Towards a New Generation of Smart Devices for Mobility Assistance:
CloudWalker, a Cloud-Enabled Cyber-Physical System

Ricardo Mello, Mario Jimenez, Franco Souza,
Moises R. N. Ribeiro, and Anselmo Frizera-Neto, Member, IEEE

Abstract—The increased computational complexity demanded by recent algorithms and techniques applied to healthcare and social robotics, often limited by the robot’s embedded hardware, coupled with advancements on networking and cloud computing enabled the so-called cloud robotics paradigm. This work explores cloud robotics concepts pointing at opportunities on the design and development of robotic platforms used for patient mobility assistance. Moreover, we present CloudWalker, a cloud-enabled cyber-physical system to assist mobility impaired individuals. The conception of such system envisions the integration of smart walkers and remote cloud computing platforms, aiming at expanding the range of features these devices can offer to users, patients, healthcare professionals, and family members. Results from validation experiments point to the emergence of a new generation of smart walkers and assistive devices in general, designed to leverage cloud computing concepts to provide an extended range of services to users, relatives, and healthcare professionals.

I. INTRODUCTION

Mobility is an important human faculty and impacts the capacity to freely move through multiple environments and to perform daily chores with ease [1]. Besides decreasing with age, neurological diseases also affect human mobility on different levels. Studies have found that mobility difficulties can be linked with psychosocial disorders and increased mortality [2].

Assistive devices can be employed to mitigate mobility impairments. The use of such devices is recommended according to the type of condition affecting mobility and taking into account the level of impairment [1]. Technological developments lead to the possibility of integrating robotics concepts, sensors, and circuitry on such devices, giving birth to a “smart” generation of mobility assistive devices. Smart wheelchairs, canes, and walkers have been developed by multiple research groups over the last few decades to provide new or improved functionalities of physical support, and sensorial and cognitive assistance [3]. Smart walkers, for instance, have been designed to improve pathological gait while exploiting users’ residual locomotion capabilities. Those devices often make use of support platforms for upper limbs and offer a variety of features, such as health monitoring and cognitive assistance [4].

The concept of cyber-physical systems (CPS) is often applied to enhance the capacities of standalone systems. CPS are systems that combine sensing, communication, control, and computing to interact with a physical entity [5]. CPS concepts encloses multiple systems from various fields, encompassing systems that integrate physical, control, computation and communication elements [6].

The evolution of the control algorithms within the robotics field in general, relying on great amounts of data and computational capabilities, combined with recent developments on communication and cloud computing technologies gave rise to the so-called cloud robotics paradigm [7]. On such paradigm, the individual robot does not rely solely on its own sensing and processing capabilities. Instead, it communicates with remote computing platforms to acquire and send data, instructions, and even control signals, as the cloud should be able to provide nearly unlimited amounts of storage space and processing power. This allows for the exploitation of techniques based on recent fields, such as big data and deep learning, on a larger range of service robots, also allowing for the use of computationally expensive control algorithms based on simultaneous localization and mapping (SLAM), computer vision, trajectory planning, among others [8].

At the light of a paradigm shift, a new generation of robotic assistive devices is rising. By leveraging the cloud capabilities, new control techniques can be applied on multirobot environments, in which assistive devices should be able to learn in a faster pace and to adapt to the ever-evolving impairment condition of individual users. Over such scenario, mobility assistive devices should evolve to offer new features to users, patients, therapists, and caretakers.

In this context, this work aims at introducing a cloud-enabled CPS for mobility assistance, the CloudWalker. This system envisions the integration of smart walkers and cloud computing platforms. CloudWalker is in its early stages of development and the results obtained from validation experiments argue for the feasibility of employing such system. This opens a door for the development of a new generation of robotic assistive devices, in which the devices are enabled by the cloud and able to cope with future connected healthcare.

II. CYBER-PHYSICAL SYSTEMS AND CLOUD ROBOTICS

Many research works have been conducted on CPS architectures, and Liu et al. [5] separate CPS’ closed loop control
in three layers. The first layer comprises the physical system (i.e., the hardware of the device, including sensors, actuators, among others). The second comprises the information system (i.e., real-time control and other data analytics elements), and the last layer is the user layer, which comprises the way the user interacts with the CPS.

The usual definitions for CPS encompasses a variety of systems throughout different engineering fields, from cochlear implants to industrial plants, and the integration of the different CPS components intensified recently [6]. In other words, multiple systems that relied solely on embedded hardware have been migrated to distributed systems employing CPS’s concepts [9]. Computational tasks such as monitoring and control can be performed by remote platforms, which makes it possible to diminish the computational capacity available on the physical local device.

CPS’ concepts are often applied to enhance the capacities of standalone systems. Despite the term not being directly linked to robotics, the concept is applied in networked and distributed robotics, in applications as teleoperation and telemedicine [5]. Smart devices for mobility assistance are no different, and those concepts are leveraged for remote health monitoring or storing patient status and history [10].

A. Cloud Robotics in Healthcare

Robotics has been applied in healthcare for some time and future medical facilities will likely rely on autonomous devices such as robotic caretakers and vehicles. It is foreseen that cloud computing can be exploited in healthcare initially in simple tasks, as in multiple networked sensors for remote patient status monitoring, moving forward to more advanced tasks, that can be as demanding as remotely controlled robotic surgery.

In current healthcare literature, most cloud-enabled solutions explore networked sensors, wearable sensors and clothing, and wireless body area network concepts. In [10], smartphones are used to perform patient localization in a cloud-supported CPS for patient monitoring. In [11], a CPS for patient-centric healthcare applications and services is proposed and a similar approach of gathering patient data and connecting stakeholders through a cloud platform is presented in [12].

With implications to rehabilitation robotics, data from an exoskeleton is monitored and stored in a cloud-enabled application presented in [13]. In [14], a cloud platform is used by a upper-limb rehabilitation robot to allow the physician to remotely monitor therapy and adjust parameters when needed.

Initiatives in social robotics aim at designing cloud-enabled caregiver and companion robots to assist the elderly. In [15], a personal health management service is presented, combining cloud computing services, a domestic robot, an Android app and a web portal. Services such as localization and speech recognition are provided and the robot is able to interact with the user.

Devices used for mobility assistance are beginning to benefit from the use of cloud computing. In [16], navigational information from a wheelchair is transmitted to a cloud storage service, and in [17], the cloud is employed to share multiple wheelchair positions and the map of the environment.

There are not many works exploring the integration of cloud computing and smart walkers. In [18], a multi-robot system integrated with cloud data center was proposed and simulated. A thorough search in the literature regarding smart walkers yielded ANG-MED robot [19] as the only smart walker currently making use of cloud-based services. It is a passive smart walker with independent brakes that can be used to stop the walker or to correct its trajectory during obstacle avoidance routines.

The ANG-MED was developed within the RAPP project [20], which aims to provide cloud-based applications for robots in general. The ANG-MED walker is supported by a cloud platform and the caregiver was able to remotely monitor and act upon the smart walker’s brakes. The ANG-MED has been tested and evaluated by care professionals and positive results were reported.

Cloud robotics can be further explored in robotic devices used for mobility assistance to provide an extended range of features and services. In the next section, we present CloudWalker, a cloud-enabled CPS that arises from the integration of smart walkers and remote clouds.

III. CLOUDWALKER: A CLOUD-ENABLED MOBILITY ASSISTIVE DEVICE

CloudWalker is conceived from the integration of smart walkers and remote cloud computing platforms, aiming at expanding smart walkers capabilities and the features those devices can offer to patients, medical staff, and family members. The system explores cloud robotics to unleash smart walkers capabilities despite possible hardware limitations, leveraging cloud-based services.

A. System Architecture

The overall architecture of CloudWalker allows for the conception of smart walkers as cloud-enabled CPS. Such system encompasses both physical and cognitive human-robot-environment interaction to assist individuals with mobility impairments. CloudWalker’s architecture is depicted in Fig. 1(a).

To provide mobility assistance services, CloudWalker can perceive user’s motion intents on the walker’s embedded sensors and process such signals on a cloud platform. The smart walker can send data to be processed on the cloud, which can provide services such as storage and data processing. The cloud platform can also generate control signals to command actuators, in case control algorithms need to be remotely processed. Moreover, CloudWalker envisions a connected healthcare, in which data stored on database services can be accessed by healthcare professionals, which should also be able to remotely tune parameters regarding therapy routines. Emergency services must also be directly triggered from monitoring services when needed, which can potentially shorten response times and improve rescue efficiency.
CloudWalker architecture decouples the smart walker and its embedded hardware from the features it can offer. The centralization of services running on the cloud allows for the use of multiple heterogeneous cloud-enabled smart walkers working under the same CloudWalker architecture while making use of subsets of the cloud-based services. The gathering of large amounts of data may allow for the implementation of algorithms able to automatically identify the user and adapt to its specific needs. The cloud is also able to offer elasticity and scalability to guarantee the proper execution of real-time services and to allow the insertion of new devices into the system.

B. Materials and Methods

CloudWalker is implemented for the first time by integrating an in-house developed smart walker, a cloud platform, and a series of controllers processed on virtual machines on the cloud.

A. V alidation Experiments

In CloudWalker’s first implementation, a mobility assistance service is instantiated in the cloud. Such service makes use of an admittance-based controller to command the physical interaction between user and smart walker.

The overall diagram is shown in Fig. 2. Sensor data is stored at the Raspberry Pi and force signals are transmitted to the cloud platform to be processed by the mobility assistance service. The admittance-based controller is based on a simplified version of the one presented in [22], and all the parameters employed by the controller are fixed and empirically established. Such controller takes the force signals as input to generate velocity commands to coordinate the interaction between assistive device and user. In other words, the service makes use of the interaction forces captured by the force sensors to provide full control over the walker to the user.

A. V alidation Experiments

The proposed scenario for CloudWalker validation experiments is based on a mobility assistive service in which all the control algorithms are remotely executed. By delegating all intelligence and processing tasks to a remote cloud platform, the system is implemented in its most latency-sensitive configuration, as network latency and packet loss rates impose
direct influence on control performance. If the feasibility of the system can be verified under such configuration, CloudWalker can be further extended to leverage different configurations, in which some processing power is retained at the local device and local safety assurance algorithms are deployed.

A set of experiments is performed to verify the feasibility of the system when exploring mobile edge computing (MEC) concepts. Edge clouds are of fundamental importance on the remote real-time control of cloud-enabled robots, as the physical proximity and reduced network complexity mitigates latency issues and packet loss rates. Our cloud platform runs on an edge data center located in the same university campus in which the experimentation takes place. Therefore, CloudWalker’s implementation is validated in a non-simulated scenario built over a non-structured environment.

The user conducts CloudWalker on a pedestrian pathway of approximately 9 m long and 1.8 m wide. An wireless AP working on the 802.11n 2.4 GHz band is positioned at approximately 10 meters away from the pathway midpoint to provide connectivity to CloudWalker. Received signal strength indicator (RSSI) levels along the pathway were measured and average values ranging from -65 to -60 dBm were observed.

Starting and finishing lines are draw to delimit the track inside the pathway. The walker starts over the starting line, the user is able to fully control CloudWalkers motion and there is no specific path to be followed. The user interacts with the walker heading towards the finishing line, stopping only when reaching the tracks limit.

Six experiment realizations are conducted over the same track. Each experiment realization starts after communication between walker and cloud is established. Sensor data and control signals are timestamped and stored in the walker for offline processing.

Another experiment realization, the seventh one, is performed until complete loss of connectivity is observed. The user commands the walker’s displacement along the pathway, moving away from the wireless AP, until there is no communication between the smart walker and the cloud platform.

B. Results and Discussion

During the first six realizations, no communication loss was observed and network and cloud parameters impact over the system could not be perceived by the user during most of the time. On two occasions, the user described a feeling of momentary disobedience or discomfort. An illustrative odometry plot is shown in Fig. 3.

Latency and packet loss measurements were performed to assess the quality of the service provided. Latency was measured as the round-trip time between the Raspberry Pi sending information to the cloud and receiving the corresponding control signal, and packet loss rates were calculated based on the rate of received and sent packets between the Raspberry Pi and the cloud.

On the first six realizations, the average round-trip latency was 6.8 ms and a variance-to-mean ratio (VMR) of 27.98 ms was observed. Maximum values observed for latency were often larger than 100 ms, but only observed in eventual spikes. This impacts latency variability, and the VMR values show that there is considerable disorder in packet arrival. An average packet loss rate of 0.47 % was also observed, and such low values are not expected to impact the use of the system.

The quality of service verified in the first six realizations of the experiment was sufficient to allow for a comfortable interaction between user and CloudWalker. Even with all control algorithms being executed on the cloud platform, the user could guide the smart walker while making use of the mobility assistance service. Interaction forces and subsequent control signals and velocities from one realization of the experiment are displayed in Fig. 4.

The readings from both force sensors are repeated in Figs. 4(a)–(b) so that the impacts of the interaction forces over
Fig. 4. Measured interaction forces and resulting velocities on one of the realizations: a,b) forward forces measured in each 3D force sensor, repeated to ease visualization of interaction effects upon velocities; c) resulting total interaction forward force; d) resulting interaction torque; e) control signal and measured values for linear velocities; f) control signal and measured values for angular velocities.

forward force and torque, control signals, and velocities can be better assessed. The oscillations on the measured force values result mainly from user gait. During each stride, there is a tendency to push or pull the walker, differing in each arm according to the stage of the gait. The total forward force and torque (Figs. 4(c)–(d)) are calculated as a result of the measured forces in each sensor, and those values dictate how CloudWalker must interact with the user. Figure 4 illustrates the beginning of the movement, the moment of each turn, and the moment in which the user attempts to stop the walker as it approaches the finishing line.

The control signal values for linear and angular velocities (Figs. 4(e)–(f)) are generated by the admittance-based controller. The control signal for linear velocity is limited to a safe value for displacement and maximum values can be observed during most of the experiment, decreasing mostly when the user is turning the walker. This can be observed on two periods of time: one ranging from 15 to 20 s, and the other one ranging from 25 to 32 s, approximately. The turning periods are indicated by the sign opposition in the forces measured by the forces sensors, which results in the largest torque values. CloudWalker could respond properly to user’s desires and no abnormal behavior could be observed in any of the first six realizations of the experiment.

The seventh experiment realization is related to connectivity loss. During this realization, latency, its variability, and packet loss increased as the walker moved away from the wireless AP. It was observed a mean end-to-end latency of 100.4 ms (VMR of 761.8 ms) and a ratio of 5.5 % packet loss. The walker lost connectivity with the cloud platform after reaching a zone in which RSSI was measured to be around -85 dBm.

Network and cloud availability are concerns due to mobile nature of the system. Wireless connectivity and seamless AP migration are also necessary to guarantee sufficient RSSI without downtimes. Such issues must be dealt with, and CloudWalker should be employed taking into consideration the wireless communication technology. The use of commercial WiFi demands an adequate distribution of AP and handover strategies to avoid downtimes during AP migration, such as the one presented in [25].

CloudWalkers first implementation was completed and, despite network simplicity and physical proximity of the edge cloud to the walker, results from the validation experiments indicates that CloudWalker can indeed be employed for mobility assistance. The analysis of the obtained results points to CloudWalkers feasibility when exploring MEC concepts. This is probably enhanced by retaining local processing on the device, which should be able to perform its own control algorithms whenever poor quality of service is detected.

V. FUTURE WORK

CloudWalker must be extended to contemplate the full range of sensors and interfaces that are already integrated into the smart walker used in this first implementation. Control and interaction strategies previously developed at the research group should be replicated using the cloud to process the necessary algorithms exploring different system configurations, regarding which tasks must be locally processed and which ones can be remotely deployed. Safety mechanisms must also be developed and implemented to assure the safe use of the system, which should lead to the clinical validation of CloudWalker.

Computationally intensive algorithms can now be incorporated to CloudWalker. The LRF sensors can be used by
probabilistic techniques, such as SLAM, to perform self-localization and create environmental maps, feeding map libraries stored by cloud services. Path planning algorithms can be implemented to assist in guidance tasks, interactively creating routes to be followed by the user, based on voice acquired destinations or previously constructed maps. A camera system can also be installed to explore computational vision in context-aware applications, exploring interaction strategies in which facial recognition or the ability to discern humans from other moving objects are important. Wearable sensors can also be coupled with the use of CloudWalker for patient health monitoring. Moreover, a cloud computing platform must be able to provide services connecting information from multiple robots scattered among different facilities and communicating with doctors and therapists via web applications, always assuring for patient privacy and personal data safety.

This work envisions a smarter, new generation of mobility assistive devices. Future work shall encompass the design of cost-effective robotics devices fully integrated with cloud computing platforms, able to provide a wider range of services for mobility impaired individuals, aiming at mitigating independence restrictions and improving quality of life.

VI. CONCLUSIONS

A cloud-enabled CPS for mobility assistance, the CloudWalker, was proposed and validated in this work. The system was implemented by integrating a smart walker and a cloud platform. CloudWalker was validated against a scenario involving a real-time mobility assistance service provided by the cloud. The implemented system proved itself capable of providing assistive services even when all control algorithms are remotely executed. These results point to the emergence of a new generation of smart walkers, designed to leverage cloud computing concepts to provide an extended range of services to users, relatives, and healthcare professionals.

REFERENCES