HEPHAISTOS

HExapode, PHysiologie, AssISTance et Objets de Service

HExapod, PHysiology, AssISTance and RobOticS

Project-team proposal, September 24, 2014

Hephaestus was the God of Fire and the Forge, the smith, craftsman and weapon maker of the gods. He was the son of Zeus and Hera ... To compensate for his lameness, Hephaestus built two golden robots to help him move around

Contents

1 Team members

Staff members

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Collaborators

- Claire DUNE, Handibio, Univ. Toulon, McF, part time in the project[4]

PhD and Post-Docs

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- Alessandro BERTI (PhD in collaboration with Bologna University, 2012-)
- Laurent BLANCHET (PhD, 2011-2015)
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- Rémy RAMADOUR (joint PhD with Lagadic, 2011-2014)
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Two additional post-doc will be hired in 2015.

2 Overview of the objectives

The goal of the project is to set up a generic methodology for the design and evaluation of an adaptable and interactive assistive ecosystem for the elderly and the vulnerable persons that provides furthermore assistance to the helpers, on-demand medical data and may manage emergency situations.

Assistance will be provided through a network of communicating devices that may be either specifically designed for this task or be just adaptation/instrumentation of daily life objects.

The targeted population is limited to people with mobility impairments[5] and the assistive devices will have to support the individual autonomy (at home and outdoor) by providing complementary resources in relation with the existing capacities of the person. Personalization and adaptability are key factor of success and acceptance.

Assistance is a very large field and a single project-team cannot address all the related issues. Hence HEPHAISTOS will focus on the following main **societal challenges**:

[1] `http://www-sop.inria.fr/members/Jean-Pierre.Merlet//merlet_eng.html`

[2] `http://www-sop.inria.fr/members/Yves.Papegay/About_me.html`

[3] `http://www-sop.inria.fr/members/Odile.Pourtallier/`

[4] `http://handibio.fr/?page_id=516`

[5] for the sake of simplicity this population will be denoted by *elderly* in the remaining of this document although our work deal also with a variety of people (e.g. handicapped or injured people, ...)

- **mobility**: previous interviews and observations in the COPRIN team have shown that this was a major concern for all the players in the ecosystem. Mobility is a key factor to improve personal autonomy and reinforce privacy, perceived autonomy and self-esteem (section 4.3.1)
- **managing emergency situations**: emergency situations (e.g. fall) may have dramatic consequences for elderly. Assistive devices should ideally be able to prevent such situation and at least should detect them with the purposes of sending an alarm and to minimize the effects on the health of the elderly (section 4.3.2)
- **medical monitoring**: elderly may have a fast changing trajectory of life and the medical community is lacking timely synthetic information on this evolution, while available technologies enable to get raw information in a non intrusive and low cost manner. We intend to provide synthetic health indicators, that take measurement uncertainties into account, obtained through a network of assistive devices (section 4.3.3). However respect of the privacy of life, protection of the elderly and ethical considerations impose to ensure the confidentiality of the data and a strict control of such a service by the medical community (section 11)
- **rehabilitation and biomechanics**: our goals in rehabilitation are 1) to provide more objective and robust indicators, that take measurement uncertainties into account to assess the progress of a rehabilitation process 2) to provide processes and devices (including the use of virtual reality, section 10.3) that facilitate a rehabilitation process and are more flexible and easier to use both for users and doctors. Biomechanics is an essential tool to evaluate the pertinence of these indicators, to gain access to physiological parameters that are difficult to measure directly (section 4.3.4) and to prepare efficiently real-life experiments (sections 10.1.3, 10.2)

Addressing these societal focus induces the following **scientific objectives**:

- **design and control of a network of connected assistive devices**: existing assistance devices suffer from a lack of essential functions (communication, monitoring, localization,...) and their acceptance and efficiency may largely be improved. Furthermore essential functions (such as fall detection, knowledge sharing, learning, adaptation to the user and helpers) are missing. We intend to develop new devices, either by adapting existing systems or developing brand-new one to cover these gaps. Their performances, robustness and adaptability will be obtained through an original design process (section 5). This evidently covers robotics development (therefore including robot analysis, kinematics, control, ..., see for example section 7) but is not exclusive. These devices will be present in the three elements of the ecosystem (user, technological helps and environment) and will be integrated in a common network (section 10.1)
- **evaluation, modeling and programming of assistive ecosystem**: design of such an ecosystem is an iterative process which relies on different types of evaluation. A large difference with other robotized environments is that effectiveness is not only based on technological performances but also on subjectively perceived dimensions such as acceptance or improvement of self-esteem. We will develop methodologies that cover both evaluation dimensions (section 6). Technological performances are still important and modeling (especially with symbolic computation) of the ecosystem will play a major role for the design process, the safety and the efficiency, which will be improved by a programming/communication framework than encompass all the assistance devices. Evaluation will be realized with the help of clinical partners (sections 13.2.2, 13) in real-life or by using our experimental platforms (section 10.1)

- **uncertainty management**: uncertainties are especially present in all of our activities (sensor, control, physiological parameters, user behavior, ...). We intend to systematically take them into account especially using interval analysis, statistics, game theory or a mix of these tools (sections 8,9)

- **economy of assistance**: interviews by the COPRIN team and market analysis have shown that cost is a major issue for the elderly and their family. At the opposite of other industrial sectors manufacturing costs play a very minor role when fixing the price of assistance devices: indeed prices result more from the relations between the players and from regulations. We intend to model these relations in order to analyze the influence of regulations on the final cost (section 8.2.1)

The societal challenges and the scientific objectives will be supported by experimentation and simulation (section 10) using our development platforms (section 10.1) or external resources (sections 10.2,13).

In terms of methodologies the project will focus on the use of **symbolic tools**(for modeling, design, interval analysis), on **interval analysis** (section 9, for design, uncertainties management, evaluation), on **game theory**, (section 8, for control, localization, economy of assistance) and on **control theory** (distributed in various sections)

3 Motivations for a project focused on assistance to persons

3.1 Introduction

Aging in France is illustrated by the probable evolution of the world population age in 2050 (figure 1) which shows a large increase of people of age ≥ 65[6]. It may create in the near future societal problems as the cost

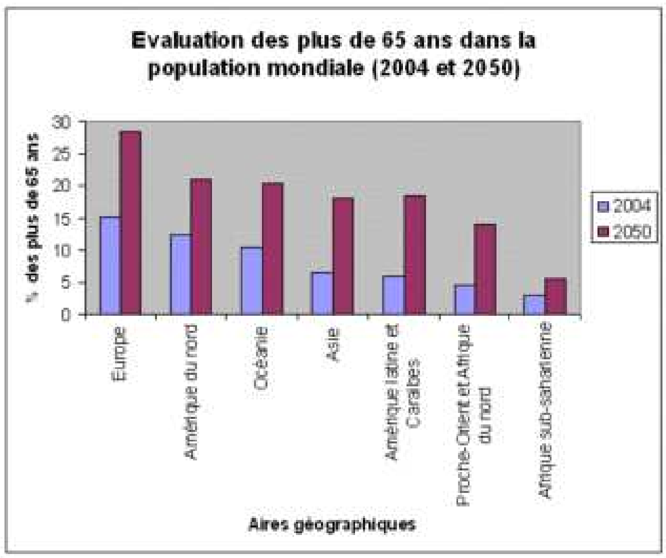

Figure 1: Percentage of the population aged over 65 years in 2004 and 2050 in various geographical areas (source:Wikipedia)

of managing a large population of elderly people will put a large pressure on the social system. Technological helps, with the goal of maintaining social relationships, may somewhat alleviate this pressure, may contribute to the well-being of this population and may reduce the physical/psychological burden of their helpers so that they can focus on maintaining the essential human relationship with the people that they have in charge. Several reports have emphasized the importance of this field [18, 15, 36, 86]

3.2 Assistance robotics

Assistance robotics is part of these technological helps. Developing these helps has been identified at the end of the life of the COPRIN project, that was focusing on the design and use of innovative industrial robots.

[6]In this document we will focus on elderly people but other frail people, such as handicapped or injured people, may share the same assistance needs

HEPHAISTOS may be considered as a follow-up of COPRIN from the view point of design science and the scientific methodologies that were used for that purpose but differs in terms of the applications, that require to broaden both our knowledge and the type of robotic devices we will develop together with introducing new elements, especially human ones, in our design strategies. The team has also evolved with the integration of an expert in interface and user evaluation.

Without claiming to be exhaustive[7] we will now describe available products at large:

- *manipulation for severely impaired*: a classical robot arm is used to allow manipulation. Examples of this case are the MANUS[8] and JACO[9] robots whose costs are high (around 25 000 euros). Simplified versions exist such as the BESTIC[10] for feeding people, still quite expensive at around 8000 euros
- *exoskeleton* that provides an actuated assistance for mobility such as the Honda Walking Assist Device[11], or the REX[12]. Prices range from 12 000 to 150 000 euros
- *smart walker and wheelchair*: mobility assistance devices such as cane, walkers, wheelchairs exist since a long time at an affordable price (around 100 euros for walker and manual wheelchair) but their functionalities is reduced to their primary task. As mobility will be one of the focus of the project we will present a state of the art on the subject in section 4.3.1,
- *companion robots*: since some time researcher have thought that robots may be used not only to relieve elderly people from functional tasks but also may play a social role (as medicine reminder, improver of social life, ...) and be used as a tool to improve/maintain cognitive abilities. They are multiple robots that has been proposed for this purpose such as the therapeutic toy seal PARO[13], 5000 euros, and various telepresence robots (Giraf[14], Care-O-bot[15], Kompai[16], 24 000 euros, from Robosoft, Jazz[17], starting at 8000 euros, and Pepper (announced at 1500 euros) from Aldebaran,). Humanoids are also a possibility and are intended to offer additional functionalities compared to telepresence robot. The most well known humanoid robot are the small-sized NAO of Aldebaran (which is preparing the larger version ROMEO) priced at around 15 000 euros and the larger ASIMO of Honda. Although research on humanoids is an exciting problem with numerous theoretical and technological issues we do not intend to work on this subject for reasons that are explained in section 4.2.
- *rehabilitation robots*: some robotic systems are used for rehabilitation as, for example, the LOKOMAT[18] for the lower limbs. They have been proven to be clinically effective but are usually large, expensive and suffer from a lack of flexibility
- *environmental robotics*: home automation will play an important role for the autonomy of elderly. Current systems allow one to control part of the house elements either in a manual way or through the web (see for example the Blyssbox of M2M[19]). But these systems lacks of flexibility and of analysis possibilities

[7] additional devices are presented at www.silvereco.fr
[8] http://www.exactdynamics.nl/site/
[9] http://kinovarobotics.com/fr/
[10] www.besticinc.com
[11] http://corporate.honda.com/innovation/walk-assist/
[12] http://www.rexbionics.com/
[13] www.parorobots.com
[14] http://www.giraff.org
[15] http://www.care-o-bot.de
[16] http://www.doc-center.robosoft.com/
[17] http://www.aldebaran.com
[18] http://www.hocoma.com/
[19] http://www.m2msolution.com

- *services*: a current trend in assistance is to provide simple services, that involve a minimal amount of hardware. For example we may mention telealarm which consists in its simple version of a push button that allows for a connection to a call center while in the most sophisticated version some events (e.g. a fall) may trigger automatically the call (provided that the user is wearing the hardware and remember to charge it regularly). Services may also be proposed for smart-phones users as for example the `Sleep as android` app which monitor the sleep and provides an intelligent wake-up system

3.3 The players: governemental, institutions and industry

Academic researches in this field will be presented in section 13. In terms of organization in France a key player is the *Caisse nationale de solidarité pour l'autonomie des personnes âgées et des personnes handicapées* (CNSA[20]) which plays at the same time a role of funding agencies and of expertise center. As funding agency the CNSA is in charge of distributing a financial help to elderly people, the *Aide personnalisée à l'Autonomie* (APA), which is very important for many elderly people. The level of this financial help is based on the evaluation grid *AGGIR* which consist in the ranking of 10 discriminant activities according to three notes (correctly done, unable to be done, difficulties).

As expertise center the CNSA has created 5 national expertise centers: CEREMH (handicap and mobility), STIMCO (cognitive stimulation), CENTICH (interfaces based on TIC), CENROB (assistance robotics and rehabilitation), HABITAT (housing), this later being initially delegated to the association *Centre National de Référence Santé à domicile + Autonomie* (CNR Santé[21]), of which INRIA is a member (David Daney, former member of COPRIN, is a member of the scientific committee of CNR). But the role and action of these centers are not always clear (for example the CENTICH is developing its own test house LENA) while the CNR Santé is now focusing on the *Silver economy*, proposing for example its own innovation house Delvalle[22]. CENROB is the center that is the closest to HEPHAISTOS objectives and we have a very active implication with this CEN. A local actor is the association *Centre d'Innovation et d'Usages en Santé* (CIU Santé[23]), an expert center of CNR Santé, of which INRIA is member. This center intends to promote the use of TIC in hospital and at home and proposes several platforms in Nice: EHPAD Valrose, Delvalle project, Institut Claude Pompidou. They are other national associations related to this domain:

- *Centre Expert en Technologies et Services pour le Maintien en Autonomie à Domicile des Personnes Agées* (MADOPA[24]) initiated by UTT that regroup all type of stakeholders
- *APPROCHE*[25]: promotes the use of new technologies for handicapped people

In term of industry we may distinguish large companies (with numerous subsidiaries) such as Invacare that sell medical (in a broad sense) products (such as walkers, wheelchairs, household appliances, ...) and start-ups that are basically focused on a single assistive product Other important industrial players are insurance companies (such as Groupama or Covea) that may have an interest in assistive devices to improve the quality of life and safety of their clients, to play a prevention role but also to sell complementary health insurance... As may be seen the assistance ecosystem (called the *Silver economy*) in France is still quite complex with several

[20] `http://www.cnsa.fr/`
[21] `http://www.cnr-sante.fr/`
[22] `http://www.cnr-sante.fr/tag/delvalle/`
[23] `http://www.ciusante.org/`
[24] `http://www.madopa.fr/`
[25] `http://www.approche-asso.com/`

interconnected layers and actors. We may now explain the project goals and how they have been established. We first present our *goals* and we will then detail *topics* (i.e. research questions) and *methodologies* (i.e. the scientific tools that are used to address the topics).

4 Project goals for the next 12 years

As a foreword we are conscious that the presented objectives may be overly ambitious for a medium-sized team. However this document addresses a twelve years term and furthermore the objectives that will be finally pursued also depend on external factors such as industrial and clinical collaborations, availability of users and technological evolution that are difficult to foresee. Hence we have preferred to present a full panel of goals that are worth being investigated. The global aim of the project is to set up a generic methodology for the design and evaluation of an interactive assistive ecosystem for the elderly and the vulnerable persons.

4.1 General requirements for an assistive ecosystem

COPRIN has already established a first list of requirements for an interactive assistive ecosystem. These requirement have been established after a two-years interview period (2009-2011) conducted through a process of questions/answers that have been consigned in an internal report. Over 200 interviews have been conducted among users and their family, associations of users, caregivers, the medical community and local authorities. Although at this time we were not familiar with such a process we believe that the number of interviews has allowed us to get a significant view of the requirements and this has been confirmed when they have been presented during various CENROB workshops. The design will follow the ecological, economical and technical requirements listed below in two groups:

user-centered

- well *adapted* to the person needs, adaptable according to his/her trajectory of life. Various levels of impairments have to be addressed by the same device. Device adaptability to deal with population heterogeneity and with the dynamic process of growing older are key factors of success and acceptability
- *acceptance*. Although this is a key issue, the understanding of acceptance mechanism has never been addressed in robotics.
- *non intrusive assistance*. A service should be available on demand / when needed / on user activation/ in case of emergency. Ideally assistance devices should be made invisible if not needed.
- *assistive rather than substitutive*. It is necessary to preserve the remaining physical/cognitive capabilities of the elderly as much as possible in order to reach the highest possible autonomy level: a device that always fully complete a task may create the opposite effect of dependency
- *safety*. This a major priority: although most of our devices are usually not a liability for elderly people they may play a fundamental role in their safety in case of an emergency
- *reliability*. The failure of an accepted assistance device may have serious psychological consequences. Hence reliability and easy maintenance should be addressed since the beginning of the design process
- *evaluation*. Efficiency and acceptance of assistive devices can be determined through rigorous experiments following an iterative process. This is classical for any high-tech object but here we have possibly also to manage medical standards

technology and science-centered

- *low cost.* This shall include the cost of the device itself but also of its installation and maintenance
- *global systemic approach.* From a personal viewpoint users, caregivers, family and the medical community have all specific and common needs that should be addressed. From a system viewpoint we claim that devices should not be considered as independent but as a part of a global ecosystem that may have to collaborate with other devices
- *energy concern.* This is an aspect that is neglected although the targeted community may be severely impacted by a power failure but may also not be conscious of this issue and/or may have problems to manage batteries and charging procedure

It must already be noted that the existing products, described in section 3, are not fulfilling many of the identified items (low cost, global approach, energy concern, acceptance, ...).

Although the determination of requirements and needs has already been started we will continue this process in a more systematic way using an ethnographic approach. There are a diversity of contexts and activities compounding a person's daily life, at home as well as outside. It points also the fact that people have different impairment and so, different needs. To deal with this heterogeneity, it will be necessary to have a clear understanding of their activities and to answer the following questions:

- who are the users?
- what are the activities?
- where are the difficulties during the course of activities?

Ethnographic studies are based on the collect of data on an ecological base, i.e. observations of people in their natural environment [35]. Based on previous collected data and academic work a first inventory of available data should be started and completed. A lot of techniques in human sciences are available to collect data about life style of people and identify their needs: in-home visits, ethnographic observations, interactive interviews, focus group ... to name few of them. This collect helps to gather insights into elderly people's daily lifestyle, activities of daily living (ADLs), attitudes and needs. Health professionals routinely refer to the ability or inability to perform ADLs as a measurement of the functional status of a person but the classification is rather rough and lack of objective measurements on how the ADLs are performed (see for example the Lawton instrumental activities of daily living scale (IADL) [62] or the AGGIR grid that is used in France by the CNSA. Activities have to be understood at macro level (e.g. cartography of "a day in the life") as well at micro level (elementary execution actions).

The above requirements provide us **guidelines**, i.e. general principles that will lead our research activities, but has also helped us to determine preliminary **application priorities**. But before going to these goals we need to define more precisely what will be our interactive assistance ecosystem.

4.2 Interactive assistance ecosystem

A fundamental choice has to be made at this point on the nature, capabilities and type of the devices that we may propose as helpers. Current available devices manage basically a single very specific task (health monitoring, fall, mobility help, ...) and have very restricted abilities in terms of communication (with the users, the helpers, the medical community, the environment, with other other devices, ...). Furthermore the communication between the devices and the user is one-way: the device provides some a priori help but does not try to determine the real intents of the users which in turn has no easy means to indicate what is her/his wishes. A consequence is that the amount of help (or its appropriateness) that the helper provides is not really influenced by the context.

At the opposite there is currently a research trend whose purpose is to develop an *universal* assistance device that may be called a *companion robot* because many of them have a humanoid form. This robot companion shall be able to provide the necessary help (physical but also cognitive) in almost all circumstances of an elderly life. Clearly developing such system represents a very ambitious and very long-term goal.

Our vision is more modest but is also grounded on realistic obstacles that a robot companion will be confronted to. For example we will see in section 4.3.1 that transfer operation (i.e. helping the user to switch position between lying, seating and standing) is a major issue in assistance. In that case the robot is confronted to the laws of mechanics and has to provide a very significant amount of physical forces (and the humanoid form is not the most efficient in term of energy for this task). With the currently available technologies a robot companion will end up with large motors, batteries and weight (typically the Care-O-Bot assistance[26] robot weights about 200 kg), will be very intrusive while its energy autonomy will be quite low. Cost is also a major issue (the price of the ROMEO of Aldebaran is expected to be 250 000 euros) without much hope that a mass production may lead to a significant decrease.

Our vision is that in the mid-term we should rely on a fleet of communicating assistance devices, that are able to manage efficiently (in terms of performances and energy consumption) a reduced number of tasks and are part of in an assistive network that allow them to cooperate to perform complex tasks or to manage an emergency situation. The required devices have to be identified according the needs of the different stakeholders (the elderly, caregivers and the medical profession). The human component is distributed between the caregivers (relatives and professionals) and the medical profession who have specific needs (assistance and communication) which have also to be understood and supported.

The HEPHAISTOS assistance ecosystem is presented in figure 2. Clearly assistance is a very large field with many possible applications. Our preliminary interviews have allowed us to determine **priorities** that will be presented in the next section.

4.3 Provisional application goals

Assistance cover a very large panel of expertise going from hardware to the most psychological aspect of acceptance. Clearly a single project team cannot cover all these aspects. Hence we have decided to focus of some of them, according to the identified priorities and our own expertise.

4.3.1 Improving mobility and autonomy

Mobility is a key factor to improve personal autonomy [8] that we restrict to local mobility, excluding transportation as other INRIA project-teams such as LAGADIC are already working on these issues. From previous interviews and observations, COPRIN has identified that the main concern of the elderly is ability to move around by themselves, and especially for intimacy purpose (e.g. going to the toilets). It is clear that providing capacity to move alone will reinforce privacy, perceived autonomy, self-esteem and avoid humiliating situation.

Currently mobility assistance [14] has focused on:

- *allowing transfer operation*, typically for sit-to-stand operation [47]. Instrumented walkers have been developed [16, 21, 52, 75] with additional mechanism to compensate for the disbalance in such operation.

[26] `http://www.care-o-bot.de/en/care-o-bot-3.html`

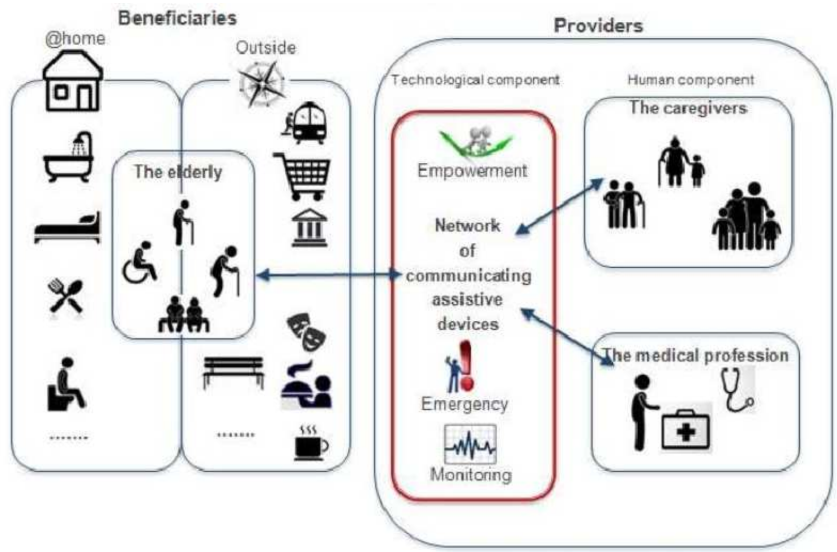

Figure 2: Hephaistos interactive assistance ecosystem

This leads to rather bulky and heavy walker that are less easy to use indoor. Other solutions that are commercially available are hoists (gantry, wall mounted, mobile)[27] which may be used for rehabilitation [10]. Those are costly system, difficult to use alone and quite intrusive.

- *Exoskeleton* that provides an actuated assistance for mobility [87]. The most elegant of such system is the Honda Walking Assist Device[28] which is currently under test in 7 japanese hospitals.
- *Walking aids*: classical walkers have been motorized mostly to provide navigation help [43, 67] but also to reduce fatigue, possibly to avoid fall [50, 51] or for rehabilitation purposes [40]. Instead of using heavy motors it has also been proposed to have simpler breaks in the rear wheels that play a role in navigation and for preventing fall [50, 51]
- *Automated wheelchairs*: roboticists have worked since a long time on mobile robots, addressing the problem of control, motion planning, automated navigation, localization and mapping (SLAM). Quite naturally they have tried to extend their works to wheelchair control [61, 77] and navigation [44] together with allowing manipulation possibilities by adding a robotics arm to the chair[29]. It must be mentioned that clinical trials have shown that fully automated navigation is not well resented by users [82] .

As may be seen current mobility assistance focus on transfer operation, navigation assistance, rehabilitation support and to a lower extent fall detection. Our global challenge in mobility assistance will be to propose innovative devices that have extended or improved functionalities, especially fall detection, medical monitoring and rehabilitation, that will be emphasized in sections 4.3.2, 4.3.3,4.3.4.

[27]see http://www.activemobility.co.uk
[28]http://corporate.honda.com/innovation/walk-assist/
[29]see http://kinovarobotics.com/products/jaco-rehab-edition/

As transfer is a major issue our first goal is to instrument our ecosystem with a low-cost and less intrusive transfer system, but which is not restricted to this task (for example allowing object manipulation). We have already started proposing an innovative solution with our family of *cable-driven parallel robots* MARIONET, whose principle will be presented in section 7.

As for other devices we intend to focus on the first devices that are used immediately after the first sign of mobility loss, namely walking aid and cane. We have already started working on the walking aid with our family of smart walkers ANG which allow for fall detection and walking analysis but also getting information on the environment of the user. Navigation will also be addressed but in a not classical way, focusing firstly on the use of friction brakes in the rear wheels. This is a challenging **control** problem [34, 48, 53, 50, 57] and we intend to develop a control strategy that takes into account the full dynamics of the system by using a musculoskeletal model of the user.

The alternate to a walker is the cane and there has been works addressing the possible development of a robotized cane with as objective: navigation [25, 70], assisted gait [2, 3] or guide for blind people [73, 88] leading often to bulky devices. We believe that a cane may contribute to walking analysis, fall detection and navigation help but also as a manipulation tool without major modification in the cane design and in its use.

Instrumenting walkers and canes require an energy source and we want to avoid to involve the user in battery charging. Hence innovative automatic recharging process and energy harvesting will be explored.

4.3.2 Detection and intervention for emergency situations

Current safety devices consist mainly in remote alarm device to facilitate emergency call, possibly with fall detection (see [55, 68] for surveys on fall detection methods) that triggers automatically the call. Currently the most sophisticated system is the Vivago watch[30] that additionally measure skin temperature and conductance to detect loss of consciousness. This watch require however to be close to a specific transmitter and it is unclear how the physiological data are calibrated. Simpler systems use a GPS/GSM with an accelerometer to detect a fall[31], possibly using the user smart phone [1].

However they are several psychological disadvantages to this kind of system:

- most of the time they are provided by the family and not on a request from the user, which induce a decrease of self-esteem,
- they are perceived as stressful by the old people, let in a drawer and forgotten,
- when used, the call is more often linked to loneliness feeling, anxiety than emergency.

A direct consequence of these drawbacks is a high return rate after the first year of use (more than 85%). There are also technological drawbacks for such system: they need to be worn at all time, communication of alarm may be deficient and accessibility of the alarm button is a concern.

A first challenge here is to ensure that an emergency situation cannot be missed by our ecosystem. For that purpose we will introduce sensing redundancy in the three elements of the ecosystem: the assistive devices (e.g. mobility devices), the user (instrumented clothes, jewels [71]) and the environment (user localization, also useful for medical monitoring, see next section). An associated problem is the transmission of the alarm: a single communication system may not be reliable enough. To address this issue we propose to use several communication technologies, especially indoor, see section 10.1.1.

[30] http://www.telealarme-vivago.fr/
[31] http://www.geotraceur.fr/traceur-gps/54-traceur-gps-geo-302.html?id_product=17

The second challenge is here to correlate the sensing data with the current context (activities, physiological state...) and past history in order to trigger alerts without being false alarm and without emergency miss. For that specific purpose we intend to explore **machine learning** and **domain knowledge** [66].

4.3.3 Medical monitoring

Currently at-home medical monitoring is ensured by devices that are essentially devoted to this task, have limited capabilities and questionable accuracy[32] and there is no sensing redundancy.

Our paradigm is that every day objects and assistance devices should be instrumented for medical monitoring with low-cost sensors, providing a large spectrum of data both in time and in type. Daily life instrumentation allows to collect data tracing the performance evolution of the elderly during their every activity at home and outdoor. It may become possible to get precise and objective performance trends (for instance increased time for completing a task, progress in a rehabilitation process, . . .) that could facilitate at-home care.

The challenge is here to realize the appropriate instrumentation and to process the raw data in order to obtain meaningful and synthetic indicators in relation with the current context (activities, physiological state, ..) and past history of the subject, that can be exploited by doctors while preserving the privacy of the subject. One of the originality of our approach will be to provide interval values of these indicators as we will take sensor measurement uncertainties into account by using interval analysis in order to provide guaranteed indicators (as opposed to statistical one). Statistics is certainly important in medical monitoring to manage human diversity and to reduce the importance of external factors that may play a role in individual measurements. But neglecting the measurement error, most of which do not satisfy usual statistical hypothesis, may introduce a severe bias in the statistical analysis. Hence we propose to introduce interval measurements in medical statistics as described in section 9. Interval analysis will also play an important role in the sensing setup (location of the sensors, coverage, best measurement quality,. . .).

A typical monitoring example is the investigation of functional status in elderly adults [91]. Walking analysis appears to be a good tool for a quick analysis [28] and consequently indicators based on walking characteristics have been proposed [84]. Gait speed and other measures of physical characteristics appear also to be relevant to assess cognitive status [32]. However current walking tests, which have the advantage of being easily implemented, suffer either from a lack of objectivity and from being relatively coarse. An instrumented walking aid such as `ANG`, which allow for a full-time trajectory analysis, provides more objective and accurate indicators. It is also able to detect unusual events occurring for a very short time that may be the sign of an emerging pathology. Furthermore experiments with 54 subjects have shown that walking patterns have a specific signature for each user. After a proper personalization of this signature through a calibration/learning process it may be of interest to follow the signature evolution with time in order to assess the physical/cognitive status of the user.

Cognitive and physical assessment may also be based on the examination of the basic activities of daily living (ADL), such as dressing or bathing, or instrumental ADL (IADL), i.e. more complex tasks, such as preparing a meal or managing finances [41]. IADL questionnaires play an important role in assessing the functional abilities of older adults and evaluating the impact of cognitive impairment on routine activities. However the objectivity and reliability of questionnaires is a concern, even for physical activities [49]. The sensors of our assistive ecosystem may allow to introduce more objective and personalized measurements to support a finer assessment of the quality of the realization of ADLs.

Finally from an ethical viewpoint it is necessary that only only authorized personnel may manage data collection and that all monitoring data must be encrypted with the exception of emergency situation.

[32] our test in walking analysis have shown that a good podometer may provide the number of steps with an error of over 200%. Recently the FDA has decided that smartphone e-health applications will not be considered as medical devices.

4.3.4 Rehabilitation and biomechanics

Assistance for rehabilitation is a natural step after medical monitoring. As a preliminary goal we will focus on physical rehabilitation more than on cognitive one. We intend to provide devices and methods to assist the management of a rehabilitation process by using three different modes:

- *passive mode*: the device is used as a monitoring tool during the rehabilitation process, just following passively and recording the patient motion. Typically any of our monitoring devices may be used for this purpose and, for example, our walkers `ANG` will soon be used for lower limb rehabilitation (see section 13.2.2). Another possibility of the use of cable-driven parallel robots (see section 7) that are convenient for monitoring motions and have already been used in clinical settings [83]. We have already used our `MARIONET-REHAB` prototype for measuring arm coordination after a cardio-vascular stroke and this use poses interesting control problems.
- *semi-active mode*: in this mode the robot moves passively along certain directions but may exert forces or torques in some others in order to reduce the effort required by the patient for performing a given task (or reducing his/her fatigue). Here again we have an interesting force-feedback control problem
- *active mode*: in this mode, that must be supervised by a pratician, the robot may exert forces or torques on the patient to correct or train him. Such systems already exists but are costly, not very flexible and rather intrusive (see for example the Lokomat[33]). Here cable-driven parallel robots have the advantage of safety (during a power loss the platform stay in its current pose and the cables are mechanical fuses), flexibility (the same robot may be used for different pathologies), low intrusivity and easy maintenance. Managing the modularity and flexibility may be done using our appropriate design approach (see section 5.3) but we will have to address force control of cable-driven parallel robots, which is still an open issue (section 7).

These modes are also valid for the walking aids and our clinical partners have expressed a strong interest in more active platforms which raise difficult control issues.

Other research axes will be to explore the clinical effects of gamification on rehabilitation as presented in section 10.3 using our full virtual reality setup described in section 10.1.3. and the application of robotics concepts in the area of biomechanics and rehabilitation. Human limbs have a mechanical structure that may be described by a complex mix of serial and parallel mechanism, possibly with flexible joints [23, 74] whose models include parameters that are difficult to measure directly (e.g. muscle forces, bones lengths): we aim at developing methodologies that use redundant measurements to provide a better estimation of the parameters through calibration. For example we have started a collaboration with the biomechanics Handibio Laboratory of University of Toulon on the subject of identifying arm muscle maximal forces forces exerted by the hand [5].

Another use of biomechanics may be illustrated with the use of instrumented walker for measuring walking patterns. The mechanical system user/walker is a closed-loop structure that is clearly different from the open-loop system of natural walking. Hence gait indicators measured with the walker may differ from the one that will be obtained for a natural gait. Measurements of indicators of natural walking may not be possible (instrumentation may be too intrusive). Our aim here will be to develop a full symbolic musculoskeletal dynamic model of the patient/walker. The measurement of the gait parameters of the closed-loop system will allow to identify the parameters of the musculoskeletal model from which we may deduce the natural walking indicators. In the following sections we will give more details on these research issues. In each of these sections the timeline will be indicated together with the investigator(s). Main investigator(s) will be underlined.

[33] `medimex.athlex.free.fr`

5 Topic: approach and methodologies for the design of an assistive ecosystem

Timeline: year 1-12, **Who**: J-P. Merlet,Y. Papegay,B. Senach

Up to now we have identified general requirements for the ecosystem (section 4.1) and we have seen that to help the elderly to deal with the variety of context and activities that they face all along a single day, our proposed assistive environment will include hacked daily objects (adding functions to well known objects that the elderly use in their daily life, as, for example, TV remote control) and new devices tailored to specific needs that will be distributed among all three elements of the ecosystem: user, assistive devices and the environment. This fleet of interactive assistive devices will provide support, services and information to the elderly,to their caregivers and to the medical profession, according to their specific needs. A key issue is then to propose a design process for the devices of the ecosystem (especially for our priorities) that will respect the guidelines. The main challenge here will be :

- To involve the elderly in the design and the evaluation
- To design a coherent pool of devices helpful for a population with heterogeneous needs
- To design devices that stay helpful when the level of impairments increase
- To set up a toolbox for the design and evaluation of user interface and interface for seniors
- To have a design methodology for the devices that guarantee proper performances and allows one to manage adaptability. and analysis

5.1 Design management

Designing for the elderly is not a new question [89] and guidelines are already available [31, 76, 78]. Nevertheless, several assistance products have not met their market. Frequent explanations refer to insufficient consideration for users' needs, including the appearance of the device [93], and participation in the design process. This is also the case for available devices specifically designed for the elderly, and commercial failure is generally explained by the fact that older people are not interested in new technologies and don't know how to use them. But recent surveys show that the later is not a satisfactory explanation: many elderly have now computer access and are present on social networks. Hence commercial failures of product for the elderly are also more easily explained by a poor understanding of users needs and a wrong representation of what is old age. An additional explanation may be that assistive devices are most often provided (or even imposed) by family, leading to poor acceptance of the elderly because of the feeling of autonomy loss. A typical example are push-button telealarm devices which have a return rate of 85% after the first subscription year.

Instead of focusing only on technological/scientific problems for the design of assistive devices (a still important topic for which we propose an original and specific methodology in section 5.3) we intend to adopt a more global process that will lead our development toward innovative devices and we claim an ecological approach in which all stakeholders are engaged in the design process. This global process covers quite different design situation as it goes from ideation phases in which creative methods are used to identify innovative concepts up to prototyping before market launch. In Hephaistos, we will have to manage very different design situation from proof of concept to prototyping and we will improve existing assistive devices as well as create new ones. Hence several questions at different abstraction level will have to be answered when starting the design process:

- Which assistive device has priority over others
- What role will be devoted to the elderly in the design process

- How to manage the design of a fleet of objects
- How to deal with technology acceptance and energy concern

Our current view of the design process is summarized in Figure 3

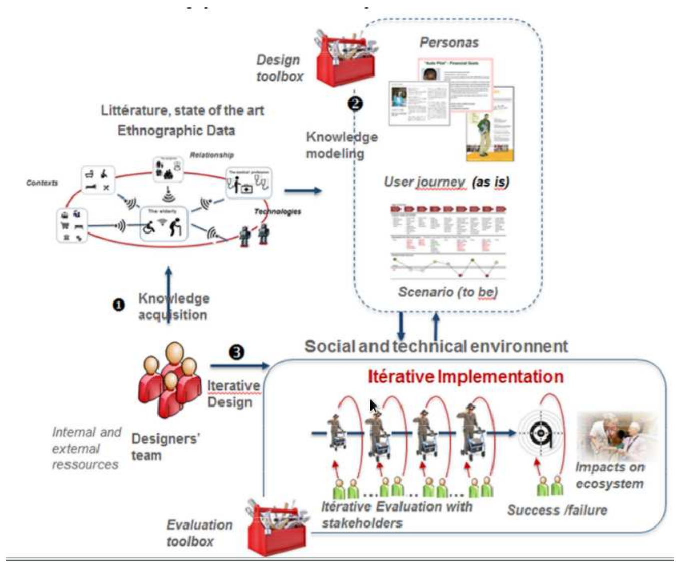

Figure 3: Hephaistos design process.

- Designers' team : besides the permanent staff which will be involved in the projects and additional internal resources (postdoc, . . .), external collaboration may concern :
  - stakeholders of the ecosystem (caregivers, elderly, physician) will be involved when appropriate and possible. Contribution could be creative workshop as well as validation sessions.
  - partnership with clinicians (see section 13.2.2)
  - partnership with Living labs (see section 18) : the role of users in the design process has often been limited to information providers (interviews, observations,. . .) or "Rat lab" as when they are subjects in experiments. The Living Lab approach has changed the role of users in the design process, putting emphasizes on their early involvement in this process, even in the ideation phase.
  - partnership with designers: designers will be involved in Hephaistos according to opportunities, in relation with research projects that will be launched. When new projects require to solve technical or formal problems (algorithm improvement, mathematical proof, . . .) designers are not a valuable resource, and mock-up and prototypes may be developed without their help. Later, when service, prototypes can be envisioned they may have a decisive role to play in the design process. We had a first contact with the Sustainable Design School in Nice[34] as we believe that the external appearance of the devices plays a major role regarding acceptance (see for example prostheses that are intended to be displayed and not hidden[35]). Hence we intend to go on cooperating with artists and designers

[34] http://www.the-sds.com/fr

[35] http://www.bespokeinnovations.comfor

at the final stage of our prototype development in order to propose attractive devices.

- Knowledge acquisition : Knowing the users is a leitmotiv of user centered design and ethnographic studies has been advocated for long in HCI community [72, 54]. Within the project, the knowledge about users will rely both on our previous extensive interviews and on existing literature which provides essential insights about specific requirements. These ethnographic data will also help to identify the relevant evaluation context, the different performance criteria according to each stakeholders and success criteria in our research context.
- Design toolbox : ethnographic data will be processed using current modeling tools from user interface design. For instance, a structured view of the design process in which context played a fundamental role is presented in [6], as well as personas [19]. Service design provides also complementary tools to represent user experience, integrating emotional journeys [85]. We will look for relevant tools and adapt them to our specific research context.
- Iterative and flexible design : the design of a fleet of objects may rely on an incremental process in which individual devices are added to the whole or it may be an open process in which the whole system is redesigned at each stage. We lean toward an incremental design within an open ecosystem because of practical reasons. In that option integration of a new device relies mostly on communication exchange for which we favor a message passing scenario.
- Iterative evaluation : evaluation has to take place at different steps of the design process, focusing on current questions (comparison of design option, validation of alternative, performance measure . . .). In addition to success/failure criteria in relation with the specified performance objective, we will have to consider effects of the new devices at the ecosystem level.

All along the project, we will focus on questions concerning the role devoted to the elderly in the design process, way to improve technology acceptance and energy consumption. Hence several questions will have to be answered before starting the design process:

- *Role of the elderly*: the role of users in the design process has often been limited to information providers (interviews, observations, . . .) or "Rat lab" as when they are subjects in experiments. The Living Lab approach has changed the role of users in the design process, putting emphasizes on their early involvement in this process, even in the ideation phase. We are also sensitive to cultural differences which explain the choice of our clinical partners

- *User acceptance and appropriation*: our context has similarities to the one of IoT and we will borrow from previous works [22, 26, 95] but our devices are not limited to high-tech connected devices. Technology acceptance will be addressed using technology acceptance models such as the Technology Acceptance Model (acceptance depend on perceived utility and perceived usability of a system), Innovation Diffusion (innovation is communicated through certain channels over time among the members of a social system) and Theory of Planned Behavior (exploration of the relationships between beliefs and attitudes). An interesting point stated by Gerling[38] and Deterding [24] is that gamification offers a great potential regarding the engagement of senior citizens with assistance systems. This approach seems to be promising for the HEPHAISTOS project and should be explored. Once acceptance barrier is raised, appropriation may be a design concern and here, persuasive technologies [33] and gamification may play a role.

- *Energy concern*: our assistive devices shall be available at any time while elderly people may have problems dealing with batteries and charging time. Hence energy consumption is a very important issue (that is often neglected in commercial or academic concepts). The design process must take this dimension into account by using available technologies: low energy consumption computers and communication network (e.g. infrared instead of hertzian), and automated recharging. We especially intend to use energy harvesting apparatus as in many cases devices require energy only when in use.

Still after having settled general rules for the design of the ecosystem it will be necessary to focus on the engineering design for the developed devices, with a methodology that guarantees performances and allows one to manage adaptability (to the user, to its trajectory of life and to his environment). The later constraint will be emphasized in the next section while the methodology will be presented in section 5.3.

5.2 Adaptability

We will distinguish two types of adaptability: *personalization* that describes the capacity of the devices to adapt its behavior to the abilities of a given user (or of a group) and *environmental adaptability* that describes the possibilities of adapting the general principles that govern the device behavior to the user environment.

As for personalization aging is a dynamic process, and the capacities and needs of a growing old person are evolving with time, which means the assistive devices should have adaptive capacities. Several academic work and models point to the importance of personal variables for interpreting acceptance and usage (see for example [38] for video games). The design of personas can help to improve adequacy and acceptance of the supportive devices. A persona is a hypothetical archetype, used during the design process and that represents a person who will interact with a system. It is for instance based on demographic, physiological, social and cognitive characteristics and will include aspects about relation to technology, self-esteem ... They are constructed using interviews, focus group, analysis of data and try to capture different characteristics of population of users. To be specific, in HEPHAISTOS, they could for instance help to capture different capabilities of a user group according to their age (for example people having similar mobility problems), to qualify their level of independence and other attributes such as their attitude towards technology and could constitute a referential for a structured evaluation. Personalization adaptability will denote the ability of a given device to manage the needs of different personna. Such an adaptability may be obtained either by respecting general guidelines or by defining performance requirements for the device that have a broad spectrum.

Environmental adaptability allows to determine a physical instance of a device whose general functioning principles are known so that it may perform efficiently in a given environment. A good example of such an adaptability is provided by cable-driven parallel robots used for transfer operation (see section 7). Environmental adaptability and to some extent personalization will be managed through a specific methodology that is described in the next section.

5.3 Appropriate design

Although the efficiency of a device regarding performances and accordance to its assigned tasks is not a sufficient factor for acceptance, we still believe that a good design may play a positive role for this aspect and is anyway necessary for safety reasons.

After having determined the general architecture for an assistive device according to the process described in section 5.1 it is necessary to determine the values of the physical parameters of the system (such as lengths, mass, actuator power, ...) with performances and adaptability in mind. More precisely the performances of the system must satisfy some given numerical requirements. For classical "industrial" robot performances are, for example, workspace size, accuracy, speed and possibly payload while requirements define upper or lower bound for the performances. The classical engineering approach to determine the physical parameters of a system is based on finding the parameters that maximize a *cost function* [29] which is a weighted sum of performance indicators f_i. There are several drawbacks of such an approach and we shall mention a few of them for example that normalization of the parameters is often arbitrary and that it is difficult to impose minimal values for the f_i and/or to manage antagonistic requirements. But a major drawback is that this approach provides a single solution while we claim that the designer may not be aware of all design constraints. Another drawback is that the approach does not take into account the uncertainties in the instantation of the design solution (and consequently that its physical instance may not satisfy a crucial requirements).

We have proposed since many years an alternate approach called *appropriate design*. The primary concept underlying this approach is that users are not really interested in optimal performances but more in requirements satisfaction (for example the volume of the robot workspace does not matter as soon as the workspace encloses a given volume), that may be translated in the constraint $f_i \geq f_i^{min}$. The second concept of the approach is a consequence of the fact that the designer may not be aware of all design constraints (e.g. of the costs of the components according to their specifications): in that context proposing a single design solution may not be satisfactory. To deal with this problem we have first to note that the set of design parameters for which $f_i \geq f_i^{min}$ hold defines a region $\mathcal{P}$ of the parameters space. In theory $\mathcal{P}$ may be unbounded but in practice, as the parameters represent physical entities we may always assume bounds on the parameters, possibly very large. Finding exactly $\mathcal{P}$, beside being a complex problem, is not of interest: indeed points on the boundary of $\mathcal{P}$ are not design solutions as a physical instance of such a point may be outside $\mathcal{P}$ because of the uncertainties. Hence we aim at determining a region $\mathcal{P}_r$ that is included in $\mathcal{P}$ and is such that the growing of this region by the uncertainty on each parameter still lead to a region strictly enclosed in $\mathcal{P}$, with the consequence that the **real** instance of a solution selected in $\mathcal{P}_r$ will be **guaranteed** to satisfy $f_i \geq f_i^{min}$. Determining $\mathcal{P}_r$ is now our main focus: although an ad-hoc analysis may provide an exact calculation, we have designed a generic methodology based on **interval analysis** (IA, section 9) for that purpose. Interval analysis is a very flexible way (and the only one to be generic) to obtain **boxes** in the parameters space such that for any point in the box we can guarantee that $f_i \geq f_i^{min}$. The general idea of our algorithm is to start with a box $\mathcal{P}_I$ that covers $\mathcal{P}$ that is progressively split in smaller boxes using a branch and bound scheme. For each box and requirement f_i we use IA to determine if either all the points in the box satisfy the requirement or violate it otherwise the box bisected unless its dimensions are all lower than a given set of thresholds ϵ in which case the box is discarded. $\mathcal{P}_r$ is obtained as the union of the boxes that satisfy the requirements and if V_d denotes the sum of the discarded boxes volumes then we have

$$\text{Volume}(\mathcal{P}_r) \leq \text{Volume}(\mathcal{P}) \leq \text{Volume}(\mathcal{P}_r) + V_d$$

Hence for a given set of thresholds ϵ $\text{Volume}(\mathcal{P}_r)/(\text{Volume}(\mathcal{P}_r) + V_d)$ is an index that indicates how good $\mathcal{P}_r$ is an approximation of $\mathcal{P}$: the closer to 1, the better the approximation. Note that the lower are the thresholds ϵ, the higher will be the computation time but also that the threshold for a parameter p_j cannot be lower than the uncertainty range for this parameter. Applied on all performance requirements this approach provides a $\mathcal{P}_r$ that is an approximation of **all** design solutions, taking uncertainties into account. Beside being flexible and able to manage almost any design problem this approach has also two advantages:

- it can be implemented in a distributed manner (either by dealing with several requirements on different computers or by using the parallel structure of IA algorithm)
- it can be implemented in two different ways: *incremental* or *parallel*. In the incremental way $\mathcal{P}_r$ is calculated for a single f_i and the result is used as search space for calculating $\mathcal{P}_r$ for the requirement f_{i+1}. As this search space is smaller than $\mathcal{P}_I$ the computation time of $\mathcal{P}_r$ is reduced. The drawback

of this approach is that if $\mathcal{P}_r$ is empty at some step of the process, then it is impossible to determine which previous requirement(s) is (are) too drastic. In the parallel way $\mathcal{P}_r$ is calculated individually for all requirements and the final result is obtained as the intersection of all individual results.

Finally as it is not possible to present to the user all the design solution the final step of the process is to select a small number of design solutions offering various compromises.

We are familiar with efficient problem formulations for classical robotics requirements but a major work will be to extend this knowledge to requirements that are specific to assistance such as energy concern, safety, user-friendliness, acceptance and low costs. Our experience has shown that introducing new requirement types imposes thorough theoretical and mathematical analyses together with a large software development effort. Section 7 provides a practical example of the use of this approach for the adaptation of a transfer robot to the user and to his environment.

6 Topic: research questions for the evaluation of an interactive assistive ecosystem

Timeline: year 1-12, **Who**: O. Pourtallier,B. Senach

This section envisions the research questions associated with the evaluation of an interactive assistive ecosystem i.e. *evaluation dimensions of an assistive device* and *evaluation methodology.*

6.1 Evaluation dimensions of an assistive device

We provide below a list of evaluation dimensions that may be selected according to the purposes of the device and its stage of development. Note that they may concern the primary subject but also other stakeholders (family, care givers and the medical community).

Utility Each stakeholders has his own goals and criterion. Evaluation will have to consider these different point of view. For instance in medical monitoring a new assistive device may provide new indicator about current health state of a patient [92]. These new measures have to convince physicians and caregivers and hence have to be involved in the device process at all steps (devices, analysis and experimentation design)

Success / failure The evaluation criteria is defined at the beginning of the design process, according to specified objectives of the assistive device. Here again, criteria may be different for each stakeholders.

Users performance Expected performances depend of the type of devices. For instance, for mobility devices, evaluation can be based on objective measure (speed, trajectories . . .), that are compared with perceived performances to assess improvement.

Usability evaluation Usability is defined by the ISO norm 9241-11 as *the extent to which a product can be used by specific users to achieve specified goals with effectiveness, efficiency, and satisfaction in specified context of use.* Several tools (grids, guidelines, . . .) are available to support the evaluation process. In the context of HEPHAISTOS, these tools will have to be tailored by specifying Key Performance Indicators (KPI) that can be objectively measured. Evaluation will be done with scenarios in which selected task have to be performed and by using classical indicators (time, errors, . . .) and satisfaction questionnaire to identify strength and weakness.

User experience User experience consider emotional reaction when interacting with a device, cognitive impact, sensorial aspect ... Regarding the elderly, as the goal of the assistive devices is to improve autonomy, it will be necessary to set up an evaluation grid with new dimensions, not only the perceived evolution of personal autonomy but also self-esteem or other dimensions to be identified: perceived benefit on mobility and autonomy, empowerment assessment, potential changes in lifestyle, emotions, pleasure in using a device, self-esteem, trust, which plays an important role in human-computer interaction as it helps people overcome risk and uncertainty (see [94] for measurement scale and [95] for a recent literature survey in the IoT field).

Technology acceptance As stated earlier, a popular stream of research has focused on identifying the conditions that facilitate technology acceptance and several models are available. Technology acceptance model (TAM) posits that two specific perceptions about technology determine one's behavioral intention to use a technology: perceived ease of use and perceived usefulness. The research question is here to identify the dimensions that influence these perception. For instance, a specific weakness of a device can be compensated by a strong perceived usefulness while computer anxiety may play an adverse role. The use of this kind of model in HEPHAISTOS can support the design of analysis grids tailored for the evaluation of assistive devices.

Appropriation Appropriation refers to the process by which a new knowledge is integrated in previous mental structure. It require to restructure existing knowledge and many studies have make proposal to understand the underlying process [80, 79, 4]. It can be evaluated through indicators such as increase of usage frequency, extension of usage contexts, but it requires long term studies.

Efficiency of persuasive strategies and gamification Gamification [60] is a new topic that emerged from videogame and that is converging towards persuasive technology [33], which is now applied to assistive devices for elder people under the name of "persuasive gerontechnology" [89] and persuasion techniques to motivate elderly people is a current challenge [37] with ethical issues. There is some emerging application in the field of silver economy, such as SilverBalance (an exergame for elderly users [11, 39]). Few evaluation of gamification principles have been done up to now [46] and it seems to be a methodological challenge.

Sociality Evaluation question is here to identify change of relationships that may be linked to the assistive environment. Sociometry [7, 20] provides tools to analyze these changes.

6.2 Evaluation methodology

Evaluation can be conducted according to very different approaches according to the users' role in the design process and experimentation with users is difficult and lengthy (see section 10.2). With an iterative design process, evaluation is distributed along the process and relies on different techniques, more or less extensive, according to the design progress (from discount usability to users testing). According to contingencies and specific research opportunities, evaluation will take place in appropriate context : labs, at home, in retirement home, outdoor. Medical evaluation relies exclusively on statistics (sometimes even if the number of subject is very low) and without considering measurement uncertainties. We hope that in some cases our studies may disrupt classical evaluation ways and that we will set up new and/or well-structured evaluation methodologies adapted to deal with elderly, taking in account cognitive and physical impairments, uncertainties and addressing the different needs of the various stakeholders.

7 Topic: cable-driven parallel robots

Timeline: year 1-10, **Who**: J-P. Merlet, Y. Papegay

Cable-driven parallel robots have great potential for assistance and will play an important role in the project. Using such type of robot is a major originality of HEPHAISTOS and raises several theoretical issues. Basically a cable-driven parallel robot (CDPR) is constituted of a mobile platform that is connected to fixed anchor points through a set of cables whose lengths is computer-controlled. An appropriate control of these lengths allow one to impose specific motions on the platform. The advantages of such a robot are the mechanical simplicity (and therefore a reduced cost and installation/maintenance facility), the low intrusivity (cables are more discrete and less dangerous than rigid legs, the robot is hidden in the ceiling when not in use) and a high energy efficiency. It must also be noted that CDPR are only an example of **closed-loop mechanism** for the analysis of which we have a recognized expertise that may be used also, for example, for walking analysis and biomechanics.

The advantages of CDPR have motivated us to build the transfer robot `MARIONET-ASSIST` that is installed in the ceiling of our experimental flat (figure 4). This robot uses 4 to 6 cables actuated with 50W motors and

Figure 4: The `MARIONET-ASSIST` transfer robot

is able to fully lift a 200 kg load whatever is its location in the room. Depending on the number of cables and the geometry of the robot we may control 3 to 6 degrees of freedom of the platform. `MARIONET-ASSIST` may also partially lift the user to provide walking assistance while monitoring the walking pattern and evaluate the assistance force required by the user. This robot is still a manipulator that may pick an object on the ground by using a visual servoing approach developed in collaboration with the LAGADIC project [81]. The elegant features of CDPR has led to develop a full family of such a robot: `MARIONET-CRANE` (a very large robot for rescue operations), `MARIONET-REHAB` (for rehabilitation purposes, section 4.3.4), `MARIONET-SCHOOL` (for dissemination purposes, section 12) and `MARIONET-VR` (in development, to be used in an immersive environment, section 10.3).

This hardware development were made in the COPRIN project, based on our knowledge of parallel robots with rigid legs and on the existing literature on CDPR. But the practical experience we got from our prototypes is that there was a high number of important theoretical issues that have not been addressed in the past, although they may play a significant role in the effectiveness of the robot. Let us assume first that the cables are non elastic and massless: in that case a key concept is the notion of *cable configuration* at a given robot pose i.e. the set of cable that are under tension at this pose. This is an important concept because a cable whose length is larger than the distance between the fixed anchor point and the attachment point on the platform neither impose a geometrical constraints nor participate to the mechanical equilibrium of the system. By looking at previous works we realize that this concept was never considered: it was always assumed that for a robot with n cables all n cables were under tension. We first show that from a kinematics viewpoint if $n \geq 6$, then there will be always **at most** 6 cables under tension. This has a very large impact on the analysis of CDPR's as the state equations that govern any analysis (kinematics, control,...) change according to the cable configuration. For example consider the forward kinematics problem (FK) in which the cable lengths are assumed to be known while the pose of the platform has to be determined. FK is known to be a very difficult problem for parallel robots but become even more complex for CDPRs. Indeed instead of having to solve a single system of equations as the one obtained for parallel robot with rigid legs we end up with a family of system of equations, one for each possible cable configuration, which furthermore has a size much larger than the one obtained for classical parallel robots. Additionally this is no more an algebraic problem but a semi-algebraic one as for a robot with m we are interested only in the solution for which the tensions in the m cables are positive. Efficiently solving the FK problem is nowadays still an open problem [13, 12]. If we assume that the cables are elastic and/or deformable (like catenary cables) the kinematics problem becomes even more complex [63] (and IA is the only tools that allow to solve them as we are now dealing with non algebraic equations) while managing the cable tension distribution in redundant CDPR (i.e. having more cables than necessary) is also an open issue. We intend to use our complete analysis of CDPR to propose original control scheme for this type of robot.

In summary CDPR's may play an important role in assistance robotics, exhibit in practice a good behavior but there is still several theoretical issues that have to be solved in order to exploit them at best. We have had a world leading position in identifying unsolved issues and in proposing preliminary solutions ([12, 42, 64, 65] and we intend to devote part of our activity in this domain.

CDPRs provides also a good test case of our *appropriate design* methodology (section 5.3). Using a CDPR intended as a transfer robot requires to find the possible locations of the winches in the ceiling so that

- the robot workspace includes the largest part of a room of given geometry
- for a given user weight determine what will be the maximal tension in the cables when the robot moves in a given room so that assistance to the user will never lead to a failure in the cables
- the actuator power is minimal (in order to reduce their cost).

Solving these problems should also take into account that the real instance of the CDPR will differ from its theoretical model. Hence our appropriate design approach that determines regions for the location of the winches while guaranteeing the performances of the real CDPR is especially appropriate.

8 Methodology: game theory

Timeline: year 1-12, **Who**: J-P. Merlet,<u>O. Pourtallier</u>

8.1 Introduction

Game theory is the mathematical tool for approaching situations where several agents (players, decision makers) interact. In an N person game, the outcome of a particular agent depends upon its own choice, but also upon the choices of the other agents. An important assumption is that the agents are rational and strive at maximizing their individual outcome. Depending on the model and the assumptions that can be made on the behavior of the agents, several approaches yielding several solutions, different concepts and techniques may be used.

The kernel concept in game theory is the Nash equilibrium. A vector choice of the agents $(u_1^*, \cdots, u_N^*)$ is said to be a Nash equilibrium, if no player, P_j, has any incentive to unilaterally deviate from its choice u_i^*, i.e. if for any $u_i \neq u_i^*$ we have,

$$\varphi_i(u_1^*, \cdots, u_N^*) \geq \varphi_i(u_1^*, \cdots, u_{i-1}^*, u_i, u_{i+1}^*, \cdots, u_N^*).$$

Here φ_i is the evaluation function of agent i. This notion can be extended in many ways to take into account various situations. For example the study of coalition formation can be handled through the notion of strongness of the equilibrium where the deviations of a subset of players are also considered. The assumption of rationality can be weakened by considering that only a subset of players are rational. In that case a *min-max* approach, where the rational players guard against the worst behavior of non-rational players while seeking for equilibrium with rational players.

The equilibrium is said to be strong if there is no incentive for any subgroup S of agents to deviate from their choice $(u_i^*, i \in S)$, i.e. if for any deviation $(u_i, i \in S)$ we have for any $i \in S$,

$$\varphi_i(u_1^*, \cdots, u_N^*) \geq \varphi_i((u_1^*, i \notin S), (u_i, i \in S)).$$

Strong Nash equilibrium notion allows one to study the coalition formation.

Although appealing since it can model numerous situations of real life interactions, game theory suffers from the lack of general methods to compute equilibrium as soon as strong assumptions on continuity and convexity cannot be assumed. When the number of agents becomes large so as each agent can be considered as atomic, limit game can be analyzed with optimization techniques (to study Wardrop equilibrium) or with EDP techniques in the recently developed theory of mean field games.

When the theory of limit games cannot be applied, the solution of a particular game needs to be found through ad hoc techniques that can be inspired by other games. The study of such games brings strong and useful understanding on the real situation.

8.2 Game theory for assistance

Assistance to persons involves several agents of various types : monitored person and monitoring system, that may include several monitoring devices and human monitoring ; economical agents such that service providers, medical devices industry ; society though social security and hospitals ; family and helpers ; assisted person. All these agents interfere and complement themselves in assistance. They nevertheless do not share the same objective. In the subsequent sections we describe two approaches based upon game theory that we intend to study in HEPHAISTOS.

The first one focus of economic. The long term objective is to built economic models to understand the relationship of the agents and hopefully propose critical analyze of the actual organization.

The second approach focus on possible yield of game theory for domestic monitoring.

8.2.1 Economics of assistance

As the older demographic group grows larger the economic impact of assistance becomes more important. Assistance involves several different economic agents ranging from the subject of assistance and his relatives, to the industrial, service providers,social security and insurance sectors. The roles of these agents are tightly intricate and this leads to difficulties to oversee the implications of economic choice. As an example, we can consider the case of medical assistance devices such as walkers or wheelchairs. For security reason these devices must fulfill binding standards yielding high price on the market. Social security provides financial support for people who need these devices. Although this financial support is necessary for some people to be able to get these devices, it does not bring any incentive for the industry to decrease its price.

One can then question the efficiency of this financial support on the final user of the device. Would it be more efficient to find economic incentive for the industry to decrease the price? This economic issue has to be put into the context of the adverse forecast that the current economy of the European Union is putting on the future generation of retired people.

Although there are many works in health economics related to assistance [90, 27, 9, 9], to the best of our knowledge there is not much work on a global vision of the sector and the interdependence of the agents. Our long term objective is to build mathematical models based on game theory in order to better understand the possible interactions between the various agents in order to bring a tool to analyze the effect of possible economic regulation in the field of assistance. Although we do think that there are much to do in that direction, and that game theory can bring understanding, we are at the early stage of this work, and a first milestone would be to have a full understanding of the ongoing work (what and who) in this domain.

8.2.2 Pursuit Evasion Game for monitoring people

The monitoring of domestic activity of a person is driven by two antagonistic aims. The first one is to obtain a precise picture of the activity on a short term (e.g to detect a fall) or to monitor changes in behavior over a long period (see section 4.3.3) while the second aim would be to respect as much as possible the privacy of the person for ethical reasons. This yields the necessity to reach a reasonable balance between these two aims. We intend to use game theory and more specially pursuit evasion game to approach this situation. Pursuit evasion game are two player zero sum games where a player, the pursuer strives to capture the second player, the evader. Pursuer wants to minimize the capture time while the evader strives to maximize the capture time or escape from a capture zone. This class of game initiated by R. Isaacs [56] has received much attention and there exists a large literature coping with several aspects and applications of pursuit evasion games [45, 17, 69].

For monitoring purpose we can think the person as an evader and the monitoring system as a pursuer. An acceptable precision on the knowledge of the behavior of the person can be used to define a capture zone. We can think the monitoring system endowed with limited observation resources (e.g. limited observation instants) and with uncertainties in the localization (section 9) and the aim to maintain the evader in the capture zone. The observation resources capacity of the monitoring system measure the degree of intrusiveness of the system.

Although not completely realistic, thinking the person in terms of an evader allows us to analyze the system is the worst case (the case where the person strives to escape from observation) and provides us with a certified result. As a matter of fact if for some observation resources capacity the system is able to maintain an evader in a capture zone, then it will also be able to maintain a person (that may not strive to escape) in this capture zone. We can think of various extension of this initial model, depending on the possible obstacle in the area or the possibility to have several persons in the area for example.

9 Methodology: interval analysis

Timeline: year 1-12, **Who**: <u>J-P. Merlet</u>,Y. Papegay,O. Pourtallier

As seen in the previous sections interval analysis (IA) is a key methodological elements for many of our works: design analysis (section 5.3), rehabilitation and biomechanics (section 4.3.4), analysis of cable-driven parallel robots (section 7), health monitoring and optimal sensor location (section 4.3.3) and, in general terms, management of uncertainties.

This extensive use of IA is motivated by

- *flexibility*: IA can manage all sort of problems (optimization, system solving, including non 0-dimensional one, differential equations, ...) and allows to use almost any type of mathematical formulation
- *closeness to reality*: it is often assumed that sensory data have a Gaussian uncertainty distribution but unfortunately this is not true for most of them. Most of the time an interval error is associated to a sensor and the real value of the measured variable may be **any** value in the interval measurement
- *guaranteed results*: a result obtained with interval analysis is **guaranteed**. This is to the best of our knowledge the only method that may consider the worst case situation (with respect to the model), which is an appropriate approach for safety critical systems

A major drawback of IA is that its efficiency is largely conditioned by the way the problem is formulated (different formulations, although mathematically equivalent, may lead to very different computation time) and by the heuristics that are used for the solving. Unfortunately there is no rule to determine which formulation and heuristics will be the most efficient because this problem is most of the time NP-hard [59]. To address these issues the project proposes the following plan:

- *library*: we benefit from having developed in the COPRIN project the very large C++ interval analysis library `ALIAS`[36]. It includes almost all classical interval analysis algorithms but also specific procedures that have been developed for robotics problems. This library will be extended with algorithms that are specific to assistance problems, especially taking into account their mathematical formulation.
- *heuristics and algorithms*: this is the kernel of our mathematical works in IA. We consider the problem formulation and develop algorithms and heuristics based on a sound mathematical background (possibly customizing theorems and their proof to improve the solving time, see the item *software customization* in this section) that will be more effective than general purpose IA methods
- *interface*: most of the problems we are dealing with are NP-hard. Fortunately the practical complexity may be different but only numerical experimentation allows one to determine the most efficient solving algorithm and hence it is crucial to have interface for fast software prototyping. `ALIAS` is already connected to `Maple` for creating problem specific C++ code and for using directly standard high-level IA algorithms (equations solving, optimization, ...) with even the possibility of using a distributed implementation
- *software customization*: most of our IA solving algorithms use general purpose mathematical theorems but for a given problem customized theorems allow to improve drastically the efficiency of the IA algorithms[37]. Up to now this customization was done by hand but we have established a collaboration with the MARELLE project in order to automatize it with the Coq proof assistant[38].

These issues are in line with what was already proposed in `COPRIN`. But we intend to address other issues in `HEPHAISTOS`:

[36] `http://www-sop.inria.fr/coprin/developpements/main.html`
[37] *drastically* means here to decrease the computation time by several order of magnitude
[38] `http://coq.inria.fr/`

- *symbolic construction of IA algorithms*: we intend to develop a symbolic scheme to describe IA algorithms and run them in different modes: *symbolic prototyping* (the algorithm is run as a program of the symbolic software to allow for fast debug), *mixed symbolic/numerical* (parts of the symbolic program are translated into `ALIAS` C++ code), and *full numerical* (the symbolic program is translated completely into C++ code)
- *heterogeneous distributed implementation*: the proposed assistive ecosystem includes several computers that may be used for interval analysis calculation (e.g. for computing locally synthetic indicators with interval values). However our current distributed implementation scheme assume that the available computers have roughly the same calculation power and are always available. In the assistance case the context is different as the computing power of the elements present in our ecosystem exhibit large differences, energy must be taken into account (e.g. for wearable computers) and availability of the resources may be rapidly changing and is not known in advance. Hence we intend to develop a distribution scheme that takes into account all the above factors.
- *statistics with interval values data*: as mentioned previously (see section 4.3.3) statistics is extensively used in the field of health but neglect the uncertainties in the data or assume an unrealistic probability distribution for these uncertainties. We argue that using interval for computing statistical index may be safer and provide a mean to assess the quality of the computed index. There has been some preliminary works in this field [30, 58] but we believe that large progress can be made.

10 Topic: experimentation and simulation

Timeline: year 1-12, **Who**: J-P. Merlet,Y. Papegay

The efficiency, reliability and flexibility of the assistive ecosystem proposed by the project has clearly to be confirmed by real life experiments which also contribute to discover development problems, new applications and may enlight unexpected theoretical issues. However there are several barriers for running these experiments with external partners and/or in external location as will be described in section 10.2. Hence we argue that we need a full experimental setup in the project workplace in order to be able to test and develop our solutions.

10.1 The project platforms

We believe that for being convincing we shall not limit our work on theoretical issues but also on developing appropriate hardware, which is also a long term manpower/time investment. Indeed we think that the staff members must be in the front-line for developing and maintaining the project platforms because they have a long term life: Phd or post-doc students and the INRIA SED support team [39] may provide some help but under the strict supervision of staff member(s) so that their development can be used after their departure.

10.1.1 Current status

HEPHAISTOS benefits from its own experimental workplace with a simulated flat that includes all the basic home elements (kitchen, bedroom, toilets, relaxation and rehabilitation area)[40] that allow one to perform realistic test in a flexible environment. The flat is instrumented with two cable-driven parallel robots

[39] *SED* is a service that may attribute engineers for software development typically for one or two years

[40] see `http://www-sop.inria.fr/coprin/prototypes/main.html`

`MARIONET-ASSIST` for transfer and manipulation and `MARIONET-REHAB` for rehabilitation purposes. Two walking aids `ANG-light` (for walking analysis) and `ANG-II` (a fully motorized rollator) are also available and will be completed with `ANG-med` (with adjustable friction brakes in the rear wheels). Several mobile robots are also available (Roomba, Wanny, PoBots) together with small industrial manipulators. The mobile robots will be used mostly for emergency situation (as fall detector and managing first aid) and for manipulation (recovering fallen objects). A motion capture system with 12 cameras is also available together with several passive cable distance sensors. Those systems allow to locate human limbs or objects within a relatively large area.

We have also started developing instrumented clothes with the purpose of monitoring walking patterns, falls and daily activities. All these devices will be tested by playing *scenarii* of real life. Scenarii are short stories that can be used for different purpose (to identify real performances, adaptability of the devices, users needs, to envision the context of usage, to describe utilization procedure , to anticipate usability problems, ...)

Our platforms are also intended for dissemination purposes: for example we have designed three portable cable-driven parallel robots, `MARIONET-SCHOOL` that are used for dissemination at all levels (see section 12).

As may be seen we have largely invested in hardware through the CPER TELIUS for a total cost of about 600 000 euros. Large investment in hardware is not expected in the future as we will need only to maintain and possibly lightly upgrade our platforms for a provisional cost of less than 10 000 euros per year. However according to opportunities we may have to duplicate some of our hardware for long term experiments with one of our clinical partners. Note that all of our current devices have efficient **communication** capabilities, not only wireless but also infrared that has the advantages of lower energy consumption.

10.1.2 Localization

Localization of the user(s) in a room plays an important role for monitoring activities of daily living, for rehabilitation and for safety (fall detection). Computer vision is usually used for that purpose (for example in the STARS project) but has drawbacks (intrusivity and acceptance, sensibility to lighting conditions and accuracy). To complement computer vision we plan to investigate the use of a combination of presence sensors and infrared distance sensors to ensure localization. Determining the location of these sensors in the environment to ensure a full coverage is an interesting issue especially if measurement uncertainties are taken into account. The interval analysis-based appropriate design methodology (section 5.3) and game theory (section 8.2.2) appear to be promising to solve this issue. In addition the possibility of controlling the measurement direction leads to interesting control issues.

10.1.3 Virtual reality

INRIA Sophia-Antipolis center is equipped with an immersive space which includes a large image wall. Such a system currently provides 3D view that is updated according to the measured position of the head of the subject. But this platform is lacking of two capabilities: realistic subject motion and force-feedback. We plan to augment the current setup with various motion systems (including the CDPR `MARIONET-VR`) and training apparatus to obtain a *full and flexible virtual reality environment* that will offer all capabilities.

We intend to use this setup for rehabilitation through gamification (section 10.3), for training and for entertainment. For example we are considering a collaboration with the REVES and HYBRID projects for using a treadmill to simulate walking or running in an hilly environment. A further possibility will be to use `MARIONET-VR` to support patients which are unable to walk alone because of their weakness in the leg(s) and for various simulators (ski, sailing, tennis), possibly in collaboration with the Handibio laboratory.

10.1.4 Middleware

It must be noted that all of our platforms are designed to be open-access and can be used by other academic and industrial partners. Accordingly it is necessary to have a middleware that allows for connecting several assistance devices (for exchanging data or downloading specific applications which is the purpose of our European project RAPP[41]) that are heterogeneous in terms of OS and computing power, prone to failure or non availability.

As middleware is not our specialty we have decided to rely on external expertise and available software to deal with this important problem. Hence we have started a long term collaboration with the INRIA INDES project that has developed the HOP language[42] for programming interactive web applications. Another possibility will be to use the software development of the PHOENIX team, of which we are specially aware as a former member of COPRIN, David Daney, is now part of this team.

10.2 The experimentation barriers

Experimentation with elderly people is an intensive and time consuming work: recruitment shall be made by praticians, experiments has to be performed in specific places, the availability of subjects is low and some experiments cannot fully take place (e.g. the one involving fall). Furthermore experimentation requires heavy authorization procedures, at least in France. We will deal with these experimentation issues in several ways:

- *intensive use of simulation*: we intend to investigate an extensive use of musculoskeletal modeling for our work on mobility and to develop other specific simulation tools in order to rely at the least resort to experimentation. Our contributions in this domain will be our expertise in the analysis of closed-loop mechanisms, automated modeling of mechanisms with symbolic computation software and an extensive use of interval analysis to manage the uncertainties in the models
- *using younger adults*: to alleviate the availability of elderly people we consider using young adults that will be instrumented with specific hardware that allows to submit the subject to specific impairments[43].
- *clinical network*: establishing a strong relationship with clinical partners is essential for HEPHAISTOS. Locally we have a strong collaboration with Nice Hospital (P. Robert), that has allowed us to test intensively one of our walking aid with elderly. We are also currently establishing a similar collaboration with a local rehabilitation center (Centre Hélio-marin de Vallauris[44]). At the same time we have gained access to 6 rooms of an EHPAD in Nice (a specific retirement house) in which we intend to experiment non intrusive devices. We are also following closely other possibilities of using the platforms of the CIU Santé namely Delvalle house and Institut Claude Pompidou. But our network is not limited to local partners as will be presented in section 13.

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[41] Robotics APPlication store: `http://rapp-project.eu/`
[42] `http://hop.inria.fr/`
[43] see for example `http://ipad.asso.fr/animations/simulateur-de-vieillissement-2/`
[44] `http://www.ugecam-pacac.fr/etablissements/centre-helio-marin-vallauris`

10.3 Gamification

The approach of gamification [24] which is the application of game elements in a non-gaming context is growing. Although the current community of elderly people may not be interested in computer entertainment games a research area has recently emerged with, for example, the development of serious games for the elderly (for instance, Eldergames[45], a project which aims at improving the cognitive/social skills of older users). We believe that gamification may play a favorable role especially in rehabilitation. Our contribution in this area will be the use of the hardware of our virtual reality setup (section 10.1.3) that includes a 6 degrees-of-freedom motion base that can support a patient and the CDPR `MARIONET-VR` that can lift the patient or can be used to provide force-feedback. An example of use of this setup is to improve the rehabilitation process proposed by Motek Medical[46] (for which clinical trials have shown a reduction of rehabilitation time of up to 30%) by using the lifting ability of `MARIONET-VR`. We intend also to enlarge the possibility of using virtual reality in rehabilitation by using more realistic situations in order to train specific musculoskeletal parts of the human body (section 10.1.3).

11 Ethics

We are fully aware that our proposal requires to address several ethical and legal issues. We have already mentioned the experimentation barriers that addresses the legal/ethical problems regarding experiments with humans. As we intend to strictly abide to current regulations and as we are quite sensitive to safety problems (for the subject and for the experimentator) we are confident that our experiments are properly managed.

But ethics involves more general issues. For example the monitoring of elderly people raise questions regarding the respect of privacy and/or the possibility of exploiting the frailty of elderly people for exploiting wrongly the monitoring results. Monitoring presents undoubtedly advantages for rehabilitation, safety and preventive medicine and hence it is quite probable that it will be used in the future: consequently we have decided to state clearly what is our position on the privacy issue.

Clearly also we need an external view on our works regarding these problems. To manage properly ethics we will firstly rely on our clinical partners but also benefit from the advice of the *Comité opérationnel d'évaluation des risques légaux et éthiques* (COERLE) that has been recently created at INRIA. If necessary we also benefit from the advice of other ethical committees (e.g the INSERM ethical committee).

12 Dissemination and teaching

12.1 Dissemination

Dissemination was a strong point of the COPRIN project and we intend to continue our activities in this field, for example organizing conferences and workshops (we have a large experience of even large conferences such as IROS 2008 and the 2007 IFToMM World congress with roughly 1000 participants). Already our instrumented flat is a classical showroom for the research activities of INRIA at Sophia-Antipolis with about 300 visitors per year ranging from classrooms, general audience, companies and officials. We intend to go on in this direction by offering this realistic setup to other INRIA teams to demonstrate their activities. Another dissemination action is based on the CDPRs `MARIONET-SCHOOL` that are modular enough to be used either on the desk of a teacher or

[45] `http://www.eldergames.org/`
[46] `www.motekmedical.com/`

to cover completely a classroom. They have been extensively used by us and by foreign colleagues for teaching, for demonstrations for general audience but also in professional fairs. In the same way we intend to propose several technological and practical solutions to effectively build cable-driven parallel robots using different low-cost technologies so that teachers and students can design their own robot. Note that these initiatives are totally in line with the plan **France Robots Initiatives** recently launched by the Research Ministry[47].

12.2 Teaching

Specific teaching in the field of assistance to persons with impairment at the master level is quite limited and addresses only special areas: human sciences at Paris 5, law at Caen and biomechanics at Paris Sud. In robotics there are several masters (UVSQ, Nantes, UPMC, ENS Cachan, Montpellier, ...) but are all general and do not cover major topics of assistance robotics. Locally there is no such master in spite of all our efforts for that purpose with the consequence that we have very few local PhD students. We will go on with actions that have already been used successfully in COPRIN such as *joint PhD students* with external partners, and *summer schools* (on average one per year). We intend also to be more active in existing robotic masters and go on for the creation of a local master.

13 Positioning, collaborations and fundings

13.1 Positioning: a panorama

The positioning of HEPHAISTOS on assistance is rather unique in the world by addressing several aspects of assistance in a global framework. There are numerous laboratories that address very specific issues in assistance (walker, wheelchair, social communication, companion robots, ...) but we will restrict the list to teams that have several projects in this field. European laboratories are especially very active in mobility, elder care and home robotics and we may mention the main laboratories that have an activity in these domains:

- *Scuola Superiore Sant'Anna, ARTS Lab, Pisa*[48]: focus on mobility assistance, wearable devices for activity recognition and companion robot. We have frequent contact with this team and we have collaborated with it in the European project AERES.
- *Danish Technological Institute (DTI)*[49] and *University of Southern Danemark (SDU)*[50]: DTI focuses on short term projects with a strong industrial involvement. They have established the showroom, *Carelab*, that displays various technological helps and collaborate with SDU regarding cognitive abilities of elderly. We have organized a workshop on assistance for elderly with the DTI
- *Austrian Institute of Technology*[51]: focuses on personal safety and establishing a linkage between elderly people, their relatives, and care givers
- *iHomeLab, Luzern*[52]: aims at developing technologies for comfortable living and life in old age that are tested in a specific building

[47] www.redressement-productif.gouv.fr/files/France_Robots_Initiatives.pdf
[48] http://www-arts.sssup.it/
[49] http://www.dti.dk/
[50] http://www.sdu.dk/en
[51] http://www.ait.ac.at
[52] http://www.ihomelab.ch

- *Delft University of Technology* [53]: focuses on design through specific short-term projects in specific areas
- *Universitat Jaume*[54]: implements an Ambient Intelligence environment in the context of a specific room inside a house, in order to perform assistive tasks. The system will be composed of a set of distributed sensors (e.g. cameras, microphones), robots (e.g. humanoid robots, mobile manipulators) and other devices (e.g. touchscreens, home automation devices) of different types, all of them integrated in a networked intelligent environment in order to provide assistance in a individualized or synchronized manner.
- *CETpD, Technical research centre for Dependency Care and Autonomous Living, Universitat Politècnica de Catalunya*[55]: develops smart-sensors, devices (including instrumented walkers) and smart-interfaces for aging people living at home. We have an informal collaboration with this team
- *DFKI Competence Center Ambient Assisted Living, Saarbruecken*[56]: promotes an open accessible intelligent environment and innovative solutions for autonomous life
- *Fraunhofer IPA*: is focusing on the social robot Care-O-bot[57]. We already have ongoing collaboration with this institute on assistance and a strong collaboration on CDPRs

Japan and Korea lead in human-like robots, and some aspects of service and personal robots (including entertainment) but with goals that differ from HEPHAISTOS guidelines (cost, medical monitoring, low intrusivity). Typical examples of this approach are the japanese nursebot RIBA[58] which is able to perform to some extent transfer operation and the korean nursebot KIRO-M5[59] from the *Korea Institute of Robot and Convergence, Pohang University.* We don't plan to work on human-like robots but we expect to maintain our relation with University of Tokyo on the dynamics of human musculo-skeletal model and with University of Osaka on ambient intelligence. USA is less present in this field except for the *Quality of Life Technologies, CMU*[60]: a research center of NSF which focus on "the development of intelligent systems that improve quality of life for everyone while enabling older adults and people with disabilities". The platforms of this large center are centered on mobile platforms with robotic arms, coaches, safe driving and smart home, which are not all among our objectives.

In France the works related to assistance robotics focus on decision making and human-robot cooperation at LAAS, assistant exoskeleton at CEA and rehabilitation at ISIR. LIRMM has also some activities in this field (human modeling, bio-physical sensors) but leans more toward medical robotics. Our activity is closer to the one proposed at:

- LM2S of UTT in terms of systems although this laboratory do not use robots.
- IBISC[61] of Evry University that has a similar view of ambient robotics but without medical monitoring

At the national level we are involved in the CNRS GDR Robotique but there is also the CNRS/INSERM GDR STIC Santé that proposes several research themes that are appropriate (e-health, wearable sensors, intelligent housing). The ALLISTENE alliance[62] has also a working group on robotics that includes assistance. They are also scientific societies that are involved in this field:

[53] http://www.io.tudelft.nl/en/research/research-themes/care-for-our-health/
[54] http://www.robot.uji.es
[55] http://www.epsevg.upc.edu/cetpd/
[56] http://ccaal.dfki.de
[57] http://www.care-o-bot.de
[58] http://rtc.nagoya.riken.jp/RIBA/index-e.html
[59] https://www.youtube.com/watch?v=KZv9NkVyueM
[60] http://www.cmu.edu/qolt/
[61] www.ibisc.univ-evry.fr
[62] https://www.allistene.fr/

- *Institut Fédératif de Recherche sur les aides techniques pour peonnes handicapées* (IFRATH[63]): focuses on technological helps for handicapped people and organize the HANDICAP conference
- *Société Française des Technologies pour l'Autonomie et de Gérontechnologie* (SFTAG[64]): intends to become the scientific society for the Silver economy

We may now indicate what will probably be the teams we will be working with.

13.2 HEPHAISTOS most favored partners

As a foreword it is necessary to specify what will be the type of collaboration with our partners, especially the one that have an expertise in a domain that is necessary for our projects but which is far away from our competence domains. At this stage of the project it is difficult to provide a definitive answer on that point because, as seen previously, parts of our research are not completely defined as we are dependent upon external factors. However we will clearly rely as most as possible on using existing software and hardware with the help of the collaborators (which will gain a showcase for their works). But we are also aware that some of our needs may involve some specific research efforts. In that case we intend to develop collaborative works (as we have already done with INDES) either on an informal basis or, if fundings are requested, based on the multiple tools that the current research system is offering either locally, nationally or at the EU level.

13.2.1 INRIA partners

We are currently working with the LAGADIC project on visual servoing for manipulation purposes (joint PhD), with the STARS project (for the monitoring of daily activities in the Dema@Care project). Within the PAL INRIA project lab (IPL) we have collaboration with the FLOWERS,LAGADIC, MAIA, MADYNE, PRIMA, E-MOTION projects and, to a lower extent, with PHOENIX. Among this PAL members we will favor to continue the strong collaboration we have with LAGADIC while the relations with STARS will increase. We have had also some exchanges with DEMAR about motion sensing and muscle behavior although our objectives are very different. We have also started a collaboration with WIMMICS regarding the interface and design of an instrumented cane and we intend to collaborate with FLOWERS, MAIA and E-MOTION for machine learning.

But our collaboration with INRIA projects is not limited to robotics and assistance. As seen in section 10.3 we intend to collaborate with REVES and HYBRID on virtual reality. On the long term we may be interested in the brain-computer interface developed by HYBRID and by ATHENA and we have some similar interests with MIMETICS (biomechanics, motion sensing). We have also an ongoing collaboration with TOSCA about the application of game theory. On the mathematical side we have an ongoing collaboration with MARELLE on the application of automated proof. On the software side, as mentioned in section 10.1.4 we have a strong collaboration with the INDES project for the programming of our assistance devices network with the HOP language. We are currently partners in the European project RAPP[65] whose purpose is to propose downloadable applications for robotic platforms, especially NAO and `ANG-med`.

[63] http://ifrath.fr/
[64] http://www.sftag.fr/
[65] http://rapp-project.eu/

13.2.2 Clinical partners

As already mentioned collaborations with clinical partners are essential for establishing our guidelines in medical monitoring (e.g. for identifying pertinent health indicators), for evaluation and for the validation of our works through experimentation. We have already a strong collaboration with the Centre Mémoire de Ressources et de Recherche,CHU de Nice (CMRR), Pr. Robert, with which we have already performed walking analysis experiments. The CMRR has created the joint team CoBTek with the INRIA project STARS and we intend to join this team. We intend to benefit also from the membership of INRIA in the CIU Santé to gain access to experimental platforms: EHPAD Valrose, with 6 rooms that are available for experiments, Institut Claude Pompidou for serious games and Living Lab PAILLON2020 with an instrumented flat and a showroom. We are also in the process of signing a formal agreement with a rehabilitation center (Centre héliomarin de Vallauris) that has agreed to test some of our devices on the long term.

But our collaboration with french clinical partners are not restricted to Nice as we are looking for collaboration with the Pôle gérontologie clinique of Bordeaux and the Centre Mémoire de Recherche et de Ressources of Toulouse (INSERM U558) which are major players in the field of gerontology.

We are also looking for abroad clinical partners. We have access to several rehabilitation centers in Tunisia through our long term partner Sousse Engineer School. Recently we have started a collaboration with the spanish foundation MATIA[66] and the greek ORMYLIA foundation[67] on the use of walking aids for rehabilitation. It must be noted that these clinical partners allow us to benefit of a large panel of potential users and of long term tests (for example CHU Nice has used `ANG` for 8 months).

13.2.3 Assistance and Robotics partners

In the field of assistance HEPHAISTOS has identified various major partners: Scuola Superiore Sant'Anna, LM2S of UTT, CETpD of UPC Barcelona, IBISC of Evry University. We have already strong contacts with the three first one and plan to contact IBISC in the near future. In biomechanics we have already a strong collaboration with Handibio of University of Toulon[68], Biorobotics and Biomechanics Lab[69], Technion Haifa and with the GRAB group of Bologna University[70]. The later group is a very strong partner for HEPHAISTOS as it is also deeply involved in CDPRs.

As already mentioned CDPR is a very strong research topics for HEPHAISTOS. We have a long standing cooperation with european partners that are the most active in this area: LIRMM Montpellier, Fraunhofer IPA and Duisburg-Essen University with which we are finishing the European project CABLEBOT[71]. Beyond this favored teams we have a very strong involvement with all international partners involved in kinematic analysis i.e the community involved in the Advances in Robot Kinematics and Computational Kinematics conferences.

13.3 Fundings

We have benefited from a large funding during the CPER TELIUS (2008-2012) that has allowed us to buy most of the hardware we plan to use in the coming years and we have applied for a complementary funding

[66] `http://www.matiafundazioa.net/en/home`
[67] `http://www.ormyliafoundation.gr/en/`
[68] `http://handibio.univ-tln.fr/`
[69] `http://brml.technion.ac.il`
[70] `http://grab.diem.unibo.it/`
[71] `www.cablebot.eu`

for the next CPER. In parallel we have benefited from PAL for a PhD student (until the end of 2014), from the European project CABLEBOT (2011-2014) and we have a new European project (RAPP[72]) in common with INDES that has started in 2014. With these fundings we don't expect to have problems with hardware platforms and at the same time they provide some fundings for PhD and post-doc students. However we are still somewhat short on student human power but we have plans to solve this issue (see section 12.2).

14 Transfer

As mentioned in the introduction assistance addresses a large part of the society which will even be growing in the future. However we cannot in general expect a transfer of the results of our work to companies on the short term for several reasons:

- although we have started working in the field of assistance robotics well before the end of the COPRIN project assistance robotics is still a drastic change in objectives compared to the one that we were pursuing up to now. Our visibility is still relatively low, especially in the academic and medical community
- the scientific challenges involved in our vision of assistance robotics are complex and require to address simultaneously technological, mathematical and human sciences issues. Furthermore the ultimate validation is real-life experimentation that are extremely time and manpower intensive (see section 10)
- we are addressing a community and a societal problems that have their own slow dynamics
- the market of assistance products involves multiple players. In term of companies they are very large companies that provide multiple products for elderly people such as Invacare[73], start-ups that have grown around a single innovative product such as the Vivago watch[74] and recent start-ups such as Bestic[75]. But being given the size of the market any existing company with knowledge in mechatronics may design an assistive device. Insurance companies (such as Groupama or Covea) may also play an important role as they have an interest in autonomy and keeping elderly people at home to improve the quality of life and safety of their clients, to play a prevention role but also to sell complementary health insurance.... However the contact we have had up to now with such companies is that they are interested only in products that are available on the short term.

Transfer is a long tradition among the team members (for example with SME and large companies such as Airbus, Paulstra or Thalès) and we intend to go on in that direction. However identifying appropriate partners among both the industry and the medical community require a huge, long term effort. Large medical companies are at the moment not really interested in innovation while SME are not easy to contact and convince. A major problem is the liability of an assistance device: this explains why current products focus on a combination of simple hardware and/or services (e.g. telealarm). However we believe that some of our ideas are mature enough to be proposed for a possible transfer (this is especially the case of the walking aids) or can be ready on the short and mid-term: in that case we will be open to any opportunity.

[72] `http://rapp-project.eu/`
[73] `www.invacare.com`
[74] `http://www.vivago.com/`
[75] `www.besticinc.com`

15 Possible changes of the project geometry

15.1 Hiring

We are a medium size group in terms of INRIA standards (especially in a center which is not joint with an University) and we are aware that our goals are very ambitious with respect to our size: hence increasing our size is a major short term objective. In an ideal world we will require:

- *two permanent engineers*: to maintain and upgrade existing platforms and develop new ones. Permanent is a key word because our platforms are long term
- *one permanent researcher and several University personnel*: for theoretical works, maintenance and exploitation of our platforms. Typically these researchers should have a background in robotics (kinematics analysis, design, dynamics, sensing, IHM) and in mathematics (control, numerical analysis, statistics)
- *medical staff*: a permanent presence of doctor(s) in our team to advise us on medical procedures and needs

Hiring a new young INRIA researcher or an INRIA engineer will be evidently beneficial but appears to be difficult for structural reasons. Hiring locally an associate professor or a professor is difficult because Nice University do not has a robotics cursus. As for medical staff we may have some opportunities but it will require some time before our visibility in this domain is sufficient. Nevertheless we are actively looking for opportunities (INRIA starting grants, delegations, new associate professors joining the team, . . .). Another approach, that is complementary, is presented in the next section.

15.2 Teams joining

We plan to possibly enlarge the team in a relatively short term using two approaches that are not exclusive:

1. getting the status of *Inria International Partner* for the GRAB group of University of Bologna. We have already a strong collaboration with this team in biomechanics and CDPRs (joint publications, PhD students). A common work on human joint modeling will be beneficial (GRAB is very advanced in modeling but lack the management of uncertainties) and HEPHAISTOS will benefit from the clinical partners of this group.
2. *bilocalisation* of the project Sophia/Bordeaux: David Daney, a former member of COPRIN, has moved at the end of 2013 to INRIA Bordeaux while still leading the PAL IPL. HEPHAISTOS may consider having an antenna in Bordeaux for the following reasons:
   - the scientific objectives of Daney are exactly in line with HEPHAISTOS, especially regarding calibration, cable-driven parallel robots and medical monitoring
   - several of our clinical partners are located in Spain and in the Basque country. Furthermore there is an intensive gerontology activity in Bordeaux/Toulouse
   - there are several projects in INRIA Bordeaux that have a research activity that may be of interest for HEPHAISTOS: PHOENIX (middleware for ambient intelligence), FLOWERS (machine learning), POTIOC (interface) and GEOSTAT (uncertainties and signal processing)

16 Who is doing what ?

In this short section we present the main activities of the staff members:

- Jean-Pierre MERLET: design, robots, platforms, IA, monitoring, control, ethics
- Yves PAPEGAY: modeling and analysis, parallel robots, virtual reality, symbolic computation, IA
- Odile POURTALLIER: game theory, IA, daily activities monitoring, economics of assistance, control
- Bernard SENACH: technology acceptance, evaluation, design, ethics

17 Objectives for the first 4 years period

We are aware that our goals are very ambitious with respect to the size of the team. However our purpose was to present what are the major problems in assistance as identified after a thorough field analysis. It must be noted also that most of the problems that we intend to deal with require the availability of external resources (subjects, medical community . . .) that we cannot completely master and consequently it is quite difficult to present a definitive research objectives related to assistance for the team. However according to the current availability of these resources we may present our focus points for the next 4 years. A major one will be **mobility**: we intend to develop mobility aids (rollators, cane, at-home devices and possibly wheelchair) that alleviate the mobility problem of elderly people (either individually or as a specific community) and provide monitoring tools for praticians, while raising **control** issues. We believe that **cable driven parallel robots** will play an important role for at-home mobility (and this is not exclusive) but they require an in-depth analysis. Mobility is also clearly related to **rehabilitation** and our mobility devices are appropriate to be part of a rehabilitation process. **Monitoring** is also a crucial topic for the medical community and our mobility devices are appropriate for such a monitoring regarding walking, rehabilitation and the analysis of daily activities. Mobility, rehabilitation and monitoring cannot be dissociated from **biomechanics** to better assess functional status that cannot be directly measured (for example human joint motion). Note that cognitive impairments will not be addressed in this period as mixing functional and cognitive problems increases significantly the complexity of the measurements analysis: hence we will restrict ourselves to the the early stage of aging where cognitive impairments are not installed. During this period a clear measure of success will be the use by praticians of our devices for monitoring over extended period of time and, ideally, by a transfer.

In parallel to these efforts we will investigate **design management** at two levels: functional through the **appropriate design** methodology and **design for acceptance** (that include users intervention at the early stage of the design). The purposes of this research axis will be to obtain a preliminary design methodology at the two levels so that at the end of the 4 years period we may start the development of final prototypes with the objective of transfer. But design cannot be dissociated from **evaluation** (either by the users or by the medical community) and we intend in this 4 years period to have a preliminary evaluation process for our devices. As for the scientific methodologies the focus points will be **symbolic modeling** (for the analysis and control of our devices, for biomechanics), **interval analysis** (for appropriate design and uncertainties management in monitoring and control) and **game theory** (for the economy of assistance and the analysis of daily activities). Here measure of success will be classical academic indicators, including publications in medical journals.

18 Annex: Living labs

But participative design is not a new concept : it has its roots in USA in the 60's with the so-called 'concurrent engineering', has later been developed in Sweden and Northern Europe in the 70' and is used in current project concerning cooperative work with families[76]. This approach has recently been promoted by European Community through the concept of Living Lab. A Living Lab is defined as a user-centered, open-innovation ecosystem, often operating in a territorial context (e.g. city, agglomeration, region), integrating concurrent research and innovation processes within a public-private-people partnership. The concept is based on a systematic user co-creation approach integrating research and innovation processes. These are integrated through the co-creation, exploration, experimentation and evaluation of innovative ideas, scenarios, concepts and related technological artefacts in real life use cases. The Living Lab concept has been promoted in 2006 by the European community, under the Finland ' presidency of EC. A label has been created in 2008, and starting with 19 LL, after several labeling waves, there is now 320 structures in several countries across the world (Europe, Brazil, USA, Africa…). At the European level, ENOLL (European Network of Living Lab[77]) is a main actor and in France, F2L (France Living Labs[78]) is a cluster of 23 structures, with 9 involved in the Silver economy[79]. Hephaistos intends to develop collaboration and possibly partnership with these structures according to future projects. ICT Usage Lab, which was the first Living Lab labeled in France in 2008 was founded by Inria, CSTB, Nice University and OrangeLab. It is located in Sophia Antipolis and its Focuslab platform provides hardware and software resources (physiological sensors, eye-tracker devices, smartphones, …) for data acquisition and usage analysis (`https://focuslab.inria.fr/`). It will be probably an important resource for us.

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[76] Cf. Interliving project `http://interliving.kth.se/`

[77] `http://www.openlivinglabs.eu/`

[78] `http://www.france-livinglabs.fr/`

[79] Tele health Aging Territory (Besançon), eCare, Activie Ageing LL2A (Troyes), Paillon 2020 (CNR Santé, Nice), The Strasbourg University hospitals Innovation Lab, Visage LL, Autonom'Lab, LUSAGE Gerontechnology Living Lab. Furthermore a CGIET report assessing the relevance of the Living Lab concept for health and autonomy (2011) is available at `http://www.cgeiet.economie.gouv.fr/Rapports/2011_10_05_2010_46_CGIET_SG_LL.pdf`

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