An IoT-Based System for Autonomous, Continuous, Real-Time Patient Monitoring and Its Application to Pressure Injury Management

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***Abstract*—In this paper, we introduce PIMAP, an IoT-based system for continuous, real-time patient monitoring that operates in a fully autonomous fashion, i.e. without the need for human intervention. To our knowledge, PIMAP is the first open system that integrates the basic patient monitoring workflow for continuous and autonomous operation and includes sensed data collection, storage, analysis, and real-time visualization. PIMAP's open design allows it to integrate a variety of sensors (custom and off-the-shelf), analytics, and visualization. Other novel features of PIMAP include its deployment flexibility, i.e., its ability to be deployed in different configurations depending on the specific application needs, setting, and resources, as well as PIMAP's self-profiling and self-tuning capabilities. While PIMAP can be applied to various patient monitoring applications and settings, in this paper we focus on the unsolved problem of preventing pressure injuries.**

I. Introduction

Despite significant advances in telemedicine and connected health, a recent survey [1] reveals that current patient telemonitoring systems are either proprietary or are one-off solutions which means that it is hard, or sometimes impossible, to modify, extend, and/or repurpose them. The same survey found that sensor-based patient monitoring is a promising approach to continuously and autonomoulsy monitor patients in a variety of healthcare settings ranging from accute care, long-term care, as well as in-home care. It can assess risk in an objective and patient-centric fashion, provide clinicians and care givers with real-time information, for example to help them focus efforts on the highest-risk patients.

To fill this gap, we propose a novel IoT-based framework for autonomous, continuous, real-time patient monitoring that can be used in different healthcare settings, e.g. hospital ICUs, clinics, skilled nursing facilities, and homes. Our research has been motivated by our ongoing collaboration with UC San Francisco and UC Davis medical researchers and clinicians and their longstanding work on understanding and treating complex wounds, in particular pressure injuries. Pressure injuries/ulcers are localized areas of skin and underlying tissue damage, that disproportionally develop in low-mobility individuals (bedridden or wheelchair-confined). Pressure injuries are considered *never events*, meaning they should never occur in healthcare settings. However, in the U.S., there are over 2.5 million patients affected annually, at a cost of $11 billion [2]. They are believed to be caused by prolonged pressure to an area of the body, typically over bony prominences, such as the sacrum or heels when a person is lying down, and ischial tuberosities if they are sitting. The result is an open wound that may descend to the bone and must be treated to avoid further wound progression and systemic infection. Treatment of deep tissue pressure ulcers/injuries (PU/Is) requires intensive treatment and can take years to heal, representing substantial downstream costs and comorbidity to patients, significant burden to caregivers and healthcare facilities [3]. Pressure injuries remain a complex, unsolved, and elusive problem in healthcare. There are two well known problems in PU/I prevention. One, periodically turning patients, which is the current best practice in healthcare facilities [4], is not trivial. Two, because pressure injuries start their formation from the bone [5], by the time one can visually see the injury it is past the point of prevention.

II. Pressure Injury Monitoring And Prevention (PIMAP)

Through autonomous, continuous patient-centric monitoring of factors such as activity, perfusion, and pressure that can lead to PU/Is, our proposed system called PIMAP for Pressure Injury Monitoring And Prevention will provide early identification and objective risk stratification of patients. PIMAP will enable early detection of conditions favorable to PU/I formation in healthcare facilities or in the home, providing visual feedback and alerting healthcare staff. Unlike existing solutions which are mostly one-off, closed, or proprietary, PIMAP integrates the fundamental patient monitoring workflow for continuous, real-time operation, and, integrates, as its main components: data collection from various sensing devices, data storage, data analysis and real-time data visualization. PIMAP's open design allows for the seamless integration of a variety of sensors (custom and off-the shelf), analytics and visualization mechanisms. Another novel feature of PIMAP is its deployment flexibility which allows PIMAP to accommodate the specific needs of different applications

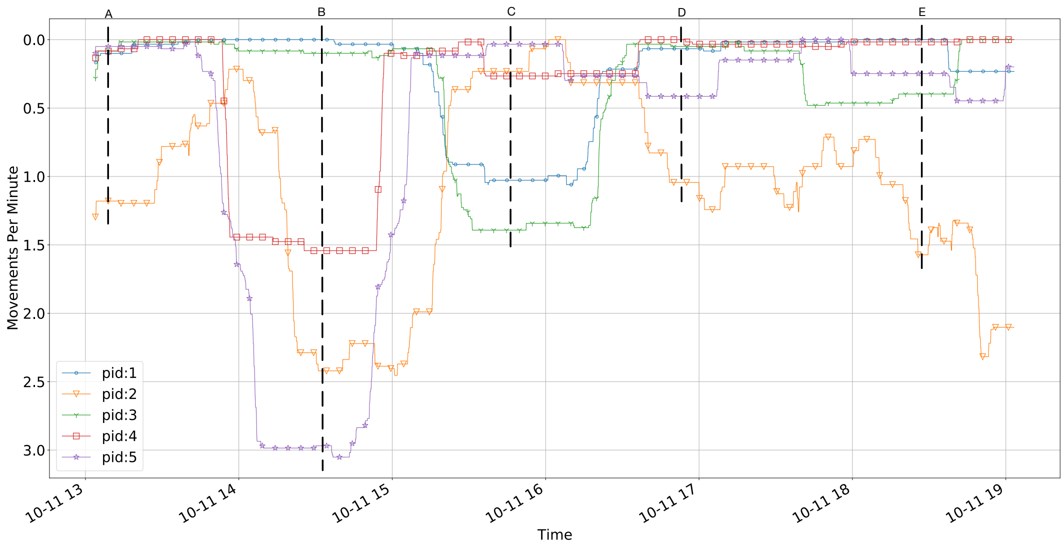

Fig. 1: Objective Mobility real-time risk stratification

(e.g., security and privacy, latency, etc), healthcare setting (e.g., home, hospital), and computing resource availability.

While the original driving application for PIMAP and the case study presented in this paper is PU/I prevention and care, PIMAP can be used by a variety of medical applications that require automated, continuous, real-time patient monitoring.

III. Related Work

Due to its interdisciplinary nature, our work can be classified under different areas in the research literature including: connected health, wireless body area networks (WBANs), ubiquitous healthcare, remote monitoring, ehealth, patient monitoring, internet of healthcare things (IoHT), mHealth, and telemedicine. In this section, we highlight related works that focus on general patient monitoring frameworks. The survey presented in [1] provides a more complete and detailed description of related work specific to pressure injury prevention.

A system application to store historical common biometric sensor data that can be analyzed offline was proposed to address the need to perform historical analysis on medical sensor data [6]. The framework relies on proprietary medical devices to gather the sensor data in the clinic and Kafka [7] to store the data for historical analysis. The analysis presented was performed by downloading data after collection from the data storage server.

An Android interconnection layer entitled TIROL was proposed [8] to collect medical sensor data from a myriad of sensors. The author's highlight that no health data protocol or standard has prevailed and typically each vendor has its own method of generating data. TIROL was developed to address this issue and was designed such that any standard can be implemented, but is abstracted by the interconnection layer so that the overarching application is agnostic to the protocol used to gather the data.

A medical sensor data collection application entitled $p^2Health$ uses a smartphone app, ModMedApp, to collect data from vendor servers, Bluetooth or Ant+ sensor devices, and questionnaires. ModMedApp stores the collected data into a cloud-based server that clinicians and patients can interact with [9].

To the best of our knowledge, PIMAP is the only open source patient monitoring system that operates autonomously, continuously, and integrates sensing, data collection, storage, data analysis, and visualization in a single system. It allows different sensors, off-the-shelf and custom, to seamlessly connect to the system and can integrate various analytics and visualizations. Additionally, PIMAP is designed to be deployed in both centralized and distributed configurations in order to cater to the needs of different deployment settings, including edge-, cloud-, and hybrid deployments.

IV. Real-Time Risk Stratification Using PIMAP

The *Objective Mobility* metric [14] was proposed as an objective way to quantify a patient's mobility using data from a custom pressure bandage developed at UC San Francisco. Mobility or the lack thereof has been associated with the risk a patient has of developing a pressure injury. The novel pressure bandage contains a four by four grid of pressure sensors and was used in a clinical trial to collect data on five patients with high risk of forming pressure injuries based on the Braden Scale [15]. To be eligible to enroll in the study, patients must score a '1' (the lowest score) for activity, mobility, and friction/sheer on the Braden Scale.

We use the pressure bandage data collected during the clinical trials to demonstrate how PIMAP can be used to objectively assess pressure injury risk. We fed the pressure data to PIMAP as if it were being collected in real time. PIMAP then calculated patient Objective Mobility over time and displayed the results in real-time.

TABLE I: Objective Mobility Real-Time Risk Stratification

A		B		C		D		E		Average	
PID	Movements Per Minute	PID	Movements Per Minute	PID	Movements Per Minute	PID	Movements Per Minute	PID	Movements Per Minute	PID	Movements Per Minute
4	0.05	1	0.00	5	0.03	4	0.00	1	0.00	4	0.10
5	0.09	3	0.13	2	0.25	3	0.05	4	0.01	1	0.12
1	0.16	4	1.68	4	0.28	1	0.07	5	0.25	5	0.19
3	0.19	2	2.41	1	1.03	5	0.42	3	0.40	2	0.27
2	1.22	5	3.02	3	1.46	2	1.06	2	1.57	3	0.32

While in the original trial five patients were monitored at non-overlapping times, we instead simulated the patients as if they were being monitored simultaneously and having their risk assessed in real-time. The original pressure bandage patient data has gaps when the bandage became disconnected (this is often intentional if the patient needs to be moved to a different location). In order to present data that is closest to reality we ran the experiment for 7 hours as this was the amount of time that all patients had consistent pressure bandage data.

We present the results in Figure 1, which displays the Objective Mobility Movements Per Minute metric for all patients over the length of the experiment. The Movements Per Minute metric is a real-time risk assessment of which patients are moving the least, regardless whether the movement was assisted. The y-axis is inverted such that the patient at the top of the graph is the most at risk of forming a pressure injury as they are making the least amount of movements. As can be seen the risk changes over time and there is no one patient that is always most at risk, which is how the status quo Braden Scale assesses patients. The patient data used had an enrollment criteria that all patients must score a 1 (the lowest score) for activity, mobility, and friction/sheer on the Braden Scale. Even though all patients had similar Braden Scale risk scores our metric is able to further distinguish patients in real-time based on their movement.

In Figure 1 we label five moments in time, labelled A-E. In Table I we rank the patients at each respective moment in time based on the Movements Per Minute metric. We demonstrate that PIMAP's objective, real-time risk assessment can highlight at any moment in time which patient is most at risk. This is invaluable to clinicians in a busy clinical setting as the healthcare staff can focus their efforts on the patients that need it most, instead of blindly having to rotate patients periodically who may be moving on their own. Additionally, in Table I, we highlight the average Movements Per Minute over the length of the experiment by patient. It is clear that this fixed value does not provide the insight that the risk a patient has of forming a pressure injury changes over time. The real-time assessment that we present does not need clinician interference and can be used in addition to any tools or standard of care.

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