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MEASUREMENT METHOD FOR SENSITIVITY ANALYSIS OF PROXIMITY SENSOR AND SENSOR ANTENNA INTEGRATION IN A HANDHELD DEVICE

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Abstract—A method for measuring the sensitivity of a capacitive proximity sensor and an application using the sensor as a proximity detector in mobile phone antennas is presented. 2D sensor data plots were physically more exact for tuning sensor placement. 3D sensor data plots were suitable for sensor intensity comparison, highlighting sensor differences in multiple sensor applications and effects in sensor's output due to shadowing mechanical objects. The antenna proximity sensor was measured and optimised with sensitivity measurements. In a PIFA application the antenna load could be detected from both sides and from above the antenna on a scale of $4.03 \cdot 10^{-14}$ F to $4.33 \cdot 10^{-14}$ F. The cases present all possible positions of holding a phone used in either the "calling" or "browsing" mode. The method and the application emphasise the physical sensitivity and electrical fields of the sensor. The characteristics can be further improved by using other sensor types, sensor data fusion and advanced imitation of multisensory spatial interaction by humans and animals.

1. INTRODUCTION

Tactile, motion and presence sensors are widely used in companies that utilise process automation. Sensors that measure slightly different physical features in automation devices, robots, or handheld devices

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are usually placed in difficult physical locations as a result of the widespread trend of saving room in electronics. From the designer's point of view, noise and ambient circumstances complicate sensing. Therefore, new capabilities not fully offered by current techniques are needed for the design process of devices and sensors. Software development trends such as open source code and reconfigurable platform characteristics offer a new type of product development and a new user experience in terms of products, and various physical sensors are needed. The combination of different sensors such as tactile, presence and machine vision is climbing into new convergence [1, 2].

The advantages of proximity sensors are precise sensing of geometric positions. Contactless sensing of objects and process events provide fast switching operation with a nearly unlimited amount of switching cycles. Monitoring and safeguarding processes are typical environments where proximity sensors are used for detection of occasions and faults. Tactile and pressure sensors are often implemented in force sensor usage such as robot gripping, device contacts or human safety issues. Current problems are high cost, difficulty in measuring in complex conditions and fusion of different sensor data [3–6]. Several applications, such as parallel manipulators in robots [5, 8], need multiple proximity sensors. Robots used in human environments have to use adaptation in order to execute complicated tasks in 3D space. The number of degrees of freedom is increased, which further leads to complicated alternative situations and problems have to be solved with incomplete information.

Capacitive sensors are a sensor type widely used for proximity detection. They are used for safety functions in chainsaws (10-cm distance) [7], in robot hand applications (0–8-cm distance) [8] and for seat occupancy sensing in cars [9], at operating frequencies of 80 kHz, 250 kHz and 500 kHz, respectively.

This paper describes the use of capacitive sensors in mobile phones. User proximity causes detrimental effects in the antennas of handheld devices, since human tissue in close proximity decreases the phone's efficiency. Much energy is consumed and shorter battery life hinders use of the devices [10–14]. The mentioned effect in phones cannot be fully compensated with current techniques [15, 16]. One technique for detecting user-antenna proximity is a capacitive proximity sensor; the method for evaluating the proximity effect is introduced in [17, 18]. Proximity sensors have to be combined with impedance matching or antenna selection techniques in order to realize the benefits of the sensor system. A capacitive sensor can sense the user proximity effect regardless of antenna matching, which is complexly changed when more than one electrical resonance is used in the same band or when matching is modified by a resistive component, e.g., human tissue absorption. In addition, capacitive sensors sense all antennas in multiple antenna applications. This characteristic saves time and energy, since the communication signal is not used for sensing purposes. Obviously, due to the room-saving trend of recent years, extra room for capacitive sensors is not available. Thus, sensors have to be designed without extra room requirements in current devices.

The combination of proximity sensors and limited availability of room challenges designers and devices. Capacitive sensors offering a simple sensing method attract interest but are skipped due to room limitation issues. A method for evaluating the effectivity of capacitive sensors is presented in detail here. The method is based on figuring out the sensitivity of the sensor in terms of an object's geometrical position. It can be used to compare different sensors or different sensor locations. A proximity sensor can be shadowed by many other objects inside the device, e.g., connectors and metal frames. This evaluation method can help the designer select optimum sensors for the device under design, saving time and resulting in a better final user experience.

This paper presents a method for evaluating the sensitivity of a capacitive sensor implemented in a mobile phone. Section 2 describes the details of the method, the system and calibration to measure the sensitivity of the sensor. Section 3 presents measurement results in a mobile phone antenna application. A discussion and conclusion are presented in Sections 4 and 5.

2. MEASUREMENT SYSTEM

The sensitivity of a sensor as a key design parameter is dependent on the place where the sensor is located. Sensitivity can be presented as the sensor output in terms of an object's geometrical position, i.e., the object's distance from the sensor. The object should resemble a real object as much as possible, which means that in the detection of human presence the object has to resemble human tissue at low frequency (16 kHz). Furthermore, sensors behind shadowing objects such as metal cases have to be measured in real usage conditions. Under these circumstances, the final product, having mature and robust testing behind it, is able provide a positive user experience.

Figure 1 shows a sensitivity measurement system for a capacitive sensor in the case of a mobile phone. The method can be applied in the same manner in corresponding products. The system consists of a device under test (DUT) and a movable load representing a phantom finger in this study. The phantom finger is a finger-sized plastic package filled with Indexar^{TM} liquid, which has electrical parameters

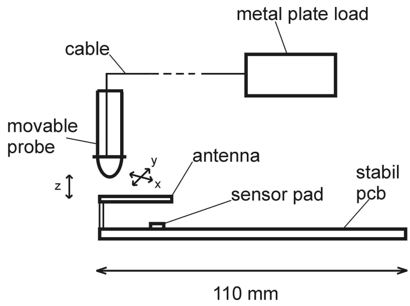


Figure 1. Sensor sensitivity measurement bench. The DUT, consisting of a PCB, antenna and sensor, is kept in a stabile position. A movable probe (60 mm length, 13 mm diameter) filled with Indexar$^{\mathrm{TM}}$ liquid is connected by a metal ring (14 mm diameter) and a 50-cm cable to a metal plate load (25 cm $\times$ 40 cm $\times$ 1.5 cm). Z is 3 mm, and the antenna-to-PCB distance is 10 mm.

characteristic of human tissue at high frequencies. The output of the sensors varies in terms of the load distance and position. What is specific in this product is that the sensor is overshadowed by the antenna pattern. It is grounded, and therefore it prevents optimal coverage above the product. On the other hand, it operates as a shield between the sensor and the load. In the current workbench the DUT is permanently positioned and the load can be moved in a 3D matrix. The phantom finger has a length of 60 mm and diameter of 13 mm. The load consisting of the Indexar$^{\mathrm{TM}}$-filled finger was measured to have a weaker electrical response than a real human finger. Thus, it was connected to large metal plate with a 50-cm-long cable. The end of the cable consists of a ring (diameter 14 mm) that can be moved vertically along the finger. The ring position was used to calibrate the load for an electrical effect equal to that of a real finger. Obviously, this kind calibration is valid for a low-frequency sensor signal, not for a RF signal.

The measurement outline seen from the XY plane with a measurement grid is presented in Fig. 2. The area covered with 10-mm grid points corresponds to normal finger dimensions. PCBs are normally used at a 3-mm or 13-mm distance from the back cover in mobile phones, which defines the Z dimension in this research. At the specific Z (3 mm) distance the XY plane was measured in steps and the values were recorded. Then results were converted into 2D maps presenting the sensor's sensitivity in measured conditions. The design was continued to the iterative process, in which the DUT was modified and measured several times. The optimised sensitivity was documented

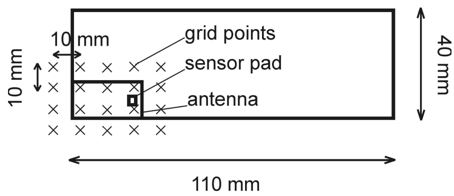


Figure 2. XY plane of a sensitivity map of the sensor is measured within a 10-mm grid, 3 mm above the desired area.

and sufficient levels for object existence could be defined. These levels can be used to programme the sensor for utilised applications.

2.1. Measurement Calibration

Calibration is important, and the sensitivity measurement system has to be calibrated for an object that imitates a real object as closely as possible. Otherwise there is a risk that the user experience or a corresponding characteristic is insufficient. Additionally a sensor's weak characteristics are difficult to correct with signal processing or other data fusion systems. On the other hand, weak characteristics constantly load the processor and waste energy.

In this research, the load to be detected is a real human finger, which itself cannot be used in the measurements. This kind of calibration is needed for all devices or robots used in contact with living tissue. Phantom hands or fingers have been designed and reliably used in high-frequency antenna measurements [13, 14]. In this study, a plastic finger-sized object was filled with Indexar liquid, which is characterized by the manufacturer to have electrical properties equivalent to human tissue properties at RF frequencies. Indexar liquid is designed for high-frequency use. According to our tests, the phantom finger induced only 10% of the capacitive load measured with the researcher's finger. Due to that, a metal ring, cable and metal plate were used to increase the load of the phantom finger. The idea of the external load was to characterize the effect of the human body in the results. The calibration measurements were started by measuring the real finger load as a reference value (from a 3-mm distance). The real finger was removed and replaced with the phantom finger (and accessories). Then a calibration adjustment was performed where the ring was moved vertically along the finger until the measured reference value was reached. That position corresponds to the real finger effect on the sensor and it was used in the following measurements.

3. RESULTS

Due to the fact that mobile phone antennas are susceptible to the human proximity effect, causing both de-tuning and absorption [10–12], the function of a proximity sensor is to locate the user's hand or finger in close proximity to the antenna. Ideal sensing functionality requires that all possible directions can be detected. In this application, at least two sensors had to be used to detect the finger on either the top, the side or the end of the phone. The size of the sensor has to be small enough to avoid inducing RF losses in the antenna. The requirements are met by the structure presented in Fig. 3. The sensor pads were connected together so that the capacitance measurement circuit used (Analog Devices 7747) saw them in parallel.

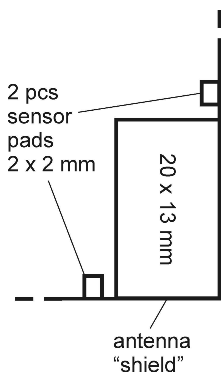


Figure 3. Zoomed-in outline of a PIFA fitted with two 2 mm × 2 mm proximity sensors on the PCB under the antenna.

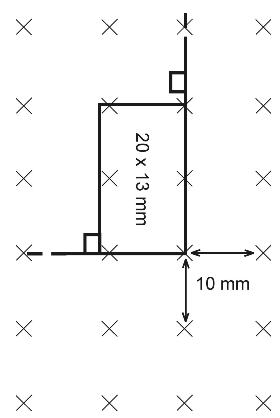


Figure 4. Grid of measurement points of the sensitivity measurement map (4 × 7 points).

After arranging the sensor places, a measurement grid was located over the area of interest. An override of 10 mm was enough for this application, having a total of 4 × 7 points, as presented in Fig. 4.

The measured sensitivity results are presented as coloured maps in Fig. 5. Bright colours like red and yellow represent more sensitive areas and dark colours indicate less sensitive areas. The maps are presented in MS Excel 2D/3D surface format and the outline of the antenna is drawn in the figure where applicable. As stated earlier, sensors should cover the areas critical from the antenna point of view. This particular knowledge comes from the product designers, especially from the antenna designer in this study. Sensor output was measured as the

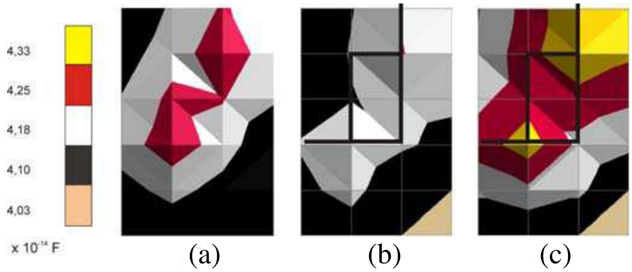


Figure 5. Measured capacitance map results. (a) Capacitance map without an antenna, (b) capacitance map with an antenna, (c) capacitance map with extended sensors, i.e., 5-mm-high metal probes on the sensor pads.

combined capacitive load of both sensors. The load was measured to be $4.25 \cdot 10^{-14}$ F without the antenna (Fig. 5(a)). After installing the antenna (Fig. 5(b)), the capacitance decreased to $4.18 \cdot 10^{-14}$, caused by the shielding effect of the grounded antenna pattern. The grounding works as an effective shield for 16 kHz sensors. In order to correct the effect, the sensors were equipped with 5-mm-high metal sticks, i.e., electronic test probes. Now the measured sensitivity map with the sticks was measured (Fig. 5(c)), reflecting an increased capacitance of $4.33 \cdot 10^{-14}$ F. Thus, sticks can increase maximum available sensitivity, but they are not necessary in all cases. The trigger level can be selected to be, e.g., $4.15 \cdot 10^{-14}$ using proper software for starting operations to find a better radio channel. However, this paper does not cover a system-level study concerning further actions after detecting a high antenna load.

The sensor optimisation is presented in detail in Fig. 6. Fig. 6(a) presents the sensitivity map in the first "guess" location. Compared with the results with the product in Fig. 2, the corner is not fully covered by the sensors. In order to achieve a robust, reliable and definite user experience, the coverage had to be improved. Thus the sensor locations had to be slightly modified. The sensor closer to the corner (Fig. 3) was moved to the right in the figure and the resulting measured coverage is presented in Fig. 6(b). The new location gives more applicable coverage for the product requiring reliable detection at the side, top and above parts of the antenna.

The objective of this sensor design method is to visualise sensitivity. The visualisation itself as a qualitative method helps human designers design with high productivity. Sensitivity maps have to be printed in different forms for evaluation and the most informative

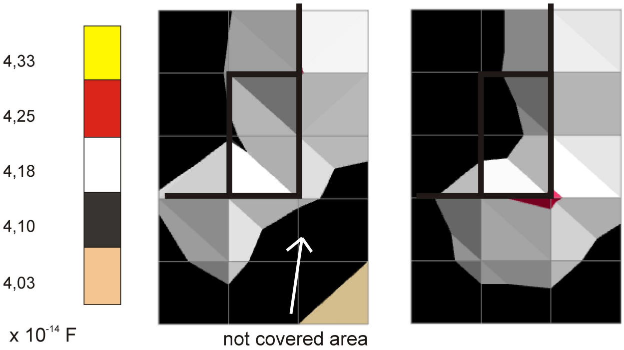


Figure 6. Measured capacitance map results (a) corner not covered by sensors, (b) corner covered with a new sensor location.

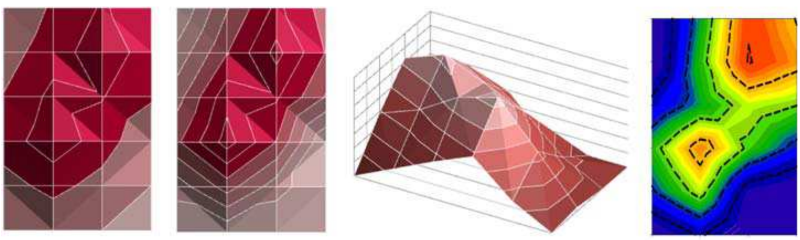
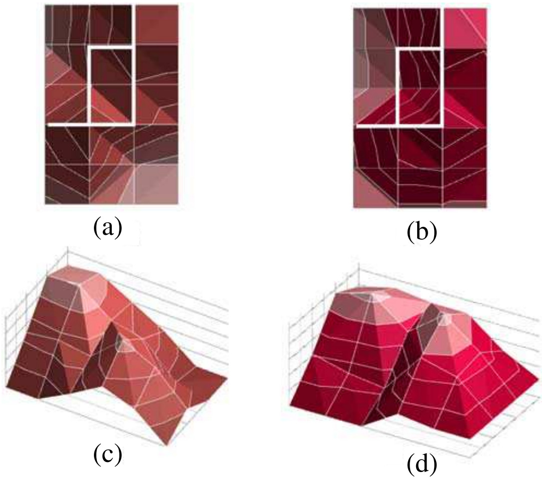


Figure 7. Sensitivity output maps printed out in different forms as Excel surface maps. (a) Output scaled in 4 steps through the capacitive range of 4.03–$4.33 \cdot 10^{-14}$ F. (b) 8 step sizes used. (c) Same map printed in 3D form. (d) Same map printed with a SigmaPlot 2D mesh.

of them selected. A colour plot with step lines is presented in Fig. 7(a), with step lines of higher density in 7(b) and a corresponding 3D plot in Fig. 7(c), which highlights the general impression of the shape. The figures are presented with Excel, but the 2D data is also presented with SigmaPlot as a 2D mesh plot in Fig. 7(d). 3D was found to be physically less accurate presentation than 2D for adjusting sensor placement by human eye. That's why values of the measure axis can be read straightforwardly from 2D plots but not from 3D plot since the angle of the figure is not rectangular. Fig. 7(b) perhaps presents the map in the most substantial way for design from the human eye point of view.



(a) (b) (c) (d)

Figure 8. Sensitivity output representing the corner coverage case. The capacitance range is $4.03\text{–}4.33 \cdot 10^{-14}$ F. (a) First state of sensor position with the maximum peak on the left side. (b) Second state with the maximum peak moved to the right side. (c) First state in a 3D drawing. (d) Second state in a 3D drawing.

For further evaluation the 3D plots are compared with 2D plots in Fig. 8. The 2D and 3D forms both present their own basis for sensor adjustment. Whereas the 2D figures work for physical placement selection, the 3D figures are applicable for sensor intensity evaluation. The intensity difference between Figs. 8(c) and 8(d) is caused by the antenna ground pin located physically closer to the sensor in Fig. 8(c). In that case, the sensor–ground pin distance is 1 mm (Fig. 8(c)), whereas it is 5 mm in Fig. 8(d). The intensity near the pin is lower than it is further away. The effect is not clearly seen in the 2D figures of 8(a) and 8(b). Human eyes are locked on the physical placements in 2D figures, and the intensities in 3D figures. In contrast to that, the intensity difference between the sensors in 2D figures is difficult to notice with eyes, whereas the exact values for xy-locations of sensors are not straightforwardly seen from the 3D figure since the angle of the figure is not rectangular. In conclusion, the physical position of the sensor can be adjusted by using 2D pictures and the intensity information is a valuable design parameter taken from 3D pictures.

As room is very limited in recent electronic products, the sensor's efficiency has to be measured in close proximity to the metal case or in the corner of the case. For example, metal connectors can form

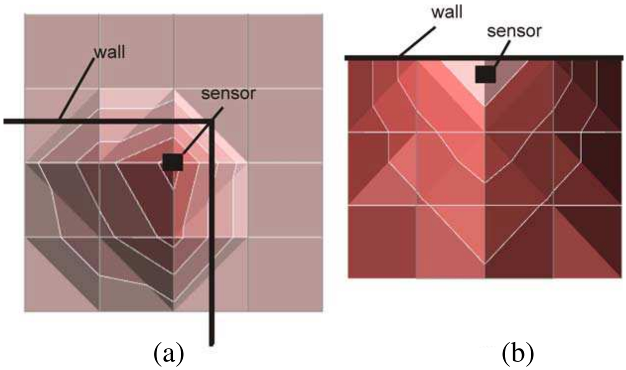


Figure 9. (a) Sensor located in a corner of a 7-mm-high metal case, which directs the sensitivity field into the open direction — A capacitance range of $1.812 \cdot 10^{-14}$–$1,841 \cdot 10^{-14}$ F was measured. (b) Sensor located beside a 7-mm-high metal case that directs the field into the open direction — a capacitance range of $1.836 \cdot 10^{-14}$–$1,860 \cdot 10^{-14}$ F was measured.

5–10-mm-high metal objects on the PCB. Free locations for capacitive proximity sensors are usually found near these objects. The corner effect on the sensors is presented in Fig. 9(a). The field distribution itself can be self-evident for experts, but without documentation it easily fails in some products. The sensor is shadowed from two directions, which information can be used to ensure the product's operation, or then the sensor can be steered in the desired directions. Obviously, the information can be combined with the metal stick techniques mentioned in Fig. 5(c), resulting in improved sensitivity. Another factor that changes the sensitivity field is the presence of a side object. A side sensitivity map is presented in Fig. 9(b). The shadow effect is effective and corresponds to that in the corner case. The field of the sensor can be directed in the desired direction or it can be seen as a weakness; high metal objects shadow the effective usage of the sensor. In order to improve the sensor system, metal sticks or additional sensors can be utilised. In conclusion, the measurement method presented in this paper should be used in order to achieve mature and robust sensor functions and especially to get positive user experiences from the device.

4. DISCUSSION

Proximity sensors used as safety products in chainsaws, as robot hands or as seat occupancy sensors in cars have physical sizes of 25 cm^2 or 30 cm^2 to 16 $\mu\mathrm{m}^2$ [7–9], having a high size variation caused by different realisations. Some are manufactured as large physical electrodes, whereas others are integrated into IC electronics. Large electrodes have higher natural sensitivity since the area increases their physical coverage. Small size and integration limit coverage and sensitivity. The sensitivity measurement method is especially advisable for small sensors. Furthermore, electronics packages can have various shielding effects due to, e.g., bonded wires or metal frames that are used as connectors or electromagnetic radiation shields. It is recommended that final products are tested from the sensor sensitivity point of view, knowing that measurements are quickly arranged with the presented test bench system.

In current applications, mobile phone antennas are sensitive to the proximity of dielectric or conductive material [10–14]. This characteristic and its deteriorating effects on the phone can be decreased by using sensors and correction methods [15, 18]. The placement of sensors is challenging because of limited room and the hand/finger load varies in terms of direction and intensity. Additionally the antenna causes shielding effects for the sensor. Sensitivity measurements are a key method for achieving reliable sensor usage in this challenging application. Large coverage, sensibility and cheap realisation are benefits that offer a good background for positive user experiences in the final product.

Proximity sensor research is going on with electrical-field-forming components [19] and sensor signal processing [20]. The direction of these studies supports this research. The efficiency of a single sensor can be increased by improving materials and optimising structures [19]. Different types of sensors, their characteristics such as resolution, range limitation, bias, variance, update rate, and environmental changes such as temperature, scale-factor effects and noise need signal processing and sensor data fusion in order to make the right decisions in terms of that information [20]. Various examples of robot applications represent the most challenging environment in the field, since the robots used in real life, as people know, are surprising and changing all the time [3–6, 8]. Additionally, natural human sensing and sensor data fusion are imitated in a combination of tactile and eye coordination systems [1], which has been under research in [2]. Previous studies are very valuable and they can be complemented by the sensitivity measurement method presented in this paper. Improved user experiences (in the case of handheld devices) can be fulfilled and assured by combining those sensor studies and methods together.

5. CONCLUSION

This paper presented a method for measuring the sensitivity of a capacitive proximity sensor and an application where the sensor was used as a proximity detector of a mobile phone antenna. 2D sensor data plots were more exact for tuning of sensor's physical placement with human eyes. 3D sensor data plots were more suitable for sensor intensity evaluation, which highlights the differences between sensors in multiple sensor applications or effects in sensor's output due to shadowing mechanical objects. The designer can get a better understanding of sensor shielding objects from 3D plots than from 2D plots. It is clear that the design of sensor applications should be arranged by using them simultaneously.

An antenna proximity sensor was measured and optimised with sensitivity measurements. In the current application the antenna load could be detected from both sides and from above the antenna on a scale of $4.03 \cdot 10^{-14}$ F to $4.33 \cdot 10^{-14}$ F. The cases present all possible positions of holding a phone used in either the "calling" or "browsing" mode. The requirements are met with two sensors located on the PCB at opposite ends of the antenna and close to the PCB sides.

This paper, the method and the application emphasise the physical sensitivity and the electrical fields of the sensor. The characteristics can be further improved by using other sensor types, sensor data fusion and advanced imitation of multisensory spatial interaction by humans and animals.

REFERENCES

1. Macaluso, E. and J. Driver, "Multisensory spatial interactions: A window onto functional integration in the human brain," *Trends in Neurosciences,* Vol. 28, 263–271, 2005.
2. Laschi, C., G. Asuni, E. Guglielmelli, G. Teti, R. Johansson, H. Konosu, Z. Wasik, M. C. Carrozza, and P. Dario, "A bio-inspired predictive sensory-motor coordination scheme for robot reaching and preshaping," *Autonomous Robots*, Vol. 25, No. 1–2, 85–101, 2008.
3. Yamada, Y., T. Morizono, and Y. Umetani, "Highly soft viscoelastic robot skin with a contact object-location-sensing capability," *IEEE Trans. Ind. Electron.*, Vol. 52, No. 4, 960–968, Aug. 2005.

4. Ohashi, E., T. Aiko, T. Tsuji, H. Nishi, and K. Ohnishi, "Collision avoidance method of humanoid robot with arm force," *IEEE Trans. Ind. Electron.*, Vol. 54, No. 3, 1632–1641, Jun. 2007.
5. Tsuji, T., K. Ohnishi, and A. Sabanovic, "A controller design method based on functionality," *IEEE Trans. Ind. Electron.*, Vol. 54, No. 6, 3335–3343, Dec. 2007.
6. Iwata, H. and S. Sugano, "Human-robot-contact-state identification based on tactile recognition," *IEEE Trans. Ind. Electron.*, Vol. 52, No. 6, 1468–1477, Dec. 2005.
7. Norgia, M. and C. Svelto, "RF-capacitive proximity sensor for safety applications," *IEEE International Instrumentation and Measurement Technology Conference*, 1–4, May 2007.
8. Lee, H.-K., S.-I. Chang, and E. Yoon, "Dual-mode capacitive proximity sensor for robot application: Implementation of tactile and proximity sensing capability on a single polymer platform using shared electrodes," *IEEE Sensors Journal*, Vol. 9, No. 12, 1748–1755, Dec. 2009.
9. George, B., H. Zangl, T. Bretterklieber, and G. Brasseur, "A combined inductive-capacitive proximity sensor and its application to seat occupancy sensing," *IEEE International Instrumentation and Measurement Technology Conference*, 13–17, May 2009.
10. Pelosi, M., O. Franek, M. B. Knudsen, M. Christensen, and G. F. Pedersen, "A grip study for talk and data modes in mobile phones," *IEEE Transactions on Antennas and Propagation*, Vol. 57, No. 4, 856–865, Apr. 2009.
11. Krogerus, J., J. Toivanen, C. Icheln, and P. Vainikainen, "Effect of the human body on total radiated power and the 3-D radiation element of mobile handsets," *IEEE Transactions on Instrumentation and Measurement*, Vol. 56, 2375–2385, Dec. 2007.
12. Berg, M., M. Sonkki, and E. Salonen, "Experimental study of hand and head effects to mobile antenna radiation properties," *Proc. 3rd Eur. Conf. on Antennas and Propagation,* 437–440, Berlin, Germany, Mar. 23–27, 2009.
13. Li, C.-H., E. Ofli, N. Chavannes, E. Cherubini, H. U. Gerber, and N. Kuster, "Effects of hand phantom and different use elements on mobile phone antenna radiation performance," *IEEE Antennas and Propagation Society International Symposium,* 1–4, Jul. 2008.
14. Ofli, E., C.-H. Li, N. Chavannes, and N. Custer, "Analysis and optimization of mobile phone antenna radiation performance in the presence of head and hand phantoms," *Turk. J. Elec. Engin.*, Vol. 16, No. 1, 67–77, 2008.

15. Ranta, T. and R. Novak, "Antenna tuning approach aids cellular handsets," *Microwaves & RF*, 82–92, Nov. 2008.
16. Komulainen, M., M. Berg, H. Jantunen, E. T. Salonen, and C. Free, "A frequency tuning method for a planar inverted-F antenna," *IEEE Transactions on Antennas and Propagation*, Vol. 56, 944–950, 2008.
17. Myllymaki, S., A. Huttunen, M. Berg, M. Komulainen, and H. Jantunen, "Method for measuring user-induced load on mobile terminal antenna," *Electronics Letters*, Vol. 45, No. 21, 1065–1066, Oct. 2009.
18. Myllymaki, S., A. Huttunen, V. K. Palukuru, H. Jantunen, M. Berg, and E. T. Salonen, "Capacitive recognition of the user's hand grip position in mobile handsets," *Progress In Electromagnetics Research B*, Vol. 22, 203–220, 2010.
19. Abu-Abed, A. S. and R. G. Lindquist, "Capacitive interdigital sensor with inhomogeneous nematic liquid crystal film," *Progress In Electromagnetics Research B*, Vol. 7, 75–87, 2008.
20. García, J. G., J. G. Ortega, A. S. García, and S. S. Martínez, "Robotic software architecture for multisensor fusion system," *IEEE Trans. Ind. Electron.*, Vol. 56, No. 3, 2009.