Wrist-Worn Capacitive Sensor for Activity and Physical Collaboration Recognition

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***Abstract*—Given the wide and increasing popularity of smartwatches, the wrist is a compelling location for placing sensors. On the other hand, only specific information such as hand/arm motions and selected physiological signals are readily available at the wrist. In this paper, we explore a novel wrist-worn sensing approach that allows information not typically associated with the wrist or the arm to be acquired by exploring the ubiquitous near-field electric phenomena. We first introduce the design of an ultra-low power near-field electric field sensing prototype, which is able to sense *uV* level potential variation caused by disturbance or movement of the human body in an environment. Then we demonstrate how our prototype can detect motions of various body parts beyond the wrist, such as touch and proximity between users and objects. Finally, a use case related to a collaborative work by two people is recorded by deploying our prototypes both at surrounding objects and on wrists, presenting the feasibility of collaborative work monitoring by sensing the variation of the near field electric field.**

I. INTRODUCTION

Ambient electric field is a ubiquitous field as every subject carries certain amount of charge, even an insulator [1]. For example, when a human body moves on the ground, the tribological interaction [2] between body and ground will generate electrostatic charge on the human body, thus setting up a static electric field between human body and ground [3]. Appliances at home also radiate electric fields [4]. Those fields could be distorted by surrounding disturbances or self-movement. For example, a refrigerator, as radiator of an electric field, its field can be distorted by an intruder like a human body. Walking can cause the variation of potential on body, namely the variation of electric field from body to ground, which could also be described by variation of *human body capacitance*(*HBC*).

The core idea behind our work is that electric field and capacitance changes related to the body can be sensed at any chosen body location, including the wrist thus significantly enhancing the type of information that can be extracted from a wrist-worn device. Since such information includes not just the activities of the user her/himself but also changes in the environment a key application that we explore is collaboration on physical activity-related tasks, which is difficult to capture using other sensors [5].

A. Related Work

Thus by sensing the variation of the human body related near-field electric field, a wide range of applications can be covered [6], [7], [8]. Pouryazdan et al. [9] used electric potential sensors to sense hair touch and restless leg movement. Grosse-Puppendahl et al. [10] developed a system called Platypus to localize and identify people by remotely and passively sensing changes of their body electric potential. Harland et al. [11] proposed remote, off-body sensing of the electrical activity of the heart at distances up to 1 m from the body to high-resolution electrocardiograms.

Here, we developed a sensing prototype being able to monitor group works with collaborative activities by sensing the body related electric potential variation. Conventionally, human activities are detected by installing accelerators on the human body, which requires the exact deployment of a sensor to the action's relevant body part. Other activity sensing modalities, like infrared [12], camera [13], Doppler signature [14], require either complicated establishment of detection system or complex data processing equipment. In contrast, electric field based activity monitoring possesses advantages over both power consumption and hardware simplification. Wilmsdorff et al. [15] also designed a power saving electric field sensing sensor with wide applications in interior spaces and outdoors. Xi Chen et al. [16] presented a non-contact method to monitor human gait including stepping, walking and running by measuring the induced electrostatic signals. However, compared with our work, the wearable application in Wilmsdorff's work needs the integrating of an expensive commercial product named electric potential integrated circuit(EPIC) [17]. In Xi Chen's work, the sensing unit design is still complex with one converter and two filters.

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Fig. 1: Electric fields related to ground at a living room

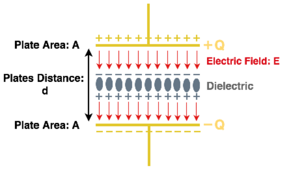

Fig. 2: Structure of a capacitor

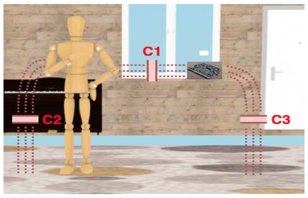

Fig. 3: Capacitive coupling between ground, human body and sensing local ground

II. Physical Background and Sensing Prototype

A. Basic Principle

Fig. 1 shows some primary electric fields related to the ground in a living room. Appliances like television, electric piano, lamps, etc., are charged from the domestic power cable, thus owning a high potential relative to the ground. Walls, doors and windows also have a close electric relationship with the ground because of the interior reinforcing bar structure. The human body, metal shelves, etc., where the charge is generated because of contact and friction with the ground, radiate a potential difference caused static electric field.

Since those electric fields occur because of the charge difference among those objects and ground, we use capacitance to describe those potential difference in the following sections, as ground and objects basically act as charge gathering conductive plates, thus, forming capacitors with air as the dielectric between those plates, as Fig. 2 shows. Fig. 3 depicts three kinds of capacitive coupling among ground and objects when our potential sensing hardware was worn on the wrist, namely capacitor between human body and ground, human body and sensing local ground, sensing local ground and ground. Those three spatially shaped capacitors empower the wearable applications with our sensing prototype.

As described above, the electric fields in our daily living environment and working space can be influenced by the surrounding subjects. Essentially the physical background of this variation can be explained by the variation of those spatially shaped capacitors. As Fig. 2 depicted, the capacitance C between two plates can be described as [18]:

$$\frac{d(C(t))}{d_t} = \varepsilon_0 \varepsilon_r \frac{d(A(t))}{d(d(t))} \tag{1}$$

ε_0 is the vacuum permittivity, ε_r is the relative permittivity, A and d are the square of overlapping area and distance between two plates, respectively. Capacitance will change with the variation of relative distance or overlapping area of the capacitor. For example, human body movement is actually changing the distance from body and ground, the presence of human body between the door and ground is actually changing the relative permittivity from air to human body. Thus, by sensing the capacitance variation among environmental objects, which is caused by the intrusion of human body, like approaching or touching, we can derive the action and position of our body.

B. Prototype

Fig. 4 shows the sensing front end of our sensing prototype. Compared with related work [9], [15], [19], we only use several discrete components, thus the overall sensing circuit consumes only uW level of power. $R4$, $R5$, $C4$, $C5$ form a low pass filter. $R1$, $R2$, $R3$ connect to the charge source. $C1$, $C2$, $C3$ are capacitance between sensing board local ground and object, object and ground, ground and local ground, respectively, as Fig. 3 shows, in which the object is a human body. Assuming there is no filter, the sensed voltage could be described as:

$$V_s = V_{cc} \frac{Z_{(R_1)\|j\omega C_c}}{Z_{(R_1)\|j\omega C_c} + R_2} \frac{j\omega C_c}{j\omega C_c + R_3} \tag{2}$$

where

$$C_c = C_1 + C_2 + C_3 \tag{3}$$

ω is the angular frequency. R_1 has the same value as R_2, and thus the relation between V_{cc} and V_s is:

$$\frac{V_{cc}}{V_s} = 2 + \frac{R_1 + 2R_3}{j\omega C_c} \tag{4}$$

Equation 4 explains that any variation of capacitance in $C1$, $C2$, $C3$ will result a variation of potential at the electrode side. And this potential variation will be balanced later by the charge redistribution. As 5 implies, the charge on C_c will implement the potential variation of v_s:

$$C_c = \frac{Q_{C_c}}{U_{C_c}}, (U_{C_c} = V_s) \tag{5}$$

Fig. 5 describes the entire hardware system. We use ADS1298 and MSP430 from Texas Instruments as the analog to digital unit and data processing unit, Bluetooth RN42 from Microchip Technology as data transmission unit. The data update rate is set to 12Hz. Fig. 6 shows the simple prototype worn on a wrist, for convenience, a black housing was printed to hold the hardware.

III. Capability Exploration

To explore the capability of our sensing modality, we deployed our prototypes on various objects, which are involved in a human body's action to monitor a collaborative work. Plenty of the related capacitive coupling based works, developed for an ambient intelligence scenario, focused on single side context, either perceiving information from the actuator

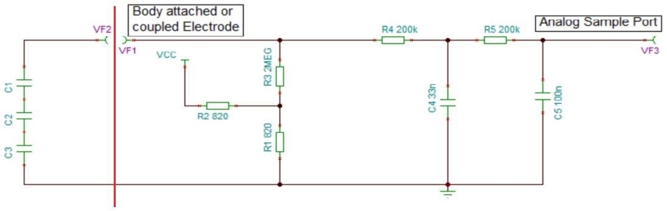

Fig. 4: Sensing front end(right part)

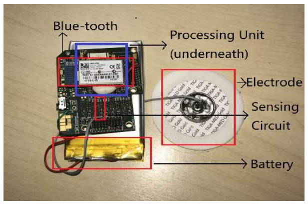

Fig. 5: Hardware including sensing, processing, wire-less transmission and battery units

Fig. 6: Hardware attached to wrist

of an action [19], [20], [21], or from the reactor of an action [22], [23], [24]. For example, Cohn et al. [19] mentioned the ability of capacitive sensing by recording repetitive motion of body, Arshad et al. [22] developed a floor-sensing model for elderly tracking and fall detection. However, we believe integration of our sensor both in actuator side and reactor side in the environment will provide more complete information and thus provide a better understanding of the interaction of the individuals with the environment, as both the source and receiving end of an action will generate signals. Thus we set up a simple collaborative task, in which two participants are involved and interact with ambient environment. First, we describe the basic sensing ability and the background principle of our prototype in the following sections, which enable the monitoring of a whole process of group work.

A. Touch Sensing

Touch is one of the basic interaction between people and surrounding. Sensing approaches like infrared camera [25], pressure sensor [26], acoustic signal [27], etc, are used to detect this action. The basis of touch sensing of our prototype is when touch happens, the human body will supply an extra path for the charge on the object to flow to a lower potential plate(sinking charge [28]), until the potential difference disappears. Once the charge flow caused voltage variation is observed, touch event can be detected. We can also use capacitive theory to explain this, as direct touch will change the dielectric of the spatially shaped capacitor(Fig. 2) from air to good conductor, thus the capacitance value will greatly decrease (Equation 1).

Fig. 7 shows the potential variation of two related prototypes, one is attached to a chair with internal metal structure and paint on surface, another one is attached to person's wrist. The potential variation happens at the same time but in opposite direction. Before the touch, the potential of the touch point at chair side is higher than the potential of touch point at human body's hand side. The charge will stop flowing when the touch position at both sides shares the same potential. Then at each electrode position, the potential will be balanced to its former level, as explained in last section (Equation 4,5). Taking hand away from chair will not cause charge flow anymore because there is no potential difference on both sides. That is to say, the prototype is able to detect touch action, but the 'remove' action is beyond the sensor's capability.

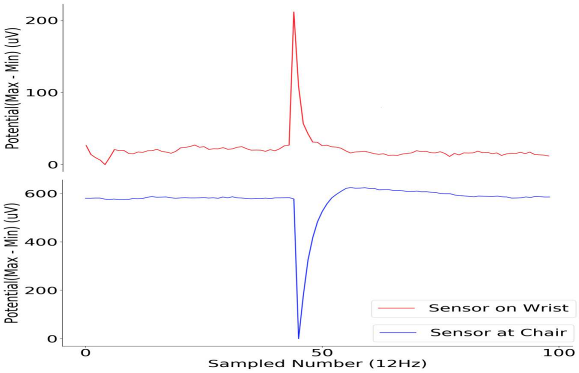

Fig. 7: Touch a chair with prototypes at chair and on wrist

B. Proximity Sensing

Proximity detection is a primary sensing approach in Ambient Intelligence scenarios. Unlike camera [29], light [30], capacitance-based proximity has the advantage of low power consumption and effortless system establishment. The basic background of this sensing approach resides at the proximity caused dielectric or distance variation in a capacitor. Capacitive proximity sensing allows not only just detecting when an object is approaching, but also distance estimation, as the scale of capacitance variation is strictly related to the distance of proximity.

Fig. 8 shows the process when a participant walks to a door from a 1.5 meter distance, then touches the doorknob, and walks backward to his original spot. An accelerometer is attached to the right calf of the participant. The potential variation of the prototype at doorknob shows the proximity of a human body, which clearly implies that the distance could also be estimated by its variation scale. The arrows show the moment when the participant touched the doorknob, causing charge flow. The potential variation direction implies that the human body was sinking charge from doorknob. Fig. 9 shows potential variation on the wrist when P2 walked by P1 two times with the nearest distance of 1m and 0.5m, where P1 just stood still.

C. Activity Sensing

In collaborative work, human body motion is a primary source of information. Equation 4 implied that a repetitive variation of the capacitance value will cause repetitive potential variation, which can be used for activity counting and recognition. Activity sensing aims to monitor the human body's actions, for example walking, running, waving arms,

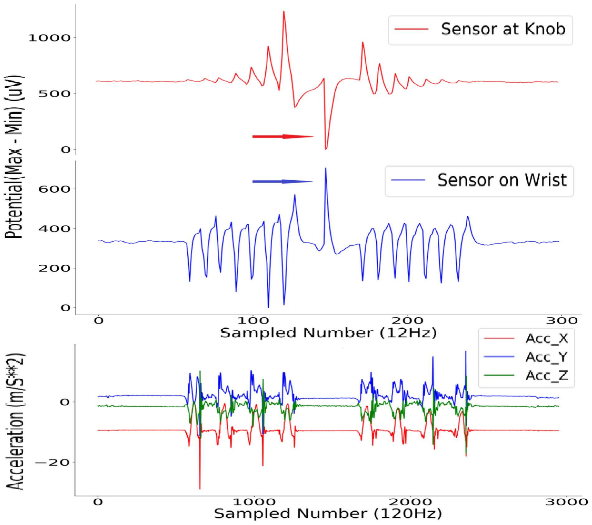

Fig. 8: Approaching a door with prototype attached at doorknob and on wrist

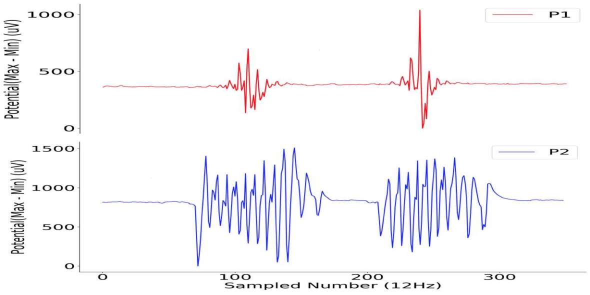

Fig. 9: Walking by detection with prototypes attached on wrists

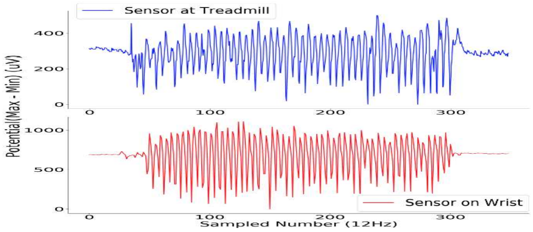

Fig. 10: Walking on treadmill with prototypes on wrist and at treadmill

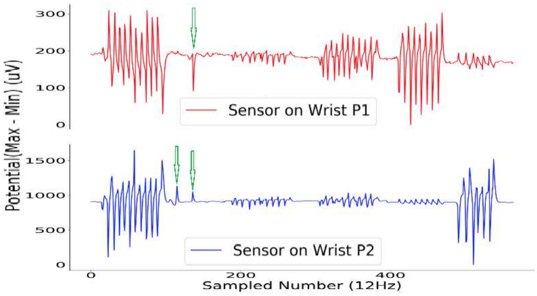

Fig. 11: Lifting leg with and without taking chair

etc., as Cohn et al. [19] discussed. Compared to other inertial measurement unit based activity sensing works [31], [32], capacitance based activity sensing enjoys firstly the advantage of full body sensing, without the requirement of wearing the sensor on the moving body part. The second advantage is the non-contact sensing ability profiting from capacitive coupling, as Fig. 10 shows when the prototype located about 20 cm away from treadmill track. In addition, capacitive sensing consumes power with only *uW* level, extending the working time for a battery based application.

As mentioned above, Fig. 10 depicts the walking information sensed by prototypes on wrist and near the treadmill track. The speed of the walker can be obtained by counting the number of peaks, because each peak means one step. From the features of repetitive activities' signal in time and frequency domain, different activities can be classified [33]. Fig. 11 shows two people's interaction with a chair. First they lift their legs at the same time, and P2 touches a chair, followed by P1(marked as green arrows). Then P1 and P2 lift their legs separately while holding the chair. Finally they drop the chair down and lift legs again separately. From the sampled signal it is clear that the scale of potential variation caused by the movement differs when they are holding the chair and not. This information could be used to detect if two people are holding the same object, which is a major factor for detecting collaborative work. The reason is that when two people are connected or coupled strictly together, the entire capacitance related to ground increases, as A in 1 almost doubles. As a result, the percentage of the same activity caused capacitance change will drop. Another point to be noted is the difference of scale in the potential of P1 and P2 from the first lift leg action, which is caused by their wearing, for example, the height and material of shoe sole, as wearing play an important role in *human body capacitance* [34].

IV. COLLABORATIVE WORK MONITORING

Based on the sensing capability described above, monitoring a collaborative work with capacitance-based sensing approach is thus feasible. Event and motion from a human body can be obtained by distributing our prototypes at the working site and on moving bodies. Traditionally, multiple person activity monitoring was fulfilled using a vision based system [35], which can collect very detailed information about group content, but requires a high computational demand and may raise privacy concerns. We set up a simple collaborative task where two people need to move a shelf from one spot to another and assemble two shelves together. Fig. 12 illustrates the working place, where prototypes are attached to two shelves, one doorknob, a toolbox, and on the wrists of two involved participants. Those objects will assist to have a better understanding of participants' actions. One common feature of those objects is that they have interior metal structure and paint on the surface. Each Participant was wearing an accelerometer on the calf.

Fig. 13 depicts the process of this collaborative work. The event actions are labeled by arrows, the motion actions are labeled by straight lines. Here are the whole steps: 1, For beginning, P1 and P2 lift their legs 10 times (P11, P12, P21,

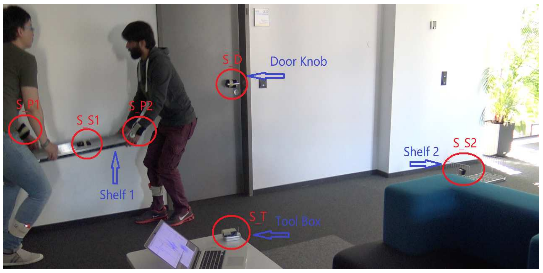

Fig. 12: Collaborative work site

P22); 2, P1 walks to P2 (P13), and they shake their hands (P1a,P2a); 3, P1 walks to shelf one (P14), walking by the door (Da), touches shelf one (P1b, S1a) and tries to lift it; 4, P1 finds it too large and not convenient for one person to carry, and calls P2 to help. P2 walks to P1 (P23), also walking by the door (Db), touches shelf one (P1c, P2b, S1b); 5, P1 and P2 lift shelf one, go to shelf two (P15, P24, S11, S21), walking by the door again (Dc, Dd); 6, They drop down shelf one, P1 manages to keep shelf one and two together (P1d, S1c, S2a); 7, P2 goes to the toolbox (P25) and takes it (P2c, Ta), then goes back to P1 (P26, T3); 8, P2 hands over the toolbox to P1 (P1e, P2d, Tb, S1d, S2b), and walks away (P27); 9, P1 uses some wire from toolbox to tie shelf one and two together, leaving the toolbox on the ground, and moves the shelves to another nearby spot (P16, S11, S22); 10, P1 walks to the toolbox (P17), takes it (P1f, Tc), then returns it back to its original place (P18, T4, Td); 11, P1 returns back to his original place (P19), walking by P2, and they lift leg for several times to finish the whole task(P110, P28). During the whole procedure, there are several signals to be declared. First, because the Toolbox is near the original spot of P2, P2's lift leg action can be perceived by the Toolbox (T1, T2, T5). Second, when P1 and P2 are coupled strictly by shelf one, their entire capacitance to ground is approximately doubled, so the walking caused capacitance variation ratio with the entire capacitance decreased (P15, P24, S11, Dc, Dd). Third, some gradually changing signals implies the approaching or leaving of a participant, like the potential variation before Ta, Tc, P2a, after P2a and during S21.

The above described potential variations from a simple collaborative work shows a feasible human activity monitoring access, with exact time synchronization of all the prototypes, actions from involved participants, like touch, motion and approximate position, could be detected. This could be used in a wide range of ambient intelligence scenarios, like ambient assistive living, factory works, etc.

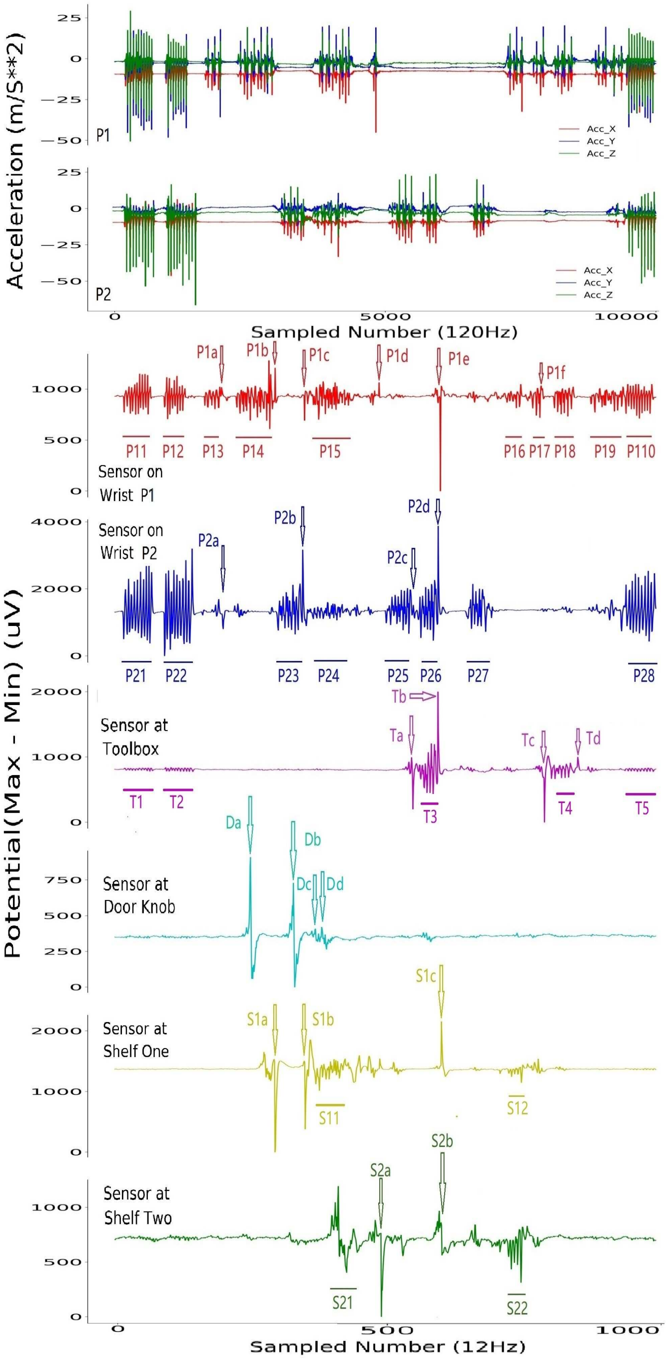

Fig. 13: Process of the collaborative work

V. CONCLUSION AND FUTURE WORK

In this work, we developed an ultra-low power, capacitance based prototype, capable of sensing human touch, proximity and body activities. We demonstrated its capability with a simple collaborative task, in which the actions of participants were recorded by our prototypes worn on wrists, and assisted by attaching prototypes to other involved objects, that the participants interact with. However there are some limitations that bound its application range. First, the object that has interaction with user needs to have good electric properties, namely the ability for charge to gather or flow. Second, our prototype is based on the passive capacitive sensing, so only movement based actions can be detected, the reason being that only movement can cause the capacitance variation, thus causing the charge redistribution. Third, this potential variation will be balanced by current source soon after the charge redistribution at the electrode side, thus the information after action is lost, as the potential before and after an action has no difference. How to maintain this variation will be a subject of future work. Besides this, more capacitance-based sensing collaborative activities will be recorded and classified.

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