Formalizing Digital Proprioception for Devices, Environments, and Users

Radu-Daniel Vatavu and Ovidiu-Andrei Schipor

Abstract We discuss the concept of *digital proprioception* for smart devices and smart environments, which we formalize and operationalize in the context of Ambient Intelligence with a dedicated event-driven software architecture. We also propose *extended digital proprioception*, by means of which devices and environments can access supplementary information about themselves from other sources, beyond their internal sensing capabilities. We use the latter concept to propose *extended human proprioception* enabled by the conjoint operation of smart devices and environments. Our contributions enable a new way to conceptualize interactions in smart environments by designing user experiences mediated by spatial communication interfaces where physical space integrates interaction.

1 Introduction

Smart environments embed a variety of sensors to detect and track the presence, location, and movement of users, devices, and non-digital things [14, 24, 32, 34]. This information is useful to deliver applications and services that are sensitive, responsive, adaptive, transparent, ubiquitous, and intelligent [10]. Smart devices, such as smartphones, smartwatches, and smart jewellery, can also leverage built-in sensors to infer their location, orientation, and usage and, thus, to enable intuitive interactions [8, 18, 44]. Proxemic interaction [14], around the body input [8], and linking physical objects and digital content [41] are relevant examples of how sen-

Radu-Daniel Vatavu
MintViz Lab, MANSiD Research Center, Ştefan cel Mare University of Suceava, Suceava 720229, Romania e-mail: radu.vatavu@usm.ro

Ovidiu-Andrei Schipor
MintViz Lab, MANSiD Research Center, Ştefan cel Mare University of Suceava, Suceava 720229, Romania e-mail: schipor@eed.usv.ro

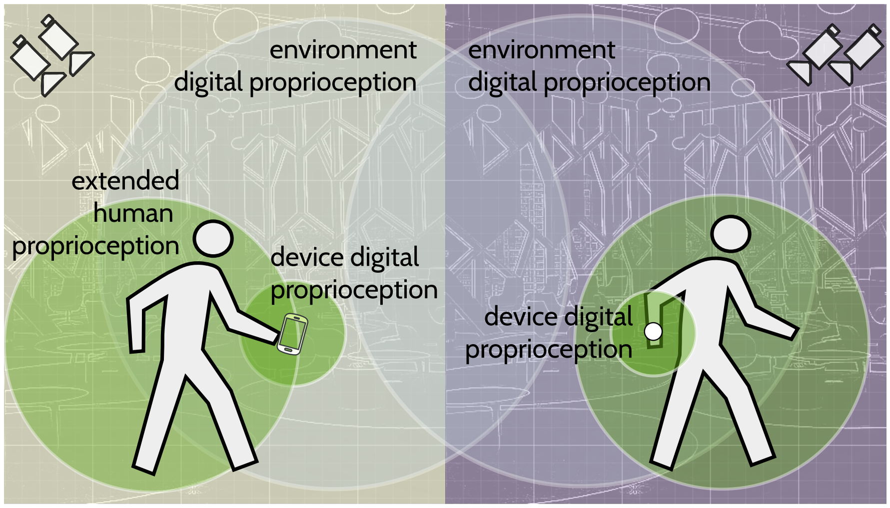

Fig. 1 Digital proprioception in smart environments: devices have access to information about their location in the environment, and environments share information as users transition from one environment to another (left to right in this figure). Also, the human sense of proprioception can be extended by making users aware of the presence of other entities from the environment.

sor data collected by smart devices and environments can be leveraged to provide intuitive and fluent interactions for users.

In this work, we revisit the capacity of smart devices to infer information about their location, orientation, and usage and, respectively, of smart environments to detect the presence and movement of entities located within through the prism of proprioception [29, 38]. Specifically, we distinguish between nuances of *digital proprioception* for smart devices and environments, which we operationalize with a dedicated software architecture. We also discuss *extended human proprioception* in the form of subtle cues provided by the environment to deliver information at the periphery of user attention; see Figure 1 for an illustration of our concepts. These contributions enable a new way to conceptualize interactions in smart environments by addressing an open challenge [36] in the area of Ambient Intelligence (AmI) about designing user experiences mediated by spatial communication interfaces.

2 Related Work

2.1 A Brief Overview of Proprioception

Proprioception, a term coined by Sir Charles Sherrington [27] to characterize the body acting as a stimulus to its own receptors, denotes senses that emerge from the activity of mechanosensory neurons located within muscles, tendons, and joints that report body position and movement, effort, force, and heaviness. The principal kinesthetic receptors are muscle spindles [29] that respond naturally to active movement [12], from which information is collected and passed to the central nervous system [38]. By integrating this information with that provided by exteroceptive sensations, such as vision and touch, the brain maintains representation models of the body, i.e., the body image and body schema [29]. The body schema is strongly embedded into one's subconscious and key for sensorimotor functioning. Even though proprioception is absent from conscious perception, loss of this sense causes the inability to coordinate one's movements into purposeful behavior. For instance, in people with chronic stroke, deficits in proprioception are negatively associated with upper extremity motor abilities [30], while evidence exists that proprioceptive training induces cortical reorganization to improve impaired sensorimotor functions [2]. We refer readers to [29] for a review of the proprioceptive senses.

2.2 Proprioception-based Interaction with Computing Systems

Proprioception has been leveraged for novel interaction techniques with computing systems. For example, Li *et al.* [20] introduced "Virtual Shelves," a technique for triggering programmable actions on a mobile device by pointing with the device in the immediate space around the user's body. Yang *et al.* [37] studied the effect of appending virtual body parts to users' avatars in VR, and reported efficient selection of targets spatially referenced to the virtual body. Chen *et al.* [8] examined around-body interactions for proprioception-enhanced input with mobile devices. Wiese *et al.* [44] introduced "phoneprioception," a technique enabling smartphones to infer where they are placed (e.g., in a pocket, on a table) for enhanced functionality, such as better ways to deliver notifications to users. Lopes *et al.* [22] described "proprioceptive interaction" in the context of eyes-free input for wearable devices. Their Pose-IO prototype was designed to accept user input via gestures performed with the wrist and to provide output via electrical muscle stimulation that puts the wrist in a specific pose. In a follow-up work addressing small form-factor devices, Lopes [21] argued that effective interactions with such devices need techniques that leverage the user's body for both input and output.

2.3 Software Architecture for Interactions in Smart Environments

Interactions in smart environments have been implemented with a variety of modalities, including speech [1, 25], gesture [23, 39], and input on mobile devices [9] and wearables [5, 13, 17], and for various audiences [7, 19, 40]. For example, Vatavu [39] introduced "nomadic gestures," a technique for reusing gesture commands in new environments. The smart pockets [41] technique enables associations between physical pockets on clothes and digital content. Popovici *et al.* [28] introduced "Hover," a deictic gesture user interface for smart TVs implementing shortcuts in mid-air. Proxemic interactions [14] operationalize proximity for smart environments along five dimensions—distance, orientation, identity, movement, and location/physical context—for people, devices, and non-digital things. This large diversity of interactions has been enabled by dedicated software architectures and platforms [32, 34, 35, 42]. For instance, GPWS [42] was the first service-based architecture for event-driven gesture recognition with application to smart homes, later extended by Lou *et al.* [23] with the Gesture Services for Cyber-Physical Environments (GS-CPE) framework. Euphoria [32] is an open-source software architecture for asynchronous event processing that models I/O devices as producers and consumers to provide an unified platform for interactive applications in smart environments with heterogeneous devices. Built on top of Euphoria, SAPIENS [34] provides a framework for peripheral interaction with specific modules for attention detection and context awareness. The Proximity Toolkit [24] enables rapid prototyping of proxemic-aware applications, and FORTNIoT [11] facilitates user understanding of smart home behavior.

3 Digital Proprioception in Smart Environments

Prior work on designing interactions in smart environments has proposed and examined many creative techniques enabled by devices aware of their orientation, location, and movement within the environment, but also by smart environments that have access to such information. In the following, we associate these capabilities with the concept of proprioception (Section 2.1), a perspective that enables us to reframe those capabilities and to operationalize them accordingly in the context of AmI. We define *digital proprioception* and *extended digital proprioception* as two distinct means by which smart devices and environments can obtain information about themselves. We also introduce the concept of *extended human proprioception*.

3.1 Digital proprioception for smart devices

By leveraging built-in sensors, mobile and wearable devices can infer information about their movement [8], utilization [18], and physical location in space [44]. For example, by fusing data from the built-in accelerometer, gyroscope, magnetometer, and front camera, a smartphone can determine its 3D position relative to the user holding it [8]. We refer to the capacity of a smart device to obtain information about its location, orientation, and utilization exclusively via its built-in sensing system as *device digital proprioception*. However, internal sensing can be limited, low resolution, and certainly is not uniformly available across the variety of mobile and wearable devices and platforms.[1] As an alternative to built-in sensing, devices can

[1] For example, both Samsung Gear Fit 2 (`https://www.samsungmobilepress.com/mediaresources/gear-fit2/techspecs`) and Galaxy Watch 3 smartwatches (`https://www.samsun`

obtain information about themselves via requests to other entities. For example, the location and orientation of a device can be provided by the smart environment via its sensors, e.g., a depth video camera that tracks both the user and their phone [45]. The device could submit a request, via a standardized protocol, to the smart environment for the 3D coordinates of its physical location in the environment. We refer to the capacity of a smart device to obtain supplementary information from an external source as *extended digital proprioception* to contrast it with the concept of device proprioception introduced above. The extended form does not require embedded sensing, but just the capacity of the device to communicate with the smart environment, e.g., via a Wi-Fi based communication protocol [32].

3.2 Digital proprioception for smart environments

Smart environments embed a variety of sensors, e.g., video cameras, depth sensors, RFID/NFC readers, and others, to detect and track users and objects. For example, KinectFusion [16] enables detailed 3D reconstructions of indoor scenes, Ahuja *et al.*'s [1] approach to direction-of-voice estimation enables effective speech-based interaction in a smart environment, and the Proximity Toolkit [24] computes orientation, distance, motion, identity, and location information about the entities within an environment using a motion tracking system. We refer to the capacity of a smart environment to obtain information about itself and the entities within exclusively by means of its built-in sensing as *environment digital proprioception.* However, smart environments are usually agnostic about other information about themselves, users, devices, and non-digital objects other than that provided by their own sensors, whereas such additional information could prove useful in many situations. For example, Guinea *et al.* [15] proposed a solution for the continuous identification of users in home and office environments based on motion patterns of the hand collected via wrist-worn inertial measurement units. We refer to the capacity of a smart environment to obtain supplemental information from an external source about the entities from the environment and about itself as *extended environment proprioception*. This capacity does not require adding more sensors to the environment, but rather implementing communications with an external source of data, such as a cloud service, the personal devices of the users from that environment, or other smart environments. For example, the smart room in which a user just entered could "talk" to the smart room from its vicinity to retrieve relevant information about the recent activity of that user and, thus, deliver a consistent user experience.

`g.com/global/galaxy/galaxy-watch3/specs`) embed accelerometers and gyroscopes, but the Gear Fit 2 model does not have a light sensor.

3.3 Extended human proprioception

In humans, the proprioception senses assist locomotion, planing, and refinement of body movements for robust and precise motor output; see Section 2.1.We consider in the following the benefits of extending this capacity with new information provided by smart devices and environments. For example, the user entering a smart environment could receive feedback in a subtle way, e.g., via vibrations delivered by their smartwatch, about entities from the environment that are relevant to the user's task, such as the presence of certain objects of interest. Or, an ambient device could subtly cue in the user with notifications as the user walks into the room or as they glance their eye gaze over the room. Absorbing information without consciously performing the act of seeking it enables users to stay focused on their goals [4, 34, 43]. We define *extended human proprioception* as the human capacity to integrate new information about one's location, orientation, and movement in a physical environment relative to other entities from that environment. Extended proprioception assumes that information is rendered at the periphery of user attention [4], for which practical implementations can leverage dedicated software architecture [33, 34].

4 Event-driven Software Architecture for Digital Proprioception in Smart Environments

We describe in this section an adaptation of Euphoria [32], a generic software architecture designed for implementing interactive applications in smart environments,[2] to propose a technical solution to digital proprioception for devices and environments; see Figure 2 for an overview. The main component of our architecture is the Proprioception Component (PROPRIOCOMP) that enables devices to access information from the smart environment regarding their location and orientation via requests implemented with messages and events. Any software component or smart device from the environment can act as a producer or consumer of proprioception-related information (Figure 2, left) by specifying its role during the registration with Euphoria; see Schipor and Vatavu [32] for details about this process as well as characteristics of producers and consumers. During registration, a description of the proprioception data that the device can provide to or requires from the environment is specified. For example, a smart bracelet with limited sensing can infer its orientation via its built-in accelerometer and gyroscope, but needs to perform requests to an external source to retrieve its spatial location in the environment, which could be an approximation represented by the location of the user wearing the bracelet.

The Euphoria engine acts as a middleware between proprioception producers and consumers. The proprioception information is collected by the Sensing Interface Module (SIM), which forwards it to the Integration Module (IM) that performs data transformation so that the same units of measurement and the same format

[2] Euphoria is available at `http://www.eed.usv.ro/mintviz/resources/Euphoria`.

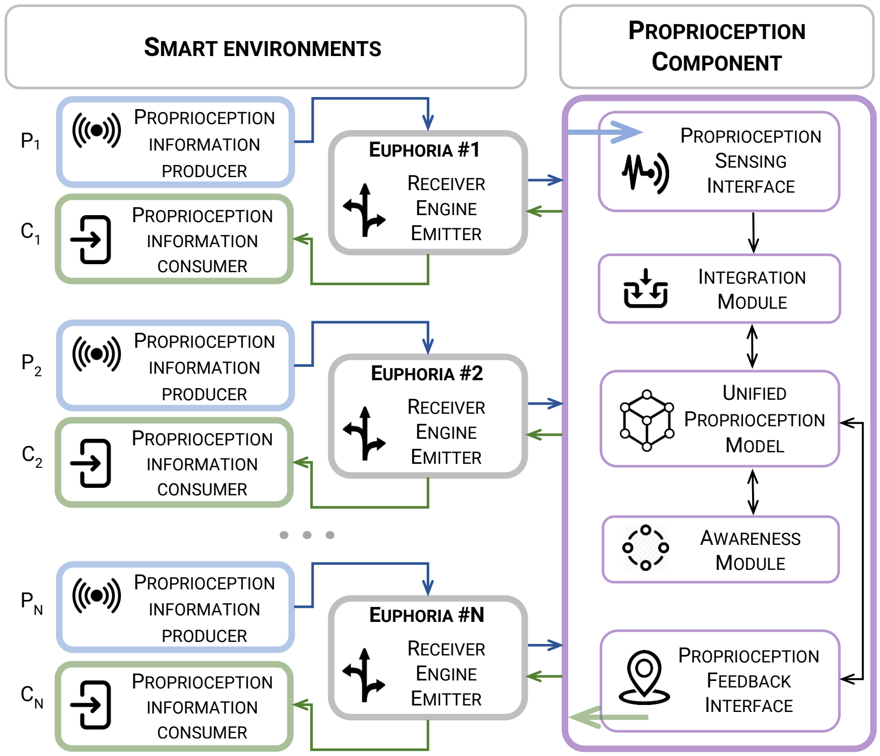

Fig. 2 Software architecture for digital proprioception in smart environments showing integration of the Proprioception Component (right) with N smart environments (left), each running an instance of Euphoria [32]. Note: P_i and C_i represent proprioception producers and consumers from the i-th environment; blue arrows show afferent data flows to ProprioComp, and green arrows the efferent data flows from ProprioComp to the consumers requesting proprioception information.

are used consistently within the architecture. This module also groups information addressing the same entity, e.g., the smart bracelet from our example, that may arrive from various sources. Then, the proprioception information is processed at the level of the Unified Proprioception Model (UPM) within ProprioComp; see Figure 2, right. The Awareness Module (AM) completes the functionality of the UPM with persistence across multiple environments, which is the level where ProprioComp is aware of the states of other environments, and uses the Feedback Interface Module (FIM) to provide software consumers with the information they requested.

Just like Euphoria [32] and other platforms [34] based on it, our extension proposes exclusive use of JavaScript, web standards (HTTP/JSON), communication protocols (WebSocket), and platforms (node.js) for the web. Our architecture proposal preserves all the quality properties—i.e., adaptability, modularity, flexibility, and interoperability—and contextual properties—i.e., web-based, JavaScript-based, open source, and smart environment orientation—of Euphoria [32]. On top of these, it adds a processing layer dedicated to digital proprioception with specialized software modules collecting proprioception data from producers and dispatching that data to consumers, constituting a *proprioception-oriented software architecture*.

5 Conclusion and Future Work

We discussed in this work digital proprioception for smart devices and smart environments, for which we proposed a possible technical solution by capitalizing on a generic-purpose software architecture designed for smart environments with heterogeneous I/O devices and platforms. Future work will consider practical implementation of our software architecture, but also expanding it with new modules. Also, future work will look at practical applications where smart devices exploit digital proprioception to provide new interactive experiences to users, such as implicit interaction with mid-air digital content [31] or enhanced motor abilities and augmented senses [26], revisited from the perspective of digital proprioception for devices, environments, and users.

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