible for choosing the most likely motion intention, given a set of measurements, and assist its completion. Based on these identified motion intentions, the control system of the I-SUPPORT service robotics system will generate customisable motion and force commands for the robotic components of the system that will assist the senior citizen to accomplish the showering tasks.

*2) Customization of automation to the senior user profile, needs and preferences:* As mentioned in the previous paragraph, the formulation of the automated behaviours themselves might be customized. Contextual system and machine learning are natural candidates to accomplish such customization. We hypothesize that an optimal trade-off in human robot control will be unique to: (i) the users sensory motor capabilities, (ii) their personal preferences, (iii) their medical condition and (iv) possibly also the task at hand. For this purpose we will develop personalized washing and drying behaviors, which take into account users preference and previous sensorimotor experience. Starting from a reference model of the human body, which defines the kinematics and dynamics of the human body based on global body parameters such as height, weight, we will derive individual models of the different users. In addition, we will develop methods based on reinforcement learning techniques, which take into account user rituals, behaviours related to bathing and preferences.

### D. Control architecture

A multilayered architecture is proposed to cope with the multiple levels of the control problem (shape, stiffness, position, and force/impedance control). Evidently, there is a high degree of interaction between the different control levels, meaning that the control problem cannot be completely decomposed into independent distinct layers of control. Moreover, there is a "meta redundancy" in the problem, in the sense that the same control objective can be accomplished with different combinations of actions in the various control levels. Therefore, the multi-layer architecture has to seamlessly integrate all levels of control, addressing problems that range from achieving low-level control specifications in terms of motion planning and tracking performance, to embedding high-level control behaviours involving task and path planning.

All modalities of the multilayered control architecture involve human-robot interaction (HRI) control, where both the end-effector interacts (physically or non-physically) with the part of the body that is being washed/scrubbed, as well as the user interacts with specific parts of the soft robotic arm (e.g. in passive control mode). A possible approach to this problem of complex interaction between the soft-arm and its environment is not to use analytic modelling techniques but, instead, to encode the relevant control skills in internal models built by learning from experience in the real physical world. The internal models will encode the correlations between sensory and motor data, consequently encoding the part of control that is done by the morphology of the body interacting with the environment. The control problem can then be formulated as a hybrid position/force control strategy, which can in fact be based on an adaptive dynamic impedance control structure, where 3D human-robot interaction tasks will be performed combining force feedback and visual servoing in an uncalibrated workspace. Successful implementation of the algorithms will validate the hypothesis that the active compliance capabilities (i.e. adjusting the stiffness) allow the successful implementation of complex human-robot interaction schemes. Other approaches (i.e. more analytic) could also be tested.

### *E. Context awareness system*

The I-SUPPORT service will also integrate context awareness and alerting functionalities and will, thus, raise proper alerts in case of events (e.g. the water temperature is too high, the bathroom is overly humid, the bathroom window is open, etc.). As falls are frequent in the bathroom/shower environment, I-SUPPORT will also integrate fall detection so that next of kin or a health centre is immediately notified via e-mail or telephone call. A wearable sensor, such as a wristwatch with integrated IMU units, will be employed which in combination with the integrated depth sensors will detect falls and trigger alerts. To cater for the needs of users in the beginning of moderate cognitive disability, the I-SUPPORT system will also detect long inactivity of the user, which may indicate that the user is disoriented and will trigger proper reactions (e.g. provide clear and simple instructions how to proceed, or alert next of kin/carers).

### *F. User and robot pose estimation*

User acceptability is of major concern, therefore we will take into full account all relevant ethical and sociological considerations; we will put special emphasis on the type of information that is collected during the shower activities and how this information is processed for 3D reconstruction and robot control purposes. We will develop efficient computer vision algorithms for accurate human pose estimation and limb localisation from Depth measurements and not from RGB camera measurements. Depth measurements capture the shape and geometry of the user but do not capture detailed face and body features that might reveal the user's ID.

This is a challenging problem where information gathered from more than one depth sensor captured in a noisy environment should be fused and yield accurate robot and human pose estimation. For this purpose, during an off-line training stage we will be using statistical machine learning to train Deformable Part Models for 3D human pose estimation; at test time we will use combinatorial optimization, such as Branch-and-Bound to rapidly deliver exact estimates of human pose. Similar algorithms will be developed to perform 3D localization of the robotic manipulator, treating it as a multi-part 3D shape. On the hardware side this will involve installation of the depth sensors and development of encasing for ensuring depth sensors are waterproof.

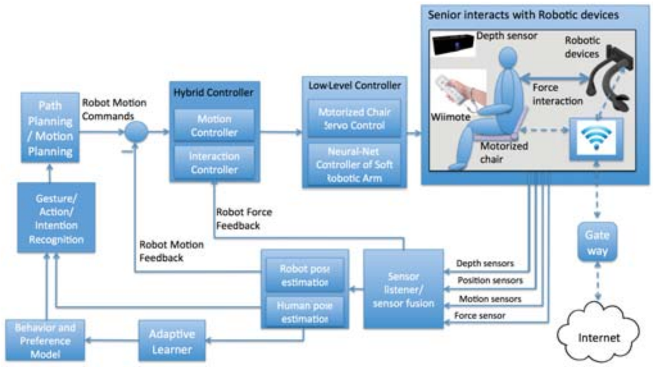


Fig. 2. Block diagram of the I-SUPPORT service robotics system architecture.

### *G. Overall system architecure*

The system architecture is depicted on Fig. 2 where all components of the system and their interconnections are presented in a block diagram structure.

## IV. System Evaluation

In terms of usability evaluation, the project will assess the ease-of-use and acceptability of the I-SUPPORT functionalities according to the relevant norm frameworks (ISO/IEC TR 25060/ ISO/IEC 25062 and DIN EN ISO 9241). In this respect, this partnership will be among the few pioneers in conducting acceptability and usability studies for service robots assisting senior citizens in the shower/bath environment. Tests will be carried out at our clinical partners sites. Overall, we suggest a threefold evaluation strategy:

1) Clinical assessment: using established and valid clinical assessment tests for validation and screening;
2) Subjective assessment: subjective perception of use of the I-SUPPORT system and potential improvements in Quality of Life (QoL);
3) Tailored assessment of the I-SUPPORT system as a whole and its components, by combining technical assessment strategies, as defined by the technical partners of the Consortium, with clinical perspectives and measures, e.g. measurement of accuracy of robot's motion in supporting the user.

Possible candidates for the standardised scales to be used for usability and acceptability evaluation during the project lifetime are enumerated below.

- The Quebec User Evaluation of Satisfaction with assistive Technology (QUEST) will indicate the subjective aspects of the assistive device usability.
- The Psychosocial Impact of Assistive Devices Scale (PIADS) consists of 26 items that have been factor analysed and have yielded three distinct subscales which can clearly be considered as indices of quality of life (QOL). These are competence, adaptability, and self-esteem.

- Technology Acceptance Usefulness TAM has been developed by Davies and looks at ease of use and perceived usefulness.
- The Unified Theory of Acceptance and Use of Technology UTAUT will evaluate the acceptance of the service robotics system.

The selected instruments will be adapted to the I-SUPPORT system and complemented by qualitative questions.

## V. Market Indicators

### A. The need expressed in numbers

The percentage of people in need of care in comparison with the total population is 2.6% today expected to rise to 3.6% by 2020 and to 4.4% by 2030 [11]. This percentage will keep rising, given that the percentage of population over 80 years of age is set to almost treble by 2060. Owing to a shortage of family-member carers, long-term care in retirement facilities will in the near future become the most common form of care and will account for almost half of all care cases. The most significant cost driver in senior citizen's homes is staff costs (approx. 70% with higher percentage for day care greater than 90% and lower percentage in hospitals). Non-labour costs make up approx. 20% of costs in residential care homes [11]. Introducing service robotic systems in care facilities will make the elderly more independent and will enable servicing a large number of seniors while reducing the incurred staff costs.

### B. The demand expressed in market size

The market size of retirement facilities (senior citizen's homes) in 2015, in US, is estimated at $60.2 billion and involves 16795 businesses. Its key performance drivers are the aging population and life expectancy, the increasing housing price index and the improvement in retirement facility living conditions. The revenue is expected to slightly increase by 2020 ($65 billion) [12]. The market size of home care in 2015, in US, is estimated to be approximately $74.5 billion and involves 304350 businesses. Its key performance drivers are the rising costs of institutional care and medicare spending and regulation changes. The revenue of this market is expected to reduce by almost 50 percent the following years (40 billions in 2020), [12]. Assistive service robotic systems such as I-SUPPORT could be provided also as a home care installation and therefore families interested in home care are also part of the I-SUPPORT market size.

Overall the aforementioned numbers reveal a market whose size is expected to be about $ 100 billion by 2020 and which is comparable to the Internet industry ($120 billion), the biotech industry ($82 billion) and the renewable energy industry ($83 billion) [13].

### C. The size of the service robots industry

According to euRobotics report [11], the number of service robots in use in both commercial applications and domestic/private applications is on the rise (average growth of over 10% per year since 2003). Robotics in personal and domestic applications is characterized by few mass-market products: floor cleaning robots, robo-mowers and robots for edutainment. According to this report, approximately 250 companies worldwide are involved into the development, manufacturing, sales and distribution of service robot systems and related components. The key category related to I-SUPPORT is that of Robotics in personal and domestic applications. These service robots are characterized by significantly lower unit value in comparison with those for professional use. They are also produced for a mass market with completely different pricing and marketing channels. Sales of all types of robots for domestic tasks have reach almost 11 million units in the period 2012-2015, with an estimated value of US $4.8 billion. Sales of all types of entertainment and leisure robots are at about 4.7 million units, with a value of about US $1.1 billion. This market is expected to increase substantially within the next 20 years.

In conclusion, there exist a strong need for assistive robots in personal and domestic applications, while at the same time the relevant market is large, is based on solid key performance drivers, and exhibits a steady rising trend, i.e. there is a large and growing demand. The industrial sector of service robots, and in particular of assistive robots for the elderly in personal and domestic applications, is on one hand an industry which has demonstrated already capacity for sustainability and growth and on the other hand it exhibits moderate competition because it is a relatively recently established sector. In particular, the competition of assistive robots for the bathroom is very low since I-SUPPORT is the first effort to provide robotic solution for assisting the elderly during shower. Hence, all market indicators show that I-SUPPORT has the potential lead to a competitive product that could successfully penetrate the large and continuously growing market of assistive devices for the elderly.

## VI. Conclusion

The I-SUPPORT service robotics system will support and enhance older adults mobility, manipulation and force exertion abilities and assist them in successfully, safely and independently completing the entire sequence of showering tasks, such as properly washing their back, their upper parts, their lower limbs, their buttocks and groin, and to effectively use the towel for drying purposes. Adaptation and integration of state-of-the-art, cost-effective, soft-robotic arms will provide the hardware constituents, which, together with advanced human-robot force/compliance control that will be developed within the proposed project, will form the basis for a safe physical human-robot interaction that complies with the most up-to-date safety standards. Human behavioural, sociological, safety, ethical and acceptability aspects, as well as financial factors related to the proposed service robotics system will be thoroughly investigated and evaluated so that the I-SUPPORT end result is a close-to-market prototype, applicable to realistic living settings. Market indicators such as market size, industry size and cost reduction, stress out the potential for a competitive product that could successfully penetrate in a large and continuously growing market.

### ACKNOWLEDGMENT

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# Design and implementation of new robotic walker devices

## Lessons learned and industrial perspectives

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***Abstract*—This talk addresses the essential methodological aspects of a collaborative development a robotic walker. Being a classical mechatronic system, created within a framework of a mixed research / engineering project, this device poses typical challenges on the developers, that need to tackled in a systematic way. Based on the lessons learned from similar projects, the author proposes an approach that might be generalisable.**

***Keywords*—mechatronic design, v-cycle, sit to stand**

## I. Introduction

The MOBOT Project aims at developing intelligent walking assistant for people experiencing certain mobility problems. The two main target groups are i) users that have sufficient own gripping force in their hands ii) the users that do not have this force. Therefore it is necessary to develop two types of walking assistants; correspondingly the 'rollator type' and the 'nurse type' devices. The project is realized by a interdisciplinary consortium constituted by a number research partners, end users and an engineering company and aims at developing a technology demonstrator covering the early prototype phases: Concept Development, Technical Development, Beta Testing.

## II. Methodology

A solid methodology is necessary due to an ambitious goal of evaluating the functional prototype in a real world environment, so the prototype must achieve the required maturity level within the project lifetime. Moreover, the MOBOT project is based on a user-centred design approach (see Figure 3), where the users' needs are concerned from the beginning of the project until the end by means of on-going user involvement into the development and evaluation of each component and of the whole system in real world tests. The major difference from other design philosophies is that the technology is designed according to how users can, want, or need to use it, rather than forcing the users to change their behaviour to accommodate to the technology.

The overall concept of the work on project is based on the V-cycle paradigm, based on "methodology of development of mechatronic systems" as of VDI2206 combined with the ISO 13407 "Human-centred design processes for interactive systems", adapted to an innovative project enabling feasibility studies, early evaluation of prototypes and possibility of revising the technical specifications. Continuous involvement of users requires that the development methodology is flexible enough to adapt to changing requirements. The development stages (User Requirements, Functional Design, Architectural Design, Component Design and Evaluation, System Integration and Evaluation) are organized in cycle resembling the letter V, see Fig. 1. The left hand side of the V is devoted to analysis and design of the system, the right hand side to the system integration and evaluation. One can also distinguish the User, System and Component Levels giving additional perspectives of top (user) and down (implementation) viewpoints. As the system maturity increases with each cycle, so deeper grows the understanding of the user needs, technological possibilities and constraints.

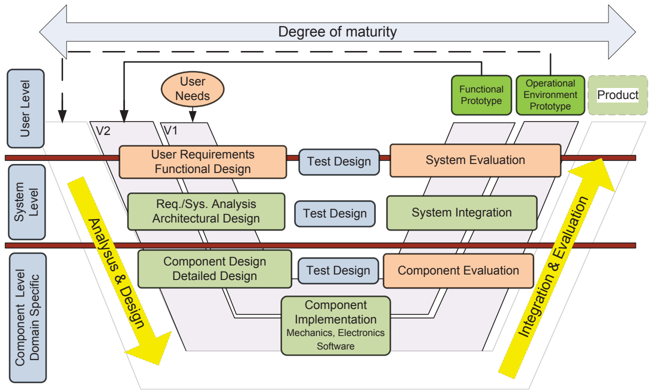


Fig.1. MOBOT development methodology blending ISO-13407 with VDI2206

Correspondingly, each development cycle begins with formulating the user requirement and ends up with the evaluation of the system by the user. As the system maturity increases with each cycle, so deeper grows the understanding of the user needs, technological possibilities and constraints. For the rollator type device, it is envisioned to perform two full cycles within the project: V1 ending with a functional prototype, and V2 ending with a prototype tested in the operational environment. For the nurse type device, only the V1 cycle is planned, timely realized in parallel to the V2 cycle for the rollator type.

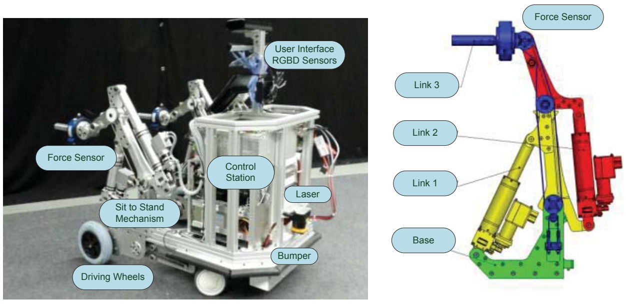


Fig. 2. V1 version of the rollator type device

## III. IMPLEMENTATION

### A. System Design

The user groups and their specific needs are captured by the clinical partners and comprise the specification of use cases, performance metrics/assessment strategies, and user evaluation studies relying on the expertise in gerontology and rehabilitation. Several design constraints were identified based on the working area (e.g. narrow spaces in bathroom, steps and slopes), anthropometrics (e.g step size, walking speeds), and user needs. Environmental conditions have been studied by the technical partners using a CAD model including walls, doors, furniture, slopes in order to study the maneuverability in the nominal (e.g. way from the patient room to cafeteria) and narrow (e.g. toilet) spaces.

The two main functionalities of the assistive walker are i) to offer active support during walking and ii) to support the user while standing up or sitting, the so called sit-to-stand (STS) transfer. In order to perform the necessary mechanical design, the geometry and the mass properties of the target user group were modeled based on human data and served as input to the biomechanical optimizations of the STS and walking [2]. The output of these computations are the optimal force/motion trajectories being used as input for the electro-mechanical design of the mechanisms.

### B. Mechanical Design

The first version of the rollator was developed based on the measurements of the desired workspace and forces profiles performed with real patients, using a steel bar with dummy handles. The forces were measured using force sensors attached to the handles and the workspace and the kinematics of the patient was recorded using vision sensors. The resulting workspace has the size of approx. 30x30cm and the required lifting force is in the range of 224 N. The device developed accordingly is shown in Fig. 2. The main components are the mobile platform, the STS mechanism and the perception and computing workstations. The mobile platform is driven by two active wheels further supported by two castor wheels. The STS mechanism contains two separately driven handles for independent control of the left and right arms. Each arm has two active degrees of freedom and 1 passive degree kept parallel to the ground by means of tendons. The arms are driven by custom made linear actuators with DC motors, ball screws and brakes. In terms of sensing, the motion of the motors is sensed by high resolution encoders; additionally the motor currents are sensed and the interaction forces are measured by force sensors in the handles. The device undergoes the evaluation studies with the clinical partners in the real world environment.

The V2 version of the rollator is developed according to the force/motion profiles resulting from [2]. It turns out the initially chosen motorization cannot handle the required performance and it is necessary to develop drive units of a different characteristics. Currently high power density drive module consisting of a torque motor, harmonic gearbox, brake and position encoder are developed by ACCREA Engineering.

The main concept behind the nurse type device is to mimic the actions of a human nurse helping a person to stand up, as shown in Fig. 3. The human supporter is exerting forces onto the patient's knees and mid-trunk, at the same time offering support for the patient's arms. The mechanism of the nurse type device shall work according to the same principle. As in the case of the rollator, the biomechanical optimization was performed in order to obtain the force/motion profiles of all the actuators. These computations resulted in desired support forces and the trajectories of their application points.

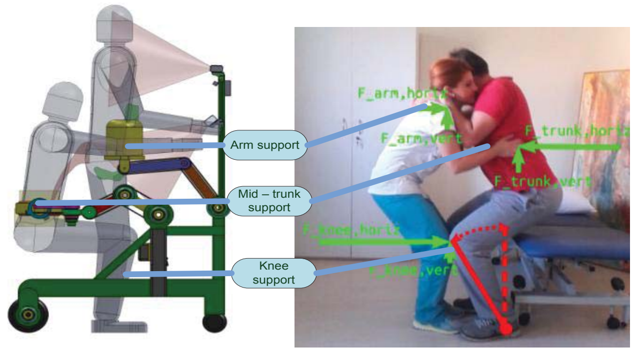


Fig. 3. Conceptual design of the nurse type device

### C. Safety Design

The main goal of the safe design is to design robots so they are intrinsically/mechanically safe, i.e. avoiding hazards instead of controlling them. Therefore low power drives limiting external forces / speeds, back drivable mechanisms are chosen. However, assuring intrinsic safety is not always possible and the full safety and risk analysis must be performed. This is planned to be accomplished according to the ISO standards ISO 13849, ISO 13482 and ISO 12100.

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# Development of a Human-Friendly Walking Assistive Robot Vehicle

Jorge Solis, *Member*, *IEEE*

*Abstract*—Up to now, the embodiment of bodily-kinaesthetic, perceptual and cognitive capabilities for assistive robots has been scarcely studied. This research aims to incorporate and develop the concept of robotic human science and to enable its application in a human-friendly robot for assistive purposes. In this paper, the author describes a human-friendly walking assist robot vehicle developed at Karlstad University designed to provide physical support to the elderly. The proposed system is composed by two-wheeled inverted pendulum mobile robot, a 3-DOFs haptic interface, a mobile computer and a wireless module for communication purposes. Preliminary experiments to verify the stability of the whole system and to validate the feasibility to exert force feedback under dynamic conditions are presented.

## I. Introduction

Even though the market size is still small at this moment, applied fields of human-friendly robots (e.g. assistive robots) are gradually spreading from the manufacturing industry to the third industry. Several companies have introduced assistive robots into the market. Some examples are the GiraffPlus telecare platform designed to help the elderly to stay in touch with care givers, relatives and friends [1], the robotic eating device Bestic designed for persons with reduced or no capability in their arms or hands [2], etc.

On the other hand, most of the research has been mainly focused in developing assistive robots for the elderly in terms of telepresence robotic platforms designed for maintaining the elderly social contacts ([3] and [4]), wheeled walker platforms designed for turning away from obstacles and prevent elderly from accidents ([5], [6] and [7]), pet-like robots designed for raising the quality of life among people with dementia in the later stage of their illness ([8]).

In particular, different walking-aid robots have been proposed during the last decades [9-14]. In particular, the walking-aid robots can be classified in two main groups according to the mobility factor [9]: active-type walkers driven by a servo motor (e.g. [11-12]) and passive-type walkers driven by a servo brake (e.g. [13-14]). Spenko proposed in [10] the PAMM system together with a smart cane robot with a relative small size but the maneuverability is compromised by the cost. Fukuda introduced in [9] an intelligent cane robot consisting of a stick, a group of sensors for recognizing the user's intentions and an omnidirectional mobile platform. However, the physical support is provided by means of a fixed length and stiffness aluminum stick and cannot be customized depending on the needs of the specific user (required level of physical support during their daily activities) and environmental conditions (indoor/outdoor). From those researches; a special focus has been done in terms to increase the level of multimodal interaction, sensing and control to facilitate the perception of the environment for a better guidance and provide a static physical support to avoid falling down. However, dynamic physical support (e.g. by means of a variable stiffness mechanism), the adaptability to the user/task needs (e.g. human-in-the-loop control), and the multipurpose design concept (e.g. provide support to the elderly and/or care gives) have been scarcely studied.

For this purpose, at Karlstad University, the author introduced in [15] to incorporate and develop the concept of robotic human science introduced by Takanishi in [16] and to enable its application in a multipurpose human-friendly robot designed to provide physical support to the elderly as well as assisting care givers. On the one hand, models of human motor control and learning, as well as cognition should allow creating truly interactive human-friendly robots; on the other hand, modelling human-friendly robots allows the development for reverse engineering and scientific understanding of human motion, perception and cognition. The focus of the research is embodying perceptual (sensing the incoming stimuli), cognitive (processing the incoming stimuli) and bodily-kinaesthetic (response to the incoming stimuli as a result of combining perceptual and motor skills) capabilities. Due to the complexity of the proposed research, currently two assistive robots vehicles are under development aiming to integrate them into a single platform: an intelligent carrying-medical tools robot vehicle [17] and a human-friendly assistive robot vehicle for supporting physically elderly [18]. In particular, a RGB-D camera and a haptic interface will be mounted in a two-wheeled inverted pendulum robot vehicle.

As for the development of a human-friendly robot vehicle for carrying-medical tools (*iCAR*) [17], the robot is designed for assisting care givers in order to transport medical tools. *iCAR* is composed by a mobile robot vehicle with two-actuated motors and four-passive wheels. A simplified fuzzy logic controller has been implemented for the navigation control and a Time-delay neural network (TDNN) was implemented for the 3D gesture recognition.

In this paper, we present the current research development of a human-friendly walking assist robot vehicle for supporting physically elderly.

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## II. Development of an Human-Friendly Assistive Robot Vehicle for Supporting Physically Elderly

The human-friendly WALKing assist robot vehicle (*hWALK*) developed at Karlstad University [18]. The *hWALK* is composed by (Figure 1): a mobile platform with on board controller and two actuated wheels, a commercial available 3-DOFs desktop haptic interface, a mobile computer and a ZigBee wireless module. In order to place the 3-DOFs Haptic Interface (HI) into the two-wheeled inverted pendulum robot, an ABS holder has been designed with ProEngineer and constructed with a 3D printer.

A desired system's response under terrain even conditions is considered as a constant distance ($d_z$) between the ground and the HI's gripper; a null feedback force ($F_z$ = 0) exerted by the HI should be expected in order to allow free walking motion. However, under uneven terrain conditions, a constant $d_z$ should be maintained by means of an applied force feedback ($F_z \neq 0$). The proposed control system is composed by 4 modules (Figure 2): gravity compensation, force feedback processing, velocity estimation and the wireless communication module (acting as master).

As for the gravity compensation, the mass of the gripper has been computed by using the recursive algorithm proposed in [19]. In particular, during the off-line mass estimation, the direction of the gravity force has been computed; a cubic grid (30 x 30 mm) partition has been defined in the center of the workspace and the apparent mass at each vertex has been estimated. For the on-line mass estimation, a trilinear interpolation has been used to estimate the mass inside the cubic grid

The model reference of the proposed system is shown in Figure 3. In order to compute the force feedback for providing support to the user, the total force is computed by Eq. 1. In particular, the feedback force $F_z$ was computed by means of a spring model as shown in Eq. 2, where $z_{ref}$ is determined as Eq. 3 and $k_{stifness}$ has been experimentally determined ($k_{stifness}$ = 5.91 N/mm). The position of the gripper of the HI along the z-axis respect to the world coordinate reference system ($z_{Pos\_Wcs}$) is computed as Eq. 4. In order to define the desired position of the gripper of the HI ($z_{Pos\_Fcs}$), the user must manually bring the gripper to the desired position and then press the lightning bolt button in the HI.

$$F_{Total\_z} = F_z + F_{z\_comp} \quad (1)$$

$$F_z = k_{stifness} * z_{ref} \quad (2)$$

$$z_{ref} = z_{Pos\_Wcs} - z_{Pos\_Fcs} \quad (3)$$

$$z_{Pos\_Wcs} = (L + z_{Pos\_Fcs}) * cos(\theta_m) - y_{Pos\_Fcs} * sin(\theta_m) \quad (4)$$

Figure 1. *hWALK* developed at Karlstad University.

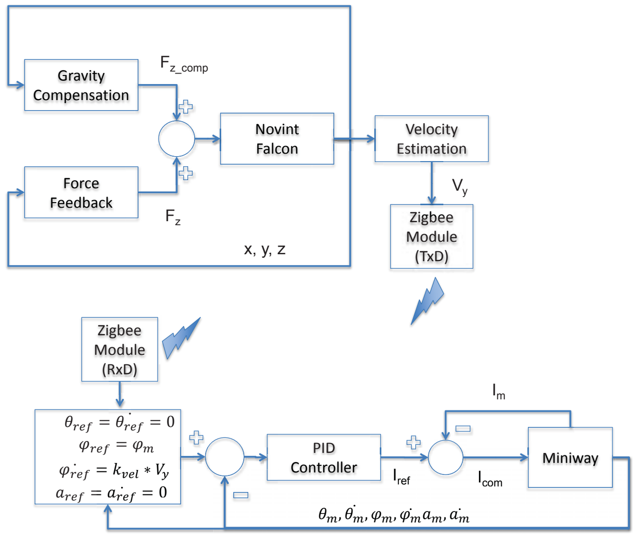


Figure 2. Block diagram of the proposed control system.

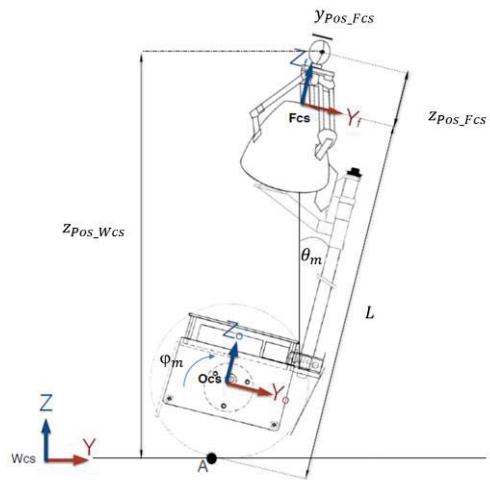


Figure 3. Model reference for *hWALK*.

In order to estimate the reference velocity of the Miniway's chassis, the angular rotation of the chassis with respect to the ground ($\theta_m$) and the position of the gripper ($x_{Pos\_Fcs}$ and $y_{Pos\_Fcs}$) transformed with respect to the ground have been used as shown in Eq. 5, where $\dot{\varphi_{ref}}$ is the desired wheel angular velocity with respect to the ground, $k_{vel}$ is the velocity gain constant that has been experimentally determined ($k_{vel}$ = 100) and $\Delta y$ is the command displacement with respect to the ground which is determined as Eq. 6. Finally, the wireless communication module (acting as master) was programmed to update the HI gripper position ($x_{pos}$, $y_{pos}$ and $z_{pos}$) every 5ms.

$$\dot{\varphi_{ref}} = k_{vel} * \Delta y \quad (5)$$

$$\Delta y = L * sin(\theta_m) + y_{Pos\_Fcs} * cos(\theta_m) \quad (6)$$

On the other hand; the control system for the two-wheeled inverted pendulum mobile robot is composed by 2 modules: the PID controller and the wireless module (acting as slave).

In order to assure the stability of the two-wheeled inverted pendulum with an estimated load of 5kg in the top of the pendulum, the integral part has been included in the proposed PD controller implemented in the commercial version as shown in Eq. 7 and Eq. 8, where $\alpha$ and $\alpha_{REF}$ is the measured and desired heading direction respectively, $i_{outR}$ and $i_{outL}$ is the control signal for the right and left motor current motor respectively, $i_R$ and $i_L$ is the measured right and left motor current motor respectively, $k_1$ is the chassis tilt angle control gain, $k_2$ is the chassis tilt angular velocity control gain, $k_3$ is the wheel angle control gain, $k_4$ is the wheel angular velocity control gain, $k_5$ is the chassis yaw angle control gain, $k_6$ is the chassis yaw angular velocity control gain, $k_7$ is the left motor current control gain, $k_8$ is the right motor current control gain, $k_9$ is the angular rotation chassis integral control gain and $k_{10}$ is the wheel angular rotation integral control gain. The gain parameters for the PID controller implemented for the *hWALK* were determined experimentally ($k_1$ = 186.3; $k_2$= 28.6; $k_3$= 5.8; $k_4$= 4.8; $k_5$= 0.024; $k_6$= 0.015; $k_7$= 1.942; $k_8$= 1.942; $k_9$= 0.01 and $k_{10}$= 0.001).

$$\begin{aligned} i_{outR} &= k_1 \cdot \theta_m + k_2 \cdot \theta'_m + k_3 \cdot (\varphi - \varphi_{REF}) + k_4 \cdot (\varphi' - \varphi'_{REF}) \\ &+ k_5 \cdot (\alpha - \alpha_{REF}) + k_6 \cdot (\alpha' - \alpha'_{REF}) + k_9 \int_0^T \theta_m dt + k_{10} \int_0^T \varphi dt \\ u_R &= k_7 \cdot (i_{outR} - i_R) \end{aligned} \tag{7}$$

$$\begin{aligned} i_{outL} &= k_1 \cdot \theta_m + k_2 \cdot \theta'_m + k_3 \cdot (\varphi - \varphi_{REF}) + k_4 \cdot (\varphi' - \varphi'_{REF}) \\ &- k_5 \cdot (\alpha - \alpha_{REF}) - k_6 \cdot (\alpha' - \alpha'_{REF}) + k_9 \int_0^T \theta_m dt + k_{10} \int_0^T \varphi dt \\ u_L &= k_8 \cdot (i_{outL} - i_L) \end{aligned} \tag{8}$$

## III. Experiments and Results

In order to verify the system stability under static conditions, the chassis of the *hWALK* was held for about 5 seconds until the calibration procedure for the rate gyro was finished. After releasing the chassis, the proposed control system was activated automatically and the system response was verified by logging the chassis tilt angle, chassis tilt angular velocity, wheel angle and wheel angular velocity.

The experimental results while testing the system on a surface with carpet padding are shown in Figure 4. As it may be appreciated Figure 4a, the chassis tilt angle was stabilized in about 16 seconds to the desired angle position (Figure 4a). On the other hand, it can be observed that the first 12 seconds, both the chassis tilt angle (Figure 4a) and chassis tilt angular velocities (Figure 4b) were oscillating periodically around the desired position every 5 seconds (mainly caused by the effect of the load of about 2.7 kilograms corresponding to the ABS holder and HI). Similarly in Figure 4c and 4d, it may be observed that the wheel angle and the wheel angular velocity respectively were deviated around the desired position (mainly caused by the effect backlash of the DC motors as well as the friction of the carpet).

On the other hand, a ramp was constructed (with an inclination angle of 6.7 degrees with a length of 50 cm and a width of 120 cm). A healthy subject was requested to hold the gripper of the HI and set the desired height by pressing

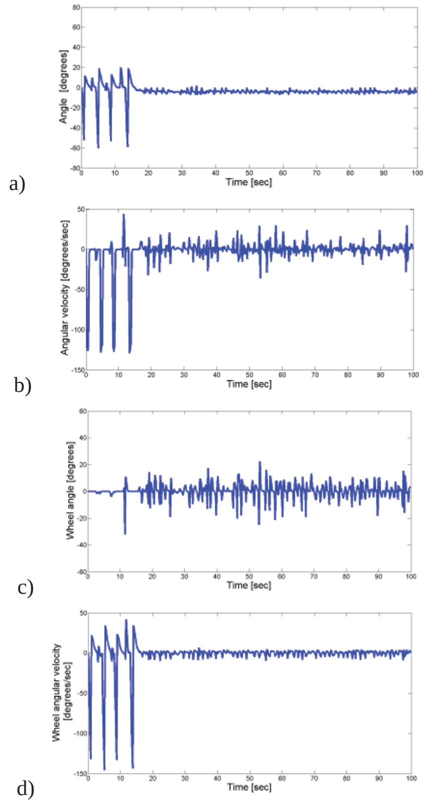


Figure 4. Experimental results obtained under static conditions on a surface with carpet padding: a) chassis tilt angle; b) chassis tilt angular velocity; c) wheel angle; d) wheel angular velocity

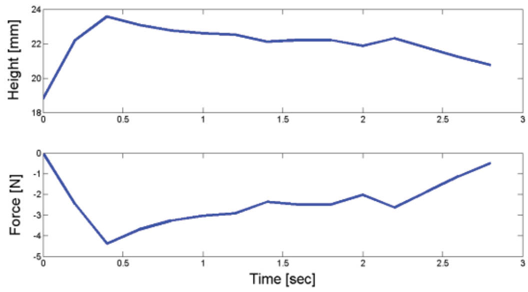


Figure 5. Experimental results with force feedback

the lightning bolt button. Then, the subject was requested to drive up the hWALK. The experimental results are shown in Figure 5. As it can be observed, the desired position of the gripper of the HI set by the subject was 18 mm. During the motion, it can be observed that a maximum force feedback of -4 N was exerted by the HI in order to compensate the height error (due to the inclination of the ramp) within a range of 4 mm. At the end of the top of the ramp, the height error was around 2mm.

## IV. Conclusion & Future Work

In this paper, the development of a human friendly walking assist robot vehicle for providing physical support to the elderly has been described. Preliminary experiment were proposed in order to verify the stability of the whole system as well as to validate the feasibility to exert force feedback under dynamic conditions

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# Socially Assistive Robot for People with Dementia in Home-Based Care

Rajiv Khosla, Khanh Nguyen, Mei-Tai Chu

*Abstract*—**The paper reports on service design, service personalization and deployment of a socially assistive robot (named Lucy) to support older people with dementia in home-based care. The results analyzed from multi-modal data collection of the first ever longitudinal field trials in Australian home-based environments demonstrate that socially assistive robots like Lucy have the ability of breaking technology barriers, positively engaging with its human partner for remarkable frequency and time duration which has a potential to reduce caring time demand and give respire to the carers. This research also provide an evidence base to enable the selection of the robot services that are perceived most positively by people with dementia in home-based care.**

## I. INTRODUCTION

The primary driving force behind this research is the predicted severe shortage of the human element and engagement in aged care in the coming decades. Like most of the developed countries, Australia's population is ageing. Over the next several decades, population ageing is projected to have the need for aged care services is growing at the rate of 68 percent but supply of health care workers is only growing at the rate of 14.8 percent labor [1].

Recently, health care researchers have shown the need for promoting person-centered care, self-identity and personhood for older persons and people with dementia [2-4]. Tobin [5]. Given the importance of pursuing this path, our research involves marrying personhood [3, 4] in health care with socially assistive robotics embodiment of care concepts [6] and context sensitive cloud computing techniques involving artificial intelligence, soft computing and computer vision techniques to realize a symbiotic robotic system. Research in this area has indicated that negative consequences of ageing and dementia can be mitigated by designing an approach towards care that respects and supports each individual's personhood [3, 4]. Personhood has been defined as 'the standing or status that is bestowed upon one human being, by others, in the context of relationship and social being' [7]. It includes three fundamental components, namely, interactional environment, subjective experience and social context. Figure 1 shows mapping of concepts related to these three components in Lucy.

The embodiment of interactional environment in Lucy involves modeling of human characteristics like gesture, emotional expressions, voice, motion, dancing, and dialog adaptation in Lucy. The subjective experience in an older person care context involves design of services personalized around the lifestyle of person with dementia. These lifestyle based services which reflect their personhood should enable a reciprocal relationship between Lucy and the older person and consequently make them more productive and useful [8].

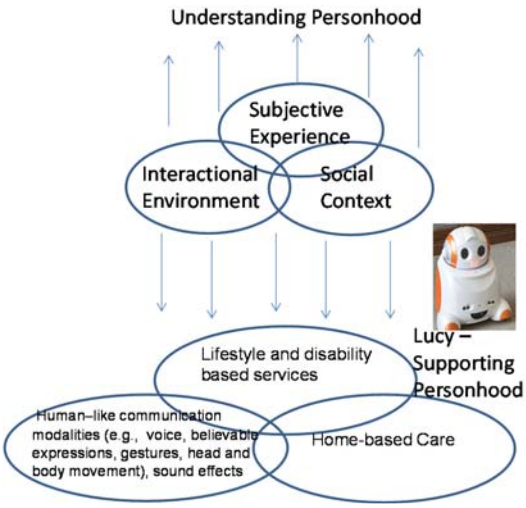


Figure 1. Mapping personhood in Lucy

The subjective experience would also imply use of flexible interaction modes (e.g., voice based, touch based, face based) between Lucy and the human partner based on their need and comfort. The interactional environment needs to employ human-like communication modalities like voice, emotive expressions, head and body movement, and gestures in an emotionally engaging manner to facilitate a reciprocal relationship [8].

The results analyzed from multi-modal data collection have shown by marrying emotional measuring techniques and adaptive service personalization in the design and applications, social robots like Lucy have the ability of breaking technology barriers, enhancing the interaction with human partner, and personalizing its services to individual's preferences which finally improves positive engagement and emotional well being of older people.

## II. FIELD TRIALS AND RESULTS

### A. *Field Trials*

The longitudinal study was conducted between 2 and 5 months in five Australian households. All participants are older people (ages 65-89) having dementia living in Victoria, Australia. Each participant has had a robot deployed at their home (figure 2). The robot has human attributes include baby face like appearance, voice vocalization, face recognition, face registration and face tracking, facial expressions, gestures,

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body motion sensors, dance movements, touch sensors, emotion recognition and speech acoustics recognition. The robot can deliver several lifestyle services in personalized way to the individual participant.

Figure 2. Snapshots of home-based trials.

## B. Results

### 1) Engagement

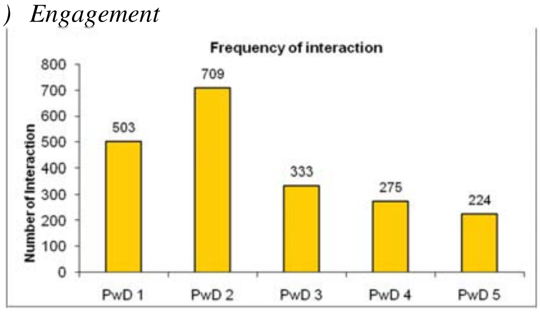


Figure 3. Interaction per participant

The total number of interaction between each participant to the robot is illustrated in Figure 3. The figure shows that the participants have approached and interacted with their robot significant of times, in which the participants 1 & 2 have the highest interactional level with 709 and 503 times of interactions respectively.

### 2) Respire to care

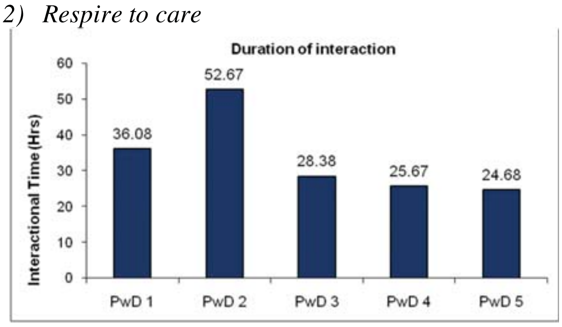


Figure 4. Interactional duration per participant

We analysed the interactional activity data to obtain the total duration time of interaction (Figure 4). The figure shows that five participants have spent 24 to 52 hours to interact with the robots. This not only gives family carers some respire but also potentially reduces caring time demand to persons with dementia.

### 3) Service preference

The statistics (Fig. 5 & 6) from activity logs indicate that all of participants prefer singing and dancing service most, with about 1000 times of interactions. The quiz, weather forecast, news reader, book reader and reminder are the next desired services. This implies that sensory enrichment service (singing & dancing) and cognitive support service (quiz) are most engaging the people with dementia at their home environment, thus should be installed in socially assistive robots to positively engage persons with dementia in the home environment.

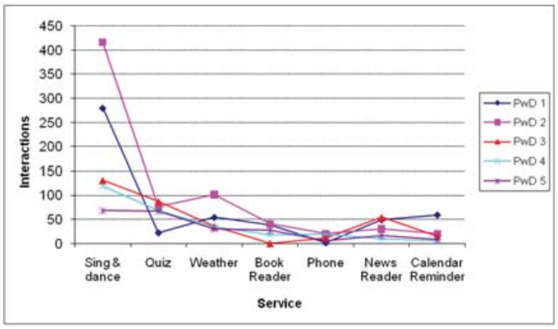


Figure 5. Pariticipants' interaction per service

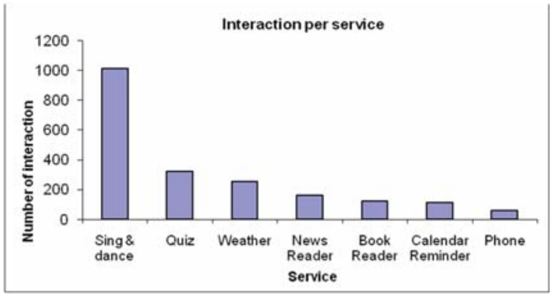


Figure 6. Service preference

### 4) Robot experience

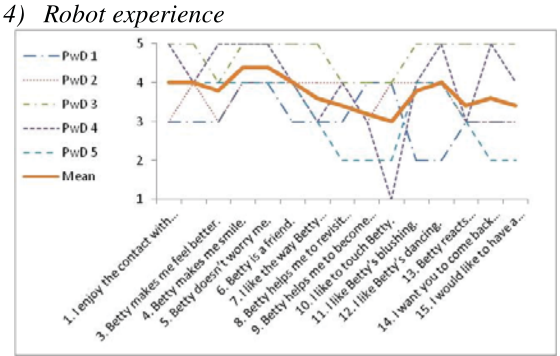


Figure 7. Quality of robot experience

The quality of robot experience survey has been conducted at the end of the trials using a standard five-point Likert scale (Strongly Disagree=1, Disagree=2, Neutral=3, Agree=4, Strongly Agree=5). Figure 7 shows the robot experience comparison amongst the participants and the mean. The figure shows that on average the responses are positive (above 3.0). This result validates that the socially assistive robots like Betty has break the technology barrier with the older people and provide positive engagement to their home living.

## III. CONCLUSION

The personhood-oriented services in couple with service adaptation has been designed and implemented to give the socially assistive robot the ability of personalising it services to each individual in dynamic manner. The results consolidated from data analysis indicate that Lucy has successfully eliminated the barriers of use of technology by older people, positively engaged with the older people and shown potential to reduce caring burden to aged care in home-based environment.

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