I-SUPPORT: ICT Supported Bath Robot

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

I. Introduction

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

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

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

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

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

II. Target Group and System Requirements

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

A. *Primary target group*

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

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

B. *Requirements*

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

III. I-SUPPORT System Description

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

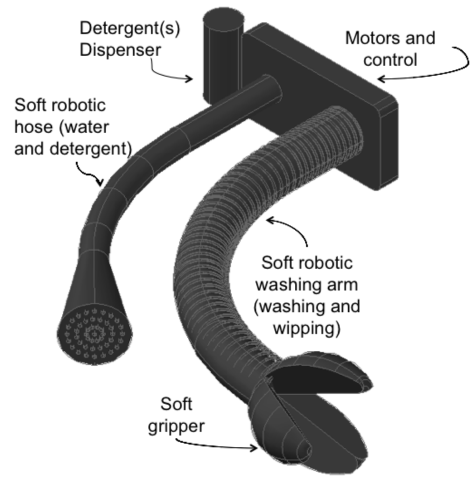

Fig. 1. Concept of the two robotic devices: (i) robotic hose and (i) robotic washing arm. The length of the robotic arm can vary depending the shower space and the ergonomic design. The concept is modular, self contained and easily interfaced with a conventional tab shower infrastructure.

system are presented in a concept level in the following paragraphs.

A. *Robotic devices*

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

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

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

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

B. Human robot interfaces

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

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

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

C. Robotic cognition system

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

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

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

D. Control architecture

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

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

E. Context awareness system

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

F. User and robot pose estimation

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

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

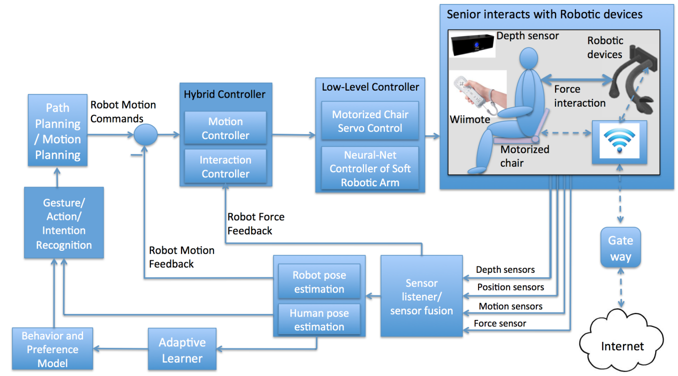

Fig. 2. Block diagram of the I-SUPPORT service robotics system architecture.

G. Overall system architecure

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

IV. System Evaluation

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

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

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

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

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

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

V. Market Indicators

A. The need expressed in numbers

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

B. The demand expressed in market size

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

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

C. The size of the service robots industry

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

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

VI. Conclusion

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

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