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Water Based Magnification of Capacitive Proximity Sensors: Water Containers as Passive Human Detectors

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Abstract— **Sensors that detect human presence received an increasing attention due to the recent advances in smart homes, collaborative fabrication cells, and human robot interaction. These sensors can be used in collaborative robot cells and mobile robots, in order to increase the robot awareness about the presence of humans, in order to increase safety during their operation. Among proximity detection systems, capacitive sensors are interesting, since they are low cost and simple human proximity detectors, however their detection range is limited. In this article, we show that the proximity detection range of a capacitive sensor can be enhanced, when the sensor is placed near a water container. In addition, the signal can pass trough several adjacent water containers, even if they are separated by a few centimeters. This phenomenon has an important implication in establishing low cost sensor networks. For instance, a limited number of active capacitive sensor nodes can be linked with several simple passive nodes, i.e. water containers, to detect human or animal proximity in a large area such as a farm, a factory or home. Analysis on the change of the maximum proximity range with sensor dimension, container size and liquid filler was performed in order to study this effect. Examples of application are also demonstrated.**

I. Introduction

Proximity sensors have been used in the automation industry for several decades. The actual increasing interest on detection of human proximity is however due to several novel applications in safe Human-Robot Interaction (HRI), in collaborative fabrication cells, home automation, ambient assisted living and novel forms of Human Machine Interactions (HMIs). Proximity can be measured with various sensing architectures. Light and sound based sensors are based on emission of an electromagnetic radiation and analysis of the returned signal. Capacitive sensors on the other hand, are probably the simplest sensing architecture. The electrodes of a capacitive sensor can be simply a conductive film [1]. They are low cost and less bulky compared to light/sound based proximity detectors, and they can be printed as a high resolution array of multiple sensor nodes. They can detect proximity of the human body and conductive objects. Capacitive sensors can be integrated in the robot body or on guarded zones to map the workspace area and to detect the proximity of the humans to avoid accidents, [2], [3], [4]. This was used for instance in robotics applications, such as robotics grippers, [5], prosthetic hands [6], [7], touch sensing applications [8], Human-Robot interaction [9], and multi mode touch-pads[10]. Fusion of Capacitive and Inductive sensors was also demonstrated for seat occupancy detection [11]. Printed electronic skins [12], [13], [14] have been also developed that can be used for various applications, including for distributed capacitive sensing over surface of the object [15], [16]. Capacitive proximity sensors installed over a robotic arm, was demonstrated for safer human-robot interactions in [17], [18]. Also, a dual mode network of capacitive sensors for detection of proximity and touch was presented in [19]. Nevertheless, one drawback of capacitive proximity sensors is the short range of detection distance, which is usually limited to a few centimetres. Capacitive sensors are excellent near field proximity detector, as for instance they are used in touch screens, but their use is limited in applications where higher proximity detection range is required.

In this manuscript, we show utilization of water for magnification of the proximity detection range of capacitive sensors, and then we show how this phenomenon can propagate through several water bottles, with direct application on low cost distributed proximity sensing.. When a conductor is attached to a water container, it can detect the proximity of the human body at higher distances when compared to the sensor on the air. This effect is extended to any water containing object, such as fruits or the human body.

Another interesting finding was that when several water containers are placed near to each other, they act as antennas, and are able to "transmit the signal". Based on this, we demonstrated an application of single button piano, in which 7 water balloons were used as Piano Buttons, using detection of the human finger proximity, while only one of them embeds a capacitive sensor. When touching the last balloon, the measured self capacitance of the conductor over the first balloon changes. Other applications for ambient assisted living or surveillance may be developed over this concept, figure 2. For instance, a water tank equipped with a simple capacitive measurement board, may be used as human/animal surveillance node in a radius around it. This concept may be also used for human presence and position detection for ambient assisted living, e.g. smart lighting, or detection of human/animals in large fields, figure 2. In both cases, a limited number of active sensor nodes surrounded by a larger number of low cost passive nodes (i.e. water containers) that enhance the proximity detection range of active nodes.

II. Materials and methods

To analyse the change of capacitance, a Cypress Semiconductor development board (CY8KIT-145-40XX) was used.

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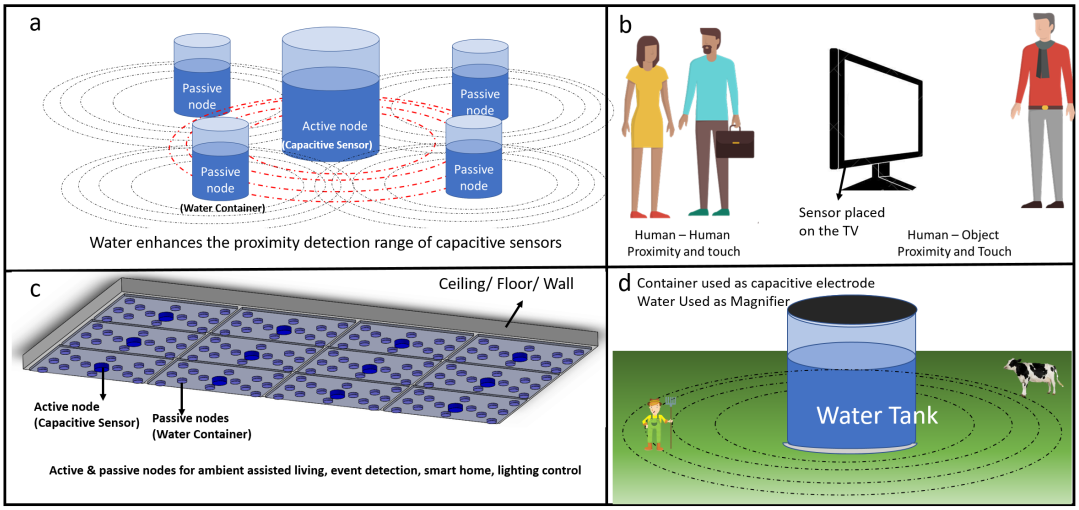

Fig. 1: Water magnification proximity range detection of the capacitive sensors and possible applications. a) One active node (capacitive sensor) surrounded by several passive nodes(water containers) to detect proximity in a large area, enhancing the maximum detection range b) This concept may be used in humans-human, human-object, and human-robot interaction c) Sensors network placed on a ceilingmay be used in smart homes, smart lighting, ambient assisted living or surveillance. d) A capacitive sensor on a large water tank can be used as human/animal surveillance and motion detector in a radius around it.

This board is able to measure changes on capacitance, using different methods of sensing: Self or Mutual capacitance [20]. For this study, since the goal is to measure proximity changes with capacitance, the Self Capacitance mode is used. In this method, only one measuring electrode is required. When an object is approached, the charge distribution over the electrode is modified, thus changing the overall capacitance value. It is well-known that the human body causes the highest changes on the capacitance value due to approximation, followed by conductive objects.

It is also known that capacitive sensors reflect a significant amount of noise due to the surrounding electrical fields and conductive objects. Therefore, a shielded cable was used for signal transmission from the electrode to the acquisition board. For the best result, we used active shielding method, shown in figure 2, in which the cable shield is connected to the shield pin of the acquisition board.

Figure 2 shows the schematics of the experimental setup. The measured variables are the range of detection of the sensor for vertical and lateral approaches. Since the effect of various parameters on the detection range of the sensor are analysed, a value of $\frac{\Delta C}{C_0} = 1,01$ was defined as the normalized threshold of proximity detection for all cases. For instance, the actual value of capacitance changes when adding various amount of water, or changing the sensor size, and thus $\frac{C}{C_0}$ is used for comparison rather than the absolute capacitance value. An aluminium tape of 0,1mm thick is used as the electrode. This way, different electrode sizes can be cut and applied easily under the containers. In order to simplify the comparison and perception of the results, we use the followings definitions: (See also figure 2:)

- P_l - distance of the hand from the lateral side of the container (cm)
- $P_{l_{max}}$ - maximum P_l value that results in $\frac{\Delta C}{C_0} = 1,01$
- P_v - distance from the hand to the liquid surface, in the vertical direction
- $P_{v_{max}}$ - maximum P_v value results in $\frac{\Delta C}{C_0} = 1,01$
- $P_s = P_v + h$ - distance from the hand to the sensor, in the vertical direction
- $P_{s_{max}}$ - maximum P_s value with$\frac{\Delta C}{C_0} = 1,01$

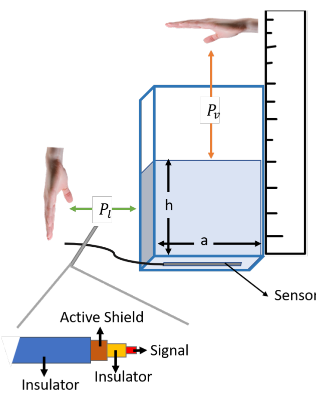

Fig. 2: Schematics of the Experimental setup. A conductive tape is placed on the bottom of a container and it is connected to the acquisition board through a shielded wire. Changes on capacitance due to vertical and lateral approximations are measured.

Using these variables, we explored the changes on the detection range of capacitive sensors in the following changes on the set-up:

- h - height of the water in the container
- Sensor size

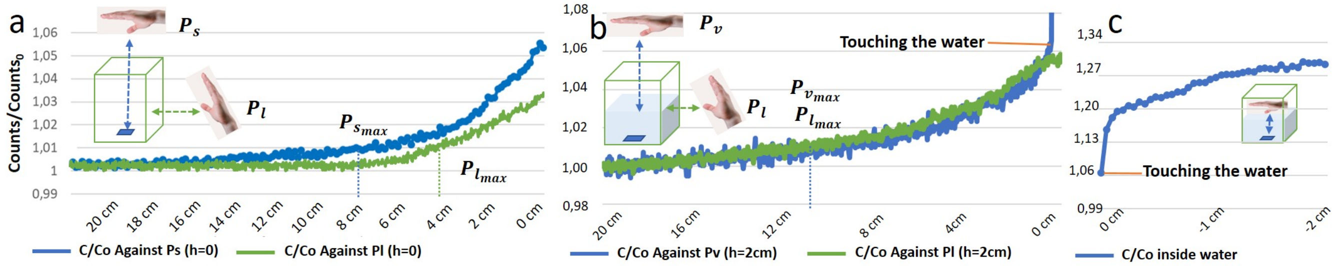

Fig. 3: a) Change of capacitance with hand approximations (P_s and P_l) with height of water $h = 0cm$. b) Change of capacitance P_v and P_l for $h = 2cm$. c) Change of capacitance, with $h = 2cm$, inside water.

- a^2 - Base area of the container
- Changing the filling liquid in the container (air, distilled water, hexane and isopropyl alcohol)

III. Results

A. Capacitive sensors with no water

In the first stage, a (30 x 30 mm) electrode was tested in the air as a reference for comparison with the next results. Figure 3a. shows the response of the sensors when a hand is approaching the sensor from a vertical direction. The sensor started to detect the presence of the hand, P_s, at a distance of 8 cm ($\frac{\Delta C}{C_0} = 1,01$). Additionally, the sensors were also tested against lateral proximity and proved to detect the presence of the hand, $P_{l_{max}}$, at a distance of 3 cm, figure 3 a.

B. Influence of Water on Proximity Measurement

Having characterized the sensors without any liquid filler, the sensors were then placed below a water container ($a = 10cm$), and the response of the sensor with the proximity of a hand was analyzed, both in the z-direction and in lateral directions. The container was filled with $h = 2cm$ of distilled water. Reffering to figures 3a and 3b, one can see that the small amount of water significantly increases the range of detection of the human hand. For instance, considering a $\frac{\Delta C}{C_0} = 1,01$, as a detection threshold, for the empty container, $P_{s_{max}} = 8cm$, while filling ($h = 2cm$) of water, $P_{v_{max}} = 13cm$, $P_{s_{max}} = 15cm$.

Figure 3 b), shows only the approach until the hand reach the water surface. However, when the hand touches the water surface, the value of capacitance increases abruptly. This effect is shown in figure 3 c), where one can see the abrupt increase of capacitance and then, after this steep increase, the capacitance changes with proximity of the hand. Consequently, this means that we can measure the changes of capacitance with proximity outside (figure3 b)) and inside of water (figure 3 c)).

To better understand the effect of water height in proximity sensors, we measured changes in P_s, P_v and P_l for different heights of water. In this test, we used a sensor of $9cm^2$ and a container with a base area of $a^2 = 14,44cm^2$. Therefore, in figure 4, one can see that the maximum range of detection, $P_{s_{max}}$ increases linearly with the increase of water in the container, after $h = 4cm$. Additionally, considering now $P_{v_{max}}$ and $P_{l_{max}}$, one can see that the detection range is constant after $h = 4cm$. The sensor achieves a maximum range of detection of $P_{v_{max}} = 18cm$ $P_{l_{max}} = 14cm$, as can be seen in figure 4.

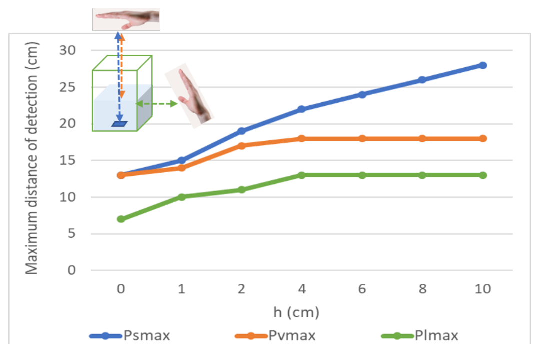

Fig. 4: Maximum range of proximity for vertical (blue and orange) and lateral approaches (green).

C. Effect of the sensors size

Keeping the same container ($a^2 = 14,44cm^2$), we varied the sensor size. Therefore, three different sensors were used:

1) $1 \times 1cm = 1cm^2$
2) $5 \times 2cm = 10cm^2$
3) $5 \times 5cm = 25cm^2$

and - $P_{s_{max}}$, $P_{v_{max}}$ and $P_{l_{max}}$ - for different h of distilled water were measured . The results are shown in figure 5. As can be seen, the size of the sensors has a significant role in the maximum detection range of the sensors. For all of the studied parameters ($P_{s_{max}}$, $P_{v_{max}}$ and $P_{l_{max}}$), the maximum range of detection is always enhanced for larger sensors. Regarding $P_{l_{max}}$ for the smallest sensor and with $h = 0cm$ (no water), the approach of the hand does not cause any change on the capacitance - remember that $P_{l_{max}}$ is the distance between the hand and the container wall. Then, when water is added to the container, the sensor starts to detect the proximity of the hand, following a similar behaviour of other cases.

It is then shown that independent from the sensor size, there is always magnification of the detection range of proximity of the sensors with water. Also, one can see

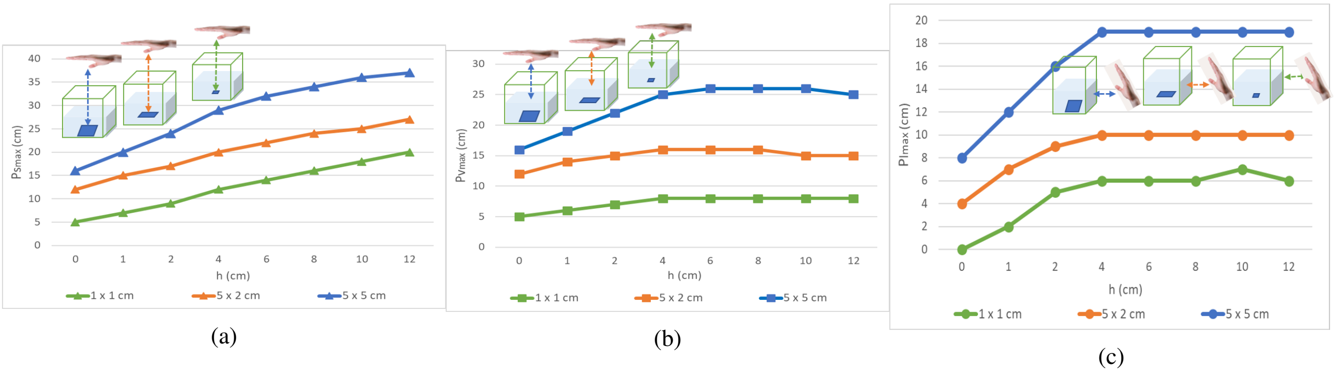

Fig. 5: a) $P_{s_{max}}$, b) $P_{v_{max}}$ and c) $P_{l_{max}}$ for three different sensors $A_1 = 1cm^2$, $A - 2 = 10cm^2$, $A_3 = 25cm^2$

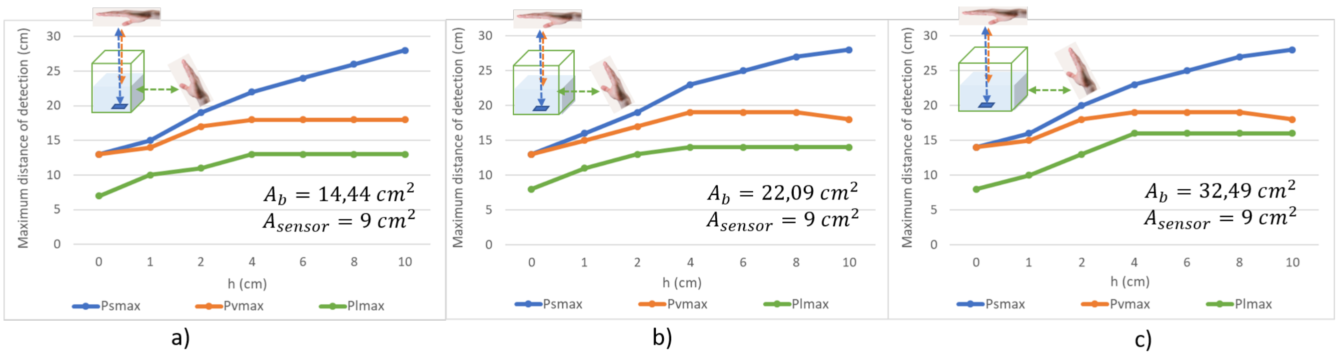

Fig. 6: $P_{s_{max}}$, $P_{v_{max}}$ and $P_{l_{max}}$, for different h, for 3 different containers. a) $a_1^2 = 14,44cm^2$, b) $a_2^2 = 22,09cm^2$ and c) $a_3^2 = 32,49cm^2$

that the $P_{v_{max}}$ is constant after the height of water reaches $h = 4cm$.

D. Effect of container dimension

The dimension of the container, and consequently the surface area and the volume of water for the same h may also be relevant for the magnification of the range of proximity of the sensor. Therefore, using always the same sensor ($3 \times 3cm$), three different containers were used with the following base area:

1) $a_1^2 = 14,44cm^2$
2) $a_2^2 = 22,09cm^2$
3) $a_3^2 = 32.49cm^2$

We performed a similar test to the previous ones, measuring $P_{s_{max}}$, $P_{v_{max}}$ and $P_{l_{max}}$ for different h in each container. The results are shown in figure 6. One can see that despite using containers with different surface areas, all containers achieve approximately the same $P_{s_{max}}$, $P_{v_{max}}$ and $P_{l_{max}}$. However if the container is significantly bigger, changes on the proximity are observable. The tests were then repeated for a larger container with a base area of $31 \times 23 = 713cm^2$ in order to disregard the boundary effects from the surfaces that are not being tested. Hand approximation was performed exactly at the center of the container, where the distance to the borders is maximized. One small and one large sensors were used, with size of $3 \times 3 = 9cm^2$ and - $23 \times 23 = 529cm^2$. Comparing the results of figure 7 and 6, one can see that $P_{s_{max}}$ is enhanced from $P_{s_{max}} = 28cm$ to $P_{s_{max}} = 44cm$. Again one can see that the maximum value for $P_{v_{max}}$ is always obtained at $h = 4cm$. On the other hand, Figure 7 also shows that the maximum range is achieved with around 4 cm of water in the container. However, contrary to the previous tests, $P_{v_{max}}$ does not maintain constant, but it starts to decrease at $h = 10cm$. Figure 8 shows the result With the same container and a larger sensor - (*$23 \times 23 = 529cm^2$). Proximity range continues to increase compared to the previous case, and the variation of P_v with h is similar to the figure 7, having the maximum at $h = 4cm$, constant up to $h = 10$, and starting to decrease after this point.

E. Magnification through second container

Another interesting phenomenon that was found during this work is that the magnification of the proximity range detection can be increased through adjacent water containers. To show this, we used the set-up shown in figure 9. Two identical containers are filled with water, and the sensor is placed under one of them. We then measured the changes on capacitance of the sensor by approaching a hand to the second container, and measured $P_{v_{max}}$ and $P_{l_{max}}$ for increasing distances between containers, and considering the same condition of $\frac{\Delta C}{C_0} = 1,01$. This effect is also shown in the multi-media extension.

Referring to figure 10, one can see that the second container works as a magnifier of the prximity detection range of

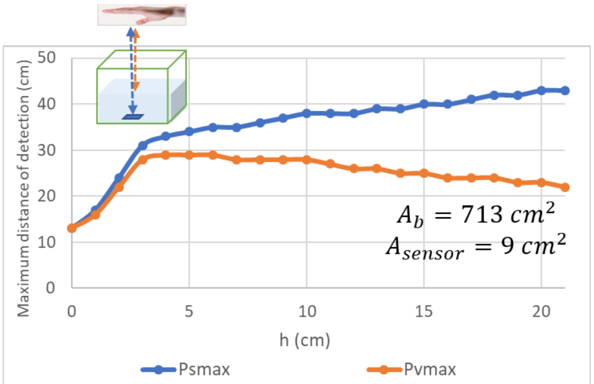

Fig. 7: $P_{s_{max}}$ and $P_{v_{max}}$ of a capacitive sensor on the bottom of a large container ($713cm^2$)

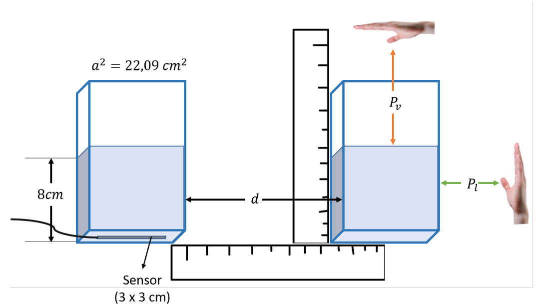

Fig. 9: Setup used to measure the maximum range of proximity of a second container, which does not have any sensing element. The second container is then separated from the first one centimeter by centimeter.

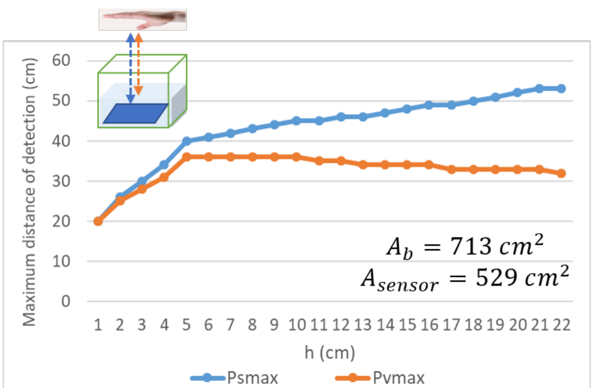

Fig. 8: $P_{s_{max}}$ and $P_{v_{max}}$ of a larger capacitive sensor ($529cm^2$) on the bottom of a large container ($713cm^2$)

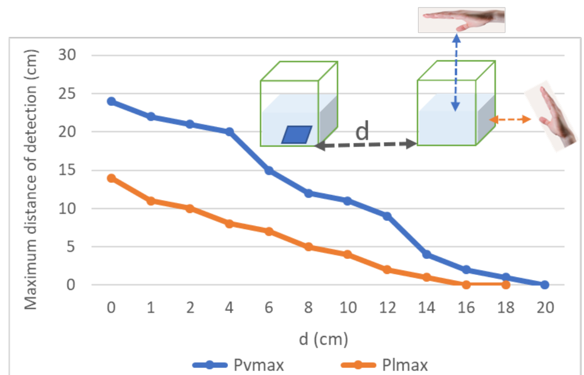

Fig. 10: $P_{v_{max}}$ and $P_{l_{max}}$ detected on a second container, for different distances (d) to the container with the sensing element.

the capacitive sensor, even when separated by a distance of up to $20cm$ from the first container. We can also observe that in the case where the 2 containers are side by side, $d = 0cm$, $P_{v_{max}}$ of the second container is $25cm$, which is even higher than the single container case($P_{v_{max}} = 19cm$). At a distance of $d = 4cm$ between containers $P_{v_{max}} = 20cm$, still higher than what observed in single container.

IV. Discussion

Our hypothesis for this behaviour is that the magnification of the range of the sensor is due to the polarity of the water. Water is a polar molecule. There is an electric dipole in the molecule of the water, where the Oxygen atom is negatively charged (mainly due to the 2 pair of free electrons in the covalent bond), while Hydrogen atoms are positively charged, as depicted in figure 11. This dipole of the molecule creates the hydrogen bonds between different molecules, which are much more weaker than the covalent bonds, being constantly broken and recreated [21]. Therefore, when the hand approaches the water container, surface charges of the human hand causes a redistribution of the orientation of the polar molecules of the water, figure 11, thus resulting in changes on the measured self-capacitance value of the sensor.

To support this theory we tested the change of capacitance with proximity for different liquids, such as distilled water, Hexane (non polar) and Isopropyl Alcohol (slightly polar). Water is a polar molecule, having two atoms of hydrogen attached to one of oxygen in such a way that the dipoles of the O - H bond add constructively (Hydrogen Bonds). In Isopropyl Alcohol, one of the H atoms is replaced by a hydrocarbon group, which is non polar. Therefore, Isopropyl Alcohol has only one O-H dipole which means that it is less polar than water. Hexane is composed by Carbons and Hydrogen, which means that there is no electro-negative elements in the Hexane, which means that it does not have dipole moment, and therefore it is non-polar

To perform this test, we filled a container of ($a^2 = 22.09cm^2$) with a ($3 \times 3cm$) sensor bonded in the bottom of the container filled with up to 4cm of each liquid. We then measured the P_v for each case. Figure 12 shows the changes of capacitance caused by the approach of a hand for the three liquids. As can be seen in the figure, the liquid that presents better magnification of the proximity is the water, followed by the Isopropyl Alcohol and then the Hexane, which supports our theory.

V. Application Examples

Finally, we demonstrate two case studies based on the proximity range magnification.

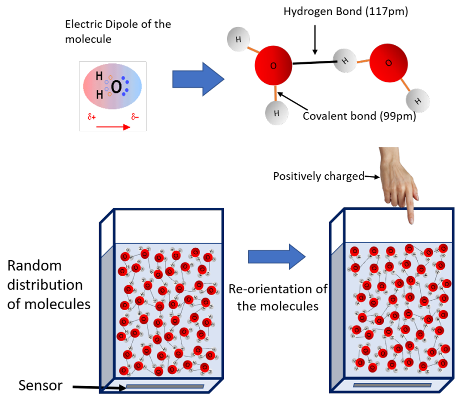

Fig. 11: Schematic showing the dipole of the water molecule and the redistribution of the molecules due to the approximation of a hand

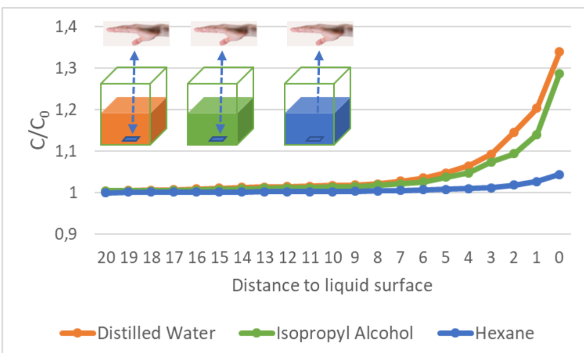

Fig. 12: Change of capacitance with proximity considering the surface of the liquids as the origin, for liquids with different levels of polarity: Distilled Water, Isopropyl Alcohol and Hexane.

A. Water Baloon Piano

Taking into account the propagation of the signal through adjacent containers, we designed an application in which one can play piano by touching several adjacent water balloons. The interesting fact about this application is that we used only a single sensor on the first balloons, and all of the following water balloons are passive (figure 13)

When touching a balloon, there is an abrupt increase on the capacitance counts. However, the amplitude of the peak is dependent to the distance to the sensor, which allows us to distinguish which balloon is being touched. Then, using thresholds to determine each peak, the information is sent to a MIDI (Musical Instrument Digital Interface), playing a musical note of a piano. The system is shown in figure (figure 13) as well as the multimedia extension.

B. Human-Human approximation

Furthermore, we also observed that even the human body can be used as a magnifier of the range of detection of the sensor. The human body is mainly constituted by water. Therefore, if the sensor is placed in contact with the skin, the

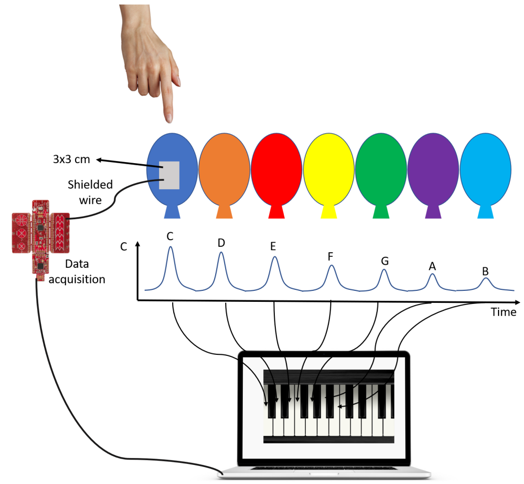

Fig. 13: Setup of the case study with one capacitive sensing element, which is placed on the first balloon but is able to detect and distinguish touches in all balloons. The capacitance is then read and processed using the acquisition board and the data are sent to a computer to run the MIDI software.

sensor is able to detect any approximation of another person, as shown in figure 14, as well as the multimedia extension.

VI. Conclusion

In this article we showed that a polar liquids, e.g. water can act as a magnifier for measuring human proximity through monitoring of self-capacitance of a conductive object. This effect is also propagated through several adjacent water containers. It shown that $P_{v_{max}}$, the maximum distance between the human hand and the container, at which proximity can be detected, depends on several factors, including the sensor size, container size and the water volume. The magnification of the detection range of capacitive sensors with proximity of water is also interesting due to the presence of water in many objects and living beings. For example, if the human body is connected to a capacitive sensing element, also the human body works as a magnifier. This can be used to detect human-human or human-robot approaching with application in HMI and HRI. It can be also used in ambient-assisted living and large area human/animal surveillance through a low-cost mesh of active-passive sensor nodes, in which the signal for each active node is magnified by several passive elements.

VII. Acknowledgment

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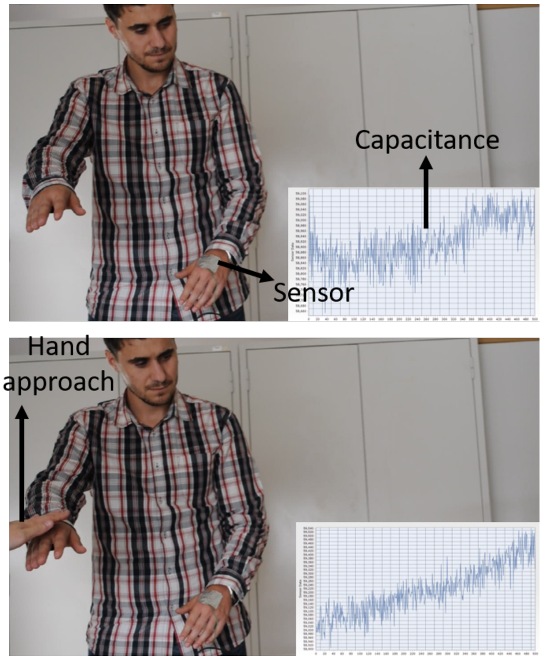

Fig. 14: Sensor placed on a person and the continuous read of the capacitance which increases with the approach of another person.

VIII. Multimedia Extension

The multimedia extension shows the magnification of the detection range of capacitive sensors with water and the effect of the second container. Furthermore it presents two cases studies. First signal propagation is demosntrated through a water baloon piano set-up which is implemented based on adjacent water containing baloons and a single capacitive sensor is presented. Then, the increase on the proximity range with the human body is shown.

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