# Kent Academic Repository
## Full text document (pdf)

## Citation for published version

Batchelor, John C. and Yeates, Stephen and Casson, A.J. (2016) Conformal electronics for longitudinal bio-sensing in at-home assistive and rehabilitative devices. In: IEEE 38th Annual International Conference of the Engineering in Medicine and Biology Society (EMBC), 2016, 16-20 August 2016, Orlando, US.

## DOI

https://doi.org/10.1109/EMBC.2016.7591399

## Link to record in KAR

http://kar.kent.ac.uk/61763/

## Document Version

Publisher pdf

# Conformal electronics for longitudinal bio-sensing in at-home assistive and rehabilitative devices

John C. Batchelor, *Senior Member, IEEE*, Stephen G. Yeates and Alexander J. Casson, *Senior Member, IEEE*

*Abstract*— Wearable electronics are revolutionizing personalized and preventative healthcare by allowing the easy, unobtrusive, and long term monitoring of a range of body parameters. Conformal electronics which attach directly to the skin in a very robust and long term manner are envisioned as the next generation of highly portable miniaturized computing devices, beyond wearables. In this paper we overview the state-of-the-art in conformal electronics created using silver nanoparticle inkjet printed techniques for home assistive and rehabilitative devices. The barriers to wider adaption, particularly the challenges of high performance antenna design when placed close to the body, are discussed in detail.

## I. INTRODUCTION

The ubiquity of smartphones is transforming personalized, preventative, and out-of-the-clinic healthcare. In many societies each individual now carries an always on, always connected, electronic device which has a high level of computational power and a number of input sensors for collecting information. This sensor data can be passed to a data centre for real-time analysis and feedback, or used for longitudal data collection to give a long term picture of the subject, their behavior, and how it changes. For example, smartphone *apps* have been released for everything from activity tracking [1], to non-invasive blood glucose monitoring [2].

While there is undoubtedly much work to do on such apps (improving their performance, trustworthiness, and integration into health systems around the world) out-of-the-clinic health and social care driven by advances such as the smartphone are now seen as central to many next generation healthcare systems [3]. Worldwide, the costs of healthcare provision are increasing, and the effect of this is compounded by the world's ageing population. Making healthcare technologies that work beyond the clinic is widely seen as a potential solution to these challenges [4]. It is envisioned that these could enable: more remote healthcare which uses fewer institutional resources; more preventative healthcare where the user takes on a more proactive role; and more personalized treatment and rehabilitation which is tailored based on longitudinal data of the individual.

Behind this transformation is the rapid advancement of computing power and microelectronic miniaturization, of which smartphones are just one part, Fig. 1. As precursors to the smartphone, in the 1990s and 2000s Internet technologies and at-home desktop and laptop computers enabled tele-health and tele-rehabilitation applications for the first time [5], allowing consultations and treatments to be delivered without the need to travel to a clinic.

As follow-ons to the smartphone, wearable electronics are now being used to longitudinally collect bio-signal information about users in an easy-to-use and non-obtrusive manner. Activity trackers such as the fitbit [6] are the most successful initial devices, and a wide number of *smartwatches* are now becoming available that include activity tracking, photophelsmograpgy for heart monitoring, and a number of other sensing modalities (see [7] as just one example). Indeed a wide-range of health-related wearable products are now available for everything from gait [8] to brainwave [9] monitoring.

*Conformal electronics*, also known as epidermal electronics, are seen as the next step in this rapid advancement of computing power and microelectronic miniaturization [10], [11], Fig. 1. Unlike wearable devices, conformal devices use non-permanent *tattoo-like* substrates to connect directly to the skin without requiring a strap or similar. The result is that the devices maintain a high quality connection to the body for many days at a time, and because they follow the contours of the skin they get a much higher contact area. This gives better quality signals and maintains signal-to-noise ratios even at very small sensor sizes. As such they intrinsically overcome the limitations of wearable devices, giving better signal quality, longer term connections to the body, and a more discrete profile for better social acceptability.

An emerging method for manufacturing conformal electronics is to use inkjet printing to deposit conductive silver nanoparticle inks onto a tattoo paper substrate [12]. As a rapid prototyping, additive manufacturing approach, inkjet printing can allow manufacturing with minimal waste, ideal for sensor nodes to be created in large numbers and then disposed en-mass after use. It is also compatible with a range of substrates to achieve tattoo-like connections to the skin.

In this paper we draw on examples from our previous work to overview the state-of-the-art in conformal sensor nodes manufactured in this way, highlighting the challenges to their wider adoption. In Section II we propose a new three-tier classification of the sensing challenges that must be tackled in order to deliver conformal sensor devices for health and social care. In Section III we consider the key technology challenges to be tackled in order to improve performance.

Fig. 1. The miniaturization of computing power from large desktop PCs in the 1980s to highly portable smart-watches in the 2010s. *Conformal electronics* are envisioned as the next step in this miniaturization process, giving electronic sensors that attach directly to the skin and provide very high quality data over long time periods. Conformal electronics picture taken from [10].
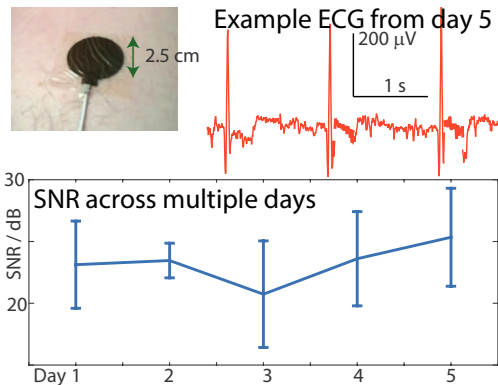


Fig. 2. Our conformal ECG electrodes reported in [15] maintain a connection to the body for 5-days at a time.

## II. SENSING CHALLENGES

For home assistive and rehabilitative devices there are a wide number of non-invasive physiological parameters that are of interest to collect: temperature; electrocardiography (for heart rate and heart rate variability); strain; pressure; sweat analysis (for example for glucose monitoring); galvantic skin response; and activity; to name a few. For example, heart monitoring has been used to optimize at-home rehabilitation routines [13], while pressure sensing can be used to monitor foot pathologies, such as diabetic foot ulcers, to prevent them from occurring and to optimize their treatment [14].

### A. Current state-of-the-art

The current research challenge is to map the above modalities into sensors that are compatible with conformal substrates. To consider, for space a single example, our previous work has demonstrated conformal ECG electrodes made using a silver nanoparticle inkjet printing process [15], Fig. 2. As a rapid prototyping approach, inkjet printing can allow personalization of electrode sizes and shapes, giving a substantial advantage over conventional Ag/AgCl ECG electrodes. Further, the longest we have kept the electrodes on for a single application is 5 days. As shown in Fig. 2 there is variance in the ECG Signal-to-Noise Ratio (SNR) (defined as the R peak amplitude to the root-mean-square amplitude of the trace between R peaks) over this time, but the SNR, and hence signal quality, is maintained.

Even from this brief example it is easily seen that there are a large number of performance factors, from signal quality to longevity, that describe the sensing performance. However,

as the development of conformal sensors is at an early stage it is rare to see all of these factors reported in a single place. Here we propose a new taxonomy of these sensing effects into three orders. The objective is to allow the clear identification of the state of a conformal sensor development, and to allow its progression to be tracked over time. To date, many conformal sensor nodes report only the first order performance and the research frontier is in characterizing and optimizing the second and third order effects to drive future healthcare take-up.

### B. First order effects: Functionality

In designing a new sensor the first order challenge is to demonstrate functional testing: that the wanted physical signal can indeed be detected by the proposed transducer. For example, we have previously demonstrated that strain sensing [16], temperature sensing [17], and liquid presence sensing (for wet nappy detection in social care scenarios) [18] modalities are possible on inkjet printed tattoo substrates.

### C. Second order effects: Non-ideal factors

Once it has been shown that the wanted signal can be fundamentally collected, the second order challenge is to characterize the non-ideal sensor properties. There is a wide list of such factors, both technical and non-technical. The technical effects include sensitivity, contact noise, and motion artifact/interference susceptibility which will be common to nearly all sensing modalities. Other technical factors will be modality specific. For example for electrophysiological sensors factors of key importance are: the contact impedance, the half-cell potential and baseline wander.

Non-technical effects can be again split, into: user factors, principally comfort, attachment duration, ease of application; and manufacturing factors, principally cost, time, ease of access, and potential for personalization.

### D. Third order effects: Variability

The third, and final, order challenge is to quantify variability in the first and second order effects. The performance parameters obtained will always have an amount of variance present, requiring a spread of values to be reported.

More significant is *non-constant-ness* due to non-linearity in the sensor response, or a hysteresis effect, or simply variance with time. Conformal sensors may attach to the body for very long periods, and will be subject to wear-and-tear, component ageing, and changes in the skin under
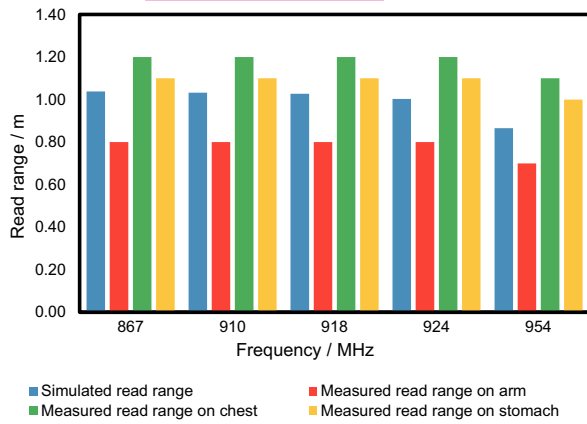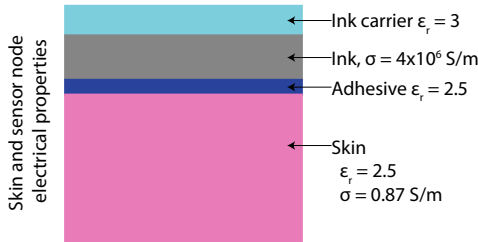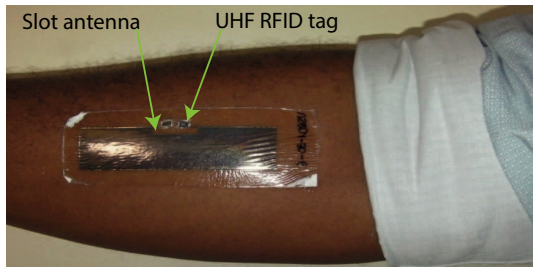
3160

Fig. 3. Cross-section of the conformal sensor capacitive loading. This significantly compromises the performance of the wireless antenna used.

the sensor over time. All of these may affect the *order 1* and *order 2* performance characteristics, as seen in Fig. 2.

## III. MANUFACTURING CHALLENGES

### A. Antenna design

Wireless transmission of the data from conformal sensors is essential for connectivity, allowing physiological data to be passed to a smartphone or into the Cloud in real-time. However, the electronics, and particularly the antenna, are separated from the skin by an adhesive layer which is approximately 10 $\mu$m thick, Fig. 3. As a result the entire sensor node is capacitively coupled to the skin, and this significantly loads the wireless antenna and reduces its performance.

The conductivities and relative permittivities of the inkjet printed conformal sensor manufacturing stack are shown in Fig. 3, together with measured results showing the read ranges that can be achieved from sensors on different parts of the body. These results are collected using VoyanticLite equipment and for a conformal antenna set up to transmit in the UHF (Ultra High Frequency) RFID (Radio-Frequency IDentification) band (860–960 MHz). Typical distances in the 1 m range are achievable, sufficient to reach a nearby smartphone, but well below the approximately 10 m read range of unloaded UHF RFID devices.
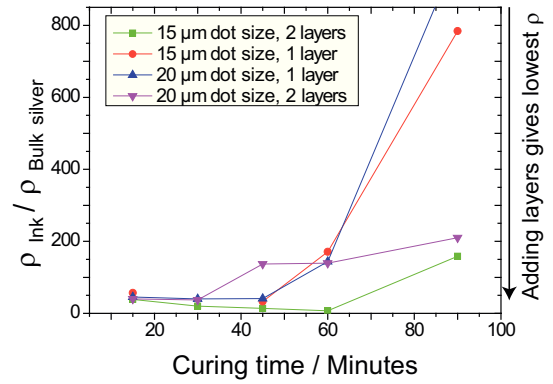


Fig. 4. Sintering at 135° C for 30 minutes (60 minutes in the 2 layer 15 $\mu$m dot size case) can lower the resistivity ($\rho$) of the deposited silver.

The distance is a strong function of where on the body the antenna is placed, with the arm (the standard smartwatch location) performing particularly poorly, and the chest performing particularly well. This suggests that current conformal approaches may be particularly suitable for ECG-type sensing, worn inconspicuously under clothes on the chest. Nevertheless it is likely that higher read ranges are required for practical use, to avoid having to keep a smartphone always within 1 m of the body.

### B. Manufacturing optimization

The above antenna loading can be overcome by improving the antenna design (a particularly challenging task) or by altering the manufacturing process to improve the electrical properties of the ink deposition. Table I shows the theoretical read range as the number of inkjet printed conductive layers is varied for an NXP transponder chip with input impedance $(15-j128)\Omega$, obtained by VoyanticLite equipment. The read range increases by a factor of 3–4 for each additional layer of silver nanoparticle printing. However, this comes at the cost of requiring an additional *expensive* ink layer.

As an alternative (or additional) approach sintering can be used, heating the deposited material to a level below its melting point sufficient to allow the diffusion of material and an improvement in conductance. Fig. 4 shows how the resistivity ($\rho$) of a silver nanoparticle ink (Sun Chemicals SA 719048) varies with sintering time, when deposited onto a tattoo substrate. Sintering for up to 60 minutes at 135°C gives the tattoo deposited silver a resistivity comparable to silver deposited on non-flexible glass. However this comes at the cost of a deformation of the tattoo paper substrate, increasing its resistivity and decreasing its flexibility. Using current approaches there is thus a direct trade-off between the conductivity of the deposited ink and the flexibly of the conformal device, and hence its longevity. Substantial investigation into low temperature, ultrasonic, or photonic sintering on thermally sensitive substrates is required in order to improve performance further.

### C. System integration

Conformal batteries are an active area of investigation [19] but many current systems use external wires to connect the

## TABLE I
### Theoretical read range of antennas with different numbers of printed layers and conductors.

| Conductor | Manufacturing method (dot space / $\mu$m) | Number of layers | Conductor thickness / $\mu$m | Port-to-port d.c. resistance / $\Omega$ | Theoretical read range / cm |
|---|---|---|---|---|---|
| Silver ink | Inkjet printed (15) | 1 | 2.4 (avg.) | 116 | 12 |
| Silver ink | Inkjet printed (15) | 2 | 3.3 (avg.) | 14 | 37 |
| Silver ink | Inkjet printed (15) | 3 | 4.5 (avg.) | 11 | 54 |
| Copper sheet | Etching | 1 | 70 | 0.17 | 75 |

conformal sensors to a battery. However these wires are very difficult to keep connected over a long time period and the are weak point in the system. As an illustration, our ECG electrode designs are currently connected to conventional ECG recording electronics using a 1.5 mm touchproof connector adhered to the electrode using silver loaded paint. This gives a suitable method for easy prototyping of different electrode shapes and manufacturing processes, but the attachment of the wire severely limits the operation of the system: it falls out long before the electrode itself looses adhesion to the body. It can be re-attached, but this requires time, expertise, and introduces artifacts into the recording.

The alternative approach to system powering is to use RFID for *passive powering* where power is wireless transferred from a reader coil to the sensor device. Many current conformal systems use the well known NFC (Near Field Communications) standard in the 13.56 MHz range which allows sufficient power for a bio-sensor node to be transferred [20] but at the cost of very short read ranges, in the range of <10 cm. For UHF RFID the power transferred is much smaller, typically in the range of $\mu$W, but at longer read ranges. In both cases, the challenge for system integration is that the power source is potentially intermittent: power is only delivered when the user is within a set read range distance of a transmitter coil. This situation is similar to bio-sensing with a smartphone. For example photoplethysmography with a smartphone only works when the user starts the app, and then places their finger on the phone's LED flash and camera. Such intermittent sensing can still be highly useful, but it falls a long way short of long term continuous bio-signal acquisition.

### D. Access to manufacturing

Finally, access to the required printing processes is currently very limited and it is difficult to print devices in a timely manner without having an inkjet expert on hand. There is no easy solution to this, but the situation is changing and it is becoming easier to access silver inkjet printing foundries at lower cost. We predict that as this improves further over the next few years the field of conformal sensors for healthcare is going to advance and expand rapidly, giving access to sensors that can monitor bio-signals over days to weeks at a time, a timespan completely infeasible with current wearable approaches.

## IV. CONCLUSIONS

Conformal sensor nodes are starting to emerge as next generation devices for very long term human body monitoring.

Paired with passive RFID powering they are of substantial use in assistive technology and rehabilitation situations to allow *fit-and-forget* sensors that do not require multiple applications and battery changes. Greater access to the inkjet printing processes for fabricating the devices will rapidly expand their availability in the next few years.

## REFERENCES

[1] A. Anjum and M. U. Ilyas, "Activity recognition using smartphone sensors," in *IEEE CNCC*, Las Vegas, January 2013.

[2] S. Singhal, P. Ralhan, and N. Jatana, "Smartphone-based colorimetric detection to measure blood glucose levels," in *IEEE IC3*, Noida, India, August 2015.

[3] L. Piwek, D. A. Ellis, S. Andrews, and A. Joinson, "The rise of consumer health wearables: Promises and barriers," *PLoS Med.*, vol. 13, no. 2, p. e1001953, 2016.

[4] P. Bonato, "Wearable sensors and systems," *IEEE Eng. Med. Biol. Mag.*, vol. 29, no. 3, pp. 25–36, 2010.

[5] R. A. Cooper *et al.*, "Telerehabilitation: Expanding access to rehabilitation expertise," *Proc. IEEE*, vol. 89, no. 8, pp. 1174–1193, 2000.

[6] fitbit. (2014) Home page. [Online]. Available: http://www.fitbit.com/

[7] Simband. (2015) Home page. [Online]. Available: http://www.voiceofthebody.io/

[8] E. S. Sazonov, G. Fulk, J. Hill, Y. Schutz, and R. Browning, "Monitoring of posture allocations and activities by a shoe-based wearable sensor," *IEEE Trans. Biomed. Eng.*, vol. 58, no. 4, pp. 983–990, 2011.

[9] A. J. Casson, D. C. Yates, S. J. Smith, J. S. Duncan, and E. Rodriguez-Villegas, "Wearable electroencephalography," *IEEE Eng. Med. Biol. Mag.*, vol. 29, no. 3, pp. 44–56, 2010.

[10] D.-H. Kim *et al.*, "Epidermal electronics," *Science*, vol. 333, no. 6044, pp. 838–843, 2011.

[11] A. Nathan *et al.*, "Flexible electronics: The next ubiquitous platform," *Proc. IEEE*, vol. 100, pp. 1486–1517, 2012.

[12] V. Sanchez-Romaguera *et al.*, "Towards inkjet-printed low cost passive UHF RFID skin mounted tattoo paper tags based on silver nanoparticle inks," *J. Mater. Chem. C*, vol. 1, no. 39, pp. 6395–6402, 2013.

[13] J. Park, J. Cho, T. Nam, and J. Choi, "A unconstrained multi-channel heart rate monitoring system for exercising rehabilitation patients," in *IEEE EMBC*, Lyon, August 2007.

[14] L. Shu *et al.*, "In-shoe plantar pressure measurement and analysis system based on fabric pressure sensing array," *IEEE Trans. Inform. Technol. Biomed.*, vol. 14, no. 3, pp. 767–775, 2010.

[15] J. C. Batchelor and A. J. Casson, "Inkjet printed ECG electrodes for long term biosignal monitoring in personalized and ubiquitous healthcare," in *IEEE EMBC*, Milan, August 2015.

[16] O. O. Rakibet, C. V. Rumens, J. C. Batchelor, and S. J. Holder, "Epidermal passive RFID strain sensor for assisted technologies," *IEEE Antennas Wireless Propagat. Lett.*, vol. 13, no. 1, pp. 814–817, 2014.

[17] M. A. Ziai and J. C. Batchelor, "Multi-state logging freeze detection passive RFID tags," *IEEE Trans. Antennas Propagat.*, vol. 62, no. 12, pp. 6406–6411, 2014.

[18] ——, "Smart radio-frequency identification tag for diaper moisture detection," *IET Healthcare Tech. Lett.*, vol. 2, no. 1, pp. 18–21, 2015.

[19] M. Koo *et al.*, "Bendable inorganic thin-film battery for fully flexible electronic systems," *Nano Lett.*, vol. 12, no. 9, p. 48104816, 2012.

[20] J. Morak, H. Kumpusch, D. Hayn, R. Modre-Osprian, and G. Schreier, "Design and evaluation of a telemonitoring concept based on NFC-enabled mobile phones and sensor devices," *IEEE Trans. Inform. Technol. Biomed.*, vol. 16, no. 1, pp. 17–23, 2012.