CYBERH: Cyber-Physical Systems in Health for Personalized Assistance

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Abstract—**Assistance systems for e-Health applications have some specific requirements that demand of new methods for data gathering, analysis and modeling able to deal with SmallData: 1) systems should dynamically collect data from, both, the environment and the user to issue personalized recommendations; 2) data analysis should be able to tackle a limited number of samples prone to include non-informative data and possibly evolving in time due to changes in patient condition; 3) algorithms should run in real time with possibly limited computational resources and fluctuant internet access.**

Electronic medical devices (and CyberPhysical devices in general) can enhance the process of data gathering and analysis in several ways: (i) acquiring simultaneously multiple sensors data instead of single magnitudes (ii) filtering data; (iii) providing real-time implementations condition by isolating tasks in individual processors of multiprocessors Systems-on-chip (MPSoC) platforms and (iv) combining information through sensor fusion techniques.

Our approach focus on both aspects of the complementary role of CyberPhysical devices and analysis of SmallData in the process of personalized models building for e-Health applications. In particular, we will address the design of Cyber-Physical Systems in Health for Personalized Assistance (CyberHealth) in two specific application cases: 1) A Smart Assisted Driving System (SADs) for dynamical assessment of the driving capabilities of Mild Cognitive Impaired (MCI) people; 2) An Intelligent Operating Room (iOR) for improving the yield of bronchoscopic interventions for in-vivo lung cancer diagnosis.

I. Introduction

Assistance systems for e-Health include different scenarios, among which this proposal focuses in two of them: assisted living and support to intervention and diagnosis. In the first case, the system should be able to provide personalized assistance in daily tasks to improve everyday life of elder and/or impaired people. In the second case, operating rooms should be equipped with intelligent systems supporting intervention guidance and final diagnosis without altering standard protocols. In any case, there are some specific requirements that are determinant for setting the optimal techniques and algorithms:

Acquisition of Multimodal Data. To issue personalized recommendations and actions, the system should be able to dynamically collect multimodal data from both, the user and its environment.

SmallData for Models Design. Since data is collected from individual patients, Health applications must deal with data samples limited to a small number of cases and possible biased backgrounds. This experimental setting is challenging for data analysis methods designed to deal with BigData, characterized by a huge amount of information.

Data Dynamics. Methods for data analysis and modelling should be able to tackle with changes in patient condition due to its disease evolution and unexpected events during intervention (short) time or life activities (longer periods). These might introduce dynamic changes in the input data features that require personalized predictive models as well as discarding non-informative data that might negatively influence predictions.

Intra-class Variability. Aside non-relevant and noisy data, the variability of patient physiological data (at low and high level) is bounded compared to BigData problems where intra-class variability is prone to be high. This restriction in intra-class variability favors the performance of predictions and could help to compensate for the low number of available samples.

Real-Time Data Processing. Algorithms should run in hard real time conditions with possibly limited computational resources and fluctuant internet access inside operating rooms or on the road, for instance. Since they require of a continuous monitoring at maximum computation speed, this suggests systems independent of internet connection.

We propose to map the algorithms tailored for personalized recommendations and actions in real-time embedded systems processing the dynamically collected data from user interactions and multi-modal sensors. Such Cyber-Physical Systems could be applied to two specific application scenarios:

1) A Smart Assisted Driving System for dynamical assessment of the driving capabilities of Mild Cognitive Impaired people.
2) An Intelligent Operating Room for in-vivo lung cancer diagnosis using bronchoscopic interventions.

II. State-of-Art

A. Intelligent Operating Room for in-vivo Lung Cancer Diagnosis

Lung cancer is both the most frequently diagnosed cancer and cause of cancer death [1]. The Lung Cancer Screening Trial showed that screening a risk population using computed tomography (CT) reduced mortality by 20%. However, CT is not sufficient and pathological confirmation of lung cancer is always needed. Transthoracic needle aspiration and bronchoscopy include the procedures available for tissue sampling. Since bronchoscopy is a minimally invasive safe procedure able to reach most pulmonary areas, it is the gold-standard for lung cancer diagnosis. A main limitation of bronchoscopy is the difficulty to reach peripheral lesions what decreases diagnostic yield to 63.7% [2]. Diagnostic yield could be improved by developing integrative multi-modality diagnostic systems able to guide the bronchoscopist to the lesion and assess in-vivo its malignancy.

Standard protocols for intervention guidance relying on fluoroscopy have a diagnostic yield around 40%, last 20 min per intervention and require 5-10 min of repetitive patient and medical staff radiation [3]. Existing alternatives like image based systems (LungPoint, NAVI) or electromagnetic navigation (inReachTM, SPinDrive®) are far from meeting clinician expectations. Electromagnetic systems [4] might not be accurate enough [5] and require specific expensive gadgets that alter the operating protocol. Image systems based on multi-modal registration require manual intra-operative adjustments of the guidance system [6]. An alternative to registration is to use anatomical landmarks describing the bronchial tree anatomy for CT-video registration [7]. Although first results show the feasibility of such a matching, identification and matching of bronchial anatomy might be distorted in the presence of unexpected sudden movements during intervention.

The current state of guidance technologies suggests a hybrid system combining video analysis with positional information collected from other sensors [8]. An alternative to electromagnetic guidance could be the use of positioning micro-sensors introduced inside the scope working channel. There are affordable commercial devices [9], [10] allowing connection to specific multiprocessor architectures for real time processing inside the operating room.

Concerning techniques for in-vivo diagnosis, Confocal Laser Endomicroscopy (CLE) is an emerging imaging technique that allows the in-vivo acquisition of cell patterns of potentially malignant lesions [11]. Up to now, CLE has been mainly used in gastrointestinal endoscopy and its use in bronchoscopy mainly reduces to clinical studies reporting the visual appearance of cellular patterns. A very recent study [11] indicates that CLE images could contain enough visual information to discriminate between inflammatory and cancerous patterns using non-supervised graph structural analysis to tackle with the low number of samples. Since samples should be previously filtered to minimize the impact of non-informative noisy images in predictions, we consider that for an accurate in-vivo biopsy, CLE analysis could be complemented with protein assays delivered through micro-sensors. Registering other significant biomedical data such as pH (to monitor nerve activity or ionic reactions in the body) are also being more popularly implemented using miniaturized biocompatible flexible substrates and even graphene transistors using the so called printed electronic technologies [12] that are successfully being applied to biological fluids [13], [14] or tissues [15] that can be integrated with wiring [16] and circuitry [17], even in our UAB campus so that they can be used in our application demonstrator.

We conclude that a hybrid system combining image and micro-sensors would be clinically feasible for in-vivo bronchoscopic diagnosis of lung cancer. In particular, such a system for in-vivo diagnosis should include:

1) A hybrid guidance system combining video processing with positional information collected by micro-sensors deployed inside the working channel
2) Multi-sensor exploration of tissue using, both, analysis of cellular patterns in CLE and cancer biomarkers collected using micro-sensors.
3) Use FPGAs, GPUs and embedded technologies to accelerate computations enough to issue a system able to run in intervention time

B. Driving Systems for Evaluating Cognitive Impaired People

Progression of neurodegenerative diseases, such as Alzheimer or Parkinson, decrease driving capabilities, as a result of the decline in cognitive and visual abilities [18]. Even at early stages, called Mild Cognitive Impairment (MCI), their performance is worse than cognitively healthy people [19] and, thus, road safety [20] might decrease if MCI patients keep on driving. However, driving cessation appears to contribute to a variety of health problems, including depression and increase in patient dependence [21]. A Smart Assisted Driving System able to identify impairments of MCI patients for driving and issue personalized recommendations would significantly contribute to safely extend the driving time of patients without losing comfort and without increasing the risk for the rest of the population.

Current screening tools for driving assessment do not give consistent cognitive predictors and reported driving outcomes in [22] MCI patients. Indeed, previous experiences with MCI patients [23] suggest that existing screening tools provide very generic indicators not dynamically collected at driving time which might not be able to each characterize drivers' performance. We propose to monitor the patient at driving time to dynamically determine his/her current deficiencies in order to design a driving assistance system personalized to driver's particular skills and disease evolution.

The different cognitive functions associated to the ability to drive, evolution in patient cognitive state and the variability across driving skills suggests that patient monitoring should collect multimodal data possibly including response to cognitive tests, physical sensors (like impedance or heart rate [24]), motor ability (especially impaired in elderly) and driving behavioral patterns (like fatigue or stress). The evaluation of these markers to find out indicators of the ability to drive of a patient, as well as the validation of any assistance system should be done in a safety environment. Thus, a simulator able to both, evaluate driving capabilities and collect enough data to compute a personalized model of the driver behavior allowing the detection of any deviation should be necessary.

Commercially available simulators are expensive, bulky and require specific hardware [25]. Other custom-made simulators more focused on evaluating driving capabilities require high computational complexity, and are intrusive, costly and energy consumption [26]. Our experience suggests that a simulator should be low-cost, easy-to-use and extendable with other non-intrusive sensors able to detect driver abilities. Besides, embedded low consumption devices can accelerate the algorithms to work at real time.

The design of systems for assistance of patients with cognitive impairments should identify the requirements and needs of patients to ensure the highest acceptance among users. In this context, results from user´s requirement analysis in [27] have demonstrated that patients, caregivers and medical personnel will accept the support from a robotic assistant in activities of daily living for participants with mild cognitive impairment and mild dementia due to Alzheimer's disease, and will prefer it to be the less bulky as possible for its functionalities (shorter than the user and approximately chest height [28]). Besides, wearable technologies (like accelerometers, textile chairs, etc) can provide vital records or behavioral markers coming from head, gaze, hands and feet and they should evaluate driver emotional and mental states such as stress or fatigue or attentional ability under specific events. We propose to map their successful personalized risk index coming from the medically supervised combination of key parameters that monitor the state of the patients [29]. Therefore, it is expected to have good acceptability among subjects with mild cognitive impairment, and is feasible to evaluate behavioral state through wearable technologies.

Moreover, before full autonomy of self-driving becomes a reality, there will be intermediate autonomy levels (as defined by SAE [30]) that will require to assess the capacity of the driver to take over the control of the car when the car is not able to do it, or, on the contrary, to keep it when the driver is not able drive. By combining the driving ability assessment with autonomous driving algorithms we could provide a novel platform for development of a new breed of algorithms focusing on intermediate levels of autonomy.

We conclude that to obtain usable SADs, the system should avoid invasive gadgets and be based on behavioral visual analysis, wearable technologies and cognitive tests. In particular, a system for assisting cognitive impaired people in driving should:

1) Collect multimodal data from the patient including cognitive tests, wearable sensors and driving behavioral markers
2) Provide personalized assistance focusing on the particular lack of each driver.
3) Use FPGAs, GPUs and embedded technologies to accelerate computations enough to issue a system able to run during driving time

III. The Cyber-Health Approach

To guarantee an effective deployment in the Health care system, methods for data analysis should be designed to ensure an easy affordable acceleration. On one hand, GPU computing [31], reconfigurable hardware [32], homogeneous many-cores or asymmetric architectures [33] are some of the "heterogeneous computing" (HC) approaches that can be used to accelerate algorithms. On the other hand, convolutional neural networks, CNNs, are very regular in structure and can be mapped quite efficiently onto HC [34].

CYBERH proposes to develop methods for adapting CNNs to analysis of homogeneous SmallData, as well as, tailor the computing architectures that implement the SmallData simplified analysis methods to allow portable devices with its computation closer to sensors and actuators.

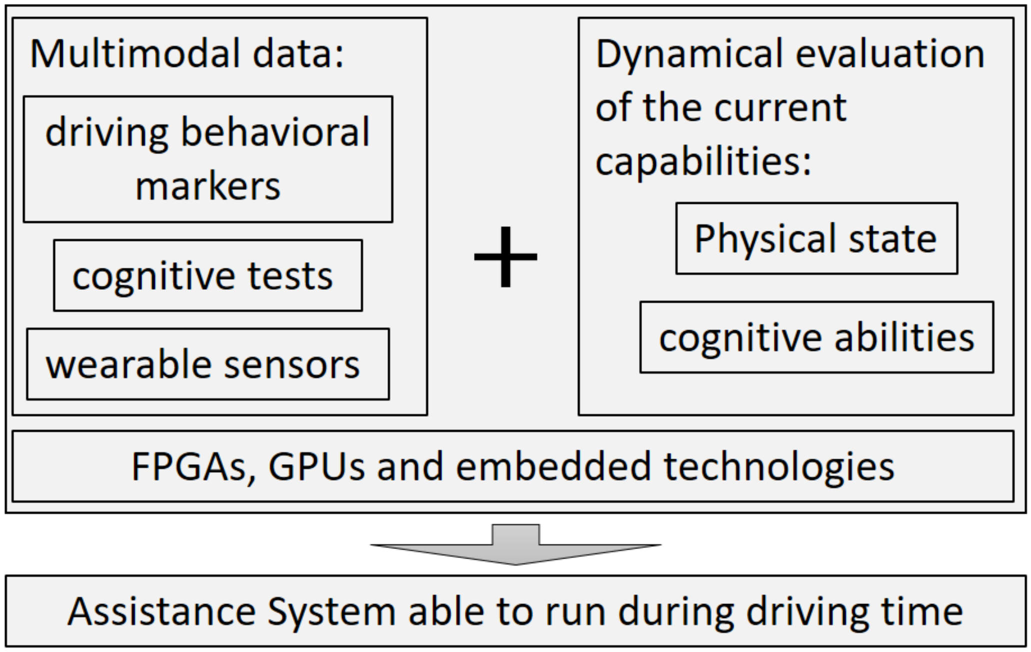
On one hand, SmallData problems in Health could be efficiently managed with CNNs provided that the sample space has been filtered. CYBERH will develop methods for data analysis able to:

1) Dynamically discard influential and non-informative data to prevent a bias in predictive models using unsupervised structural analysis of data feature spaces.
2) Explore the potential of CNNs to define low level features for a characterization of anatomical structures easy to accelerate using specific hardware architectures.
3) Adapt CNNs architectures to SmallData with low intra-class variability and homogeneous high-level contents using hybrid data augmentation strategies combining virtual data simulated from real cases with real samples.

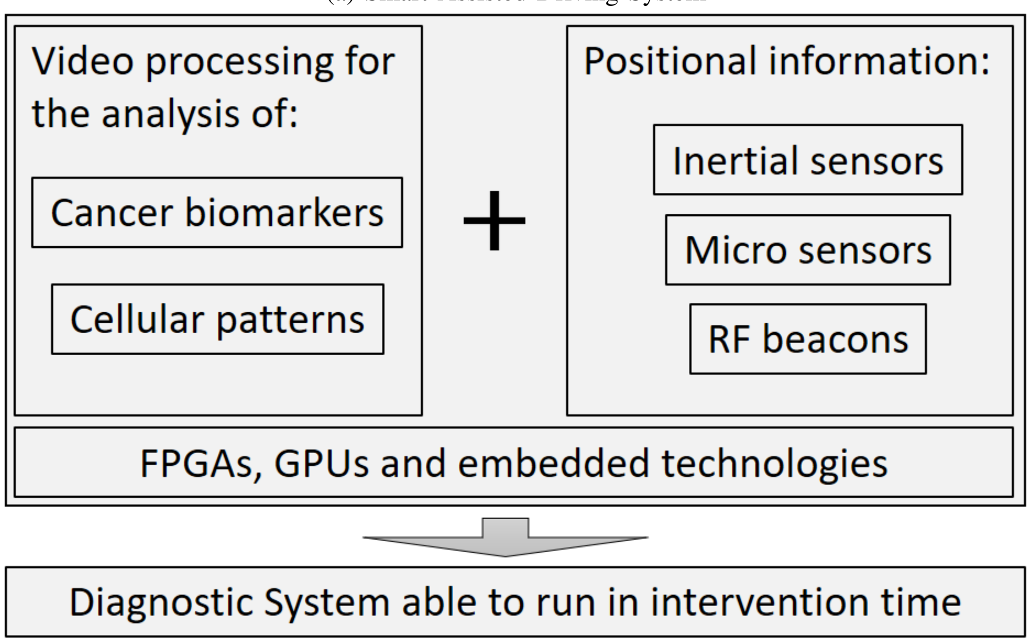
On the other hand, embedded multi-processor platforms can be an efficient cost-effective alternative to Cloud Computing. CYBERH will develop implementation methods able to:

1) Map easier and more efficiently (in terms of energy, space and cost) the algorithmic solutions developed into ad-hoc platforms embedding custom computing when dealing with application specific problems.
2) Map tasks into individual processors to better guarantee the required hard real-time conditions
3) Better customize ad-hoc interfaces and communication protocols in a flexible way adapting to new instrument add-ons.

The methods developed will be applied to design a simulation platform for evaluation of driving assistance systems for MIC people and a hybrid navigation system for in-vivo bronchoscopic biopsy. In the first case, the goal will be to design a complete simulation platform to dynamically evaluate, both, the driver's current capabilities for secure driving and the benefits of a personalized driving assistance system taking into account both the cognitive abilities and (measurable) physical state of the user/patient. Meanwhile, in the second case the goal will be to develop a hybrid system combining



(a) Smart Assisted Driving System



(b) Integrative Multi-modality Diagnostic System

Fig. 1. Application systems approach schemes

video information with positioning micro-sensors for an in-vivo diagnosis ideally based on confocal endomicroscopy and biomarkers deployed by micro-sensors working together with other sensors such as inertial and RF beacons. Figure **??** shows the scheme for approaching both systems, the Smart Assisted Driving System on fig.1(a), and the Integrative Multi-modality Diagnostic System on fig.1(b).

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