Wearables that Work: Getting it Right the First Time

Greg Caswell

SMTA San Jose, CA June 25, 2015
Wearables Market is Hot, Hot, Hot!

Wearable device market value from 2010 to 2018 (in million U.S. dollars)

This statistic provides a forecast for the market value of the wearable device market from 2010 to 2018. Wearable technology in the future is expected to include products such as Google Glass and the iWatch as well as other medical technology. By 2018, it is estimated that this market will be worth some 12.6 billion U.S. dollars.

FitBit and GoPro (Fitness Tracker, Internet Video)

Fitbit’s and GoPro’s success? Focused application, strong commitment to quality, **seamless wireless engagement**

![Image of Fitbit and GoPro devices]

*GoPro Made Nearly $1 Billion in Sales Last Year*
Revenue and net income of GoPro (in million U.S. dollars)

- **2010**: $64.46m, $11.58m
- **2011**: $234.24m, $24.61m
- **2012**: $526.02m, $32.26m
- **2013**: $985.74m, $60.58m

Source: GoPro 8-K Filing | statista
An Explosion of New Applications

NeuroOn: World’s First Sleep Mask for Polyphasic Sleep

FreeWavz: Smart Earphones With Built-In Fitness Monitoring

runScribe: Wearable for the Data-Driven Athlete

Carry Less, Adventure More: Survival Belt
...Including This...

Habit-forming wearable that will literally shock you!

Failure just waiting to happen?
...and now here!!! - Apple Watch

Expects to sell 20 million units in 2015 at $350 each because the typical iPhone user looks at his/her phone 110 times a day
We Have a Problem: Wearables Are Not Workable
There are strong indications that wireless reliability is a key player in this failure of wearable technology.

Think Wireless is Easy? Already Solved?

2015 U.S. Vehicle Dependability Study:
Technology is playing an increasingly critical role in perceptions of vehicle reliability.

The top two problems reported by owners are Bluetooth pairing/connectivity and built-in voice recognition systems misinterpreting commands. These are also the most frequent problems reported by owners at 90 days, according to the J.D. Power 2014 U.S. Initial Quality Study.\textsuperscript{SM}

"As we’ve seen in our Initial Quality Study, owners view in-vehicle technology issues as significant problems, and they typically don’t go away after the ownership honeymoon period is over," said Renea Stephens, vice president of U.S. automotive at J.D. Power. "Furthermore, early indications from our upcoming 2016 U.S. Tech Choice Study show that vehicle owner expectations of advanced technology capabilities are growing. Owners clearly want the latest technology in their vehicles, and they don’t hesitate to express their disapproval when it doesn’t work. Their definition of dependability is increasingly influenced by usability."

Because issues with technology impact overall dependability, they also impact repurchase intent. The study finds that 56 percent of owners who report no problems with their vehicle say they "definitely will" purchase the same brand next time, compared with 43 percent of those who report three or more problems. Together with the fact that 15 percent of new-vehicle buyers indicate they assisted a model because it lacked the latest technological features—up from just 6 percent in 2014—technology clearly plays a key role in affecting future purchase decisions.

Key Study Findings

- Among owners who experienced a Bluetooth pairing/connectivity problem, 55 percent say that their vehicle would not recognize their phone, and 31 percent say the phone would not automatically connect when entering their vehicle.
Reliability is Letting Wearable Tech Down

“Another month, another bad experience with regard to reliability of wearable tech — this time with the Fitbit Flex. When the silicone wristband was only about a month old, it started coming apart…..”

“Did you try turning it off, and then on again? How about charging it?”

“After the first time you go through that dance, you realize it will never ever work. The failure mode is 100% catastrophic from the point of view of the user.”

http://wearabletechwatch.net/2013/09/06/reliability-is-letting-wearable-tech-down/
Terrible Wearables: Hall of Shame

- “In taking blood pressure readings, the Withings blood pressure monitor failed every time (but one), all at the same point”

- Contacts rubbing skin raw
  - Heat & sweat
    - http://www.n3rdabl3.co.uk/2014/07/lg-g-watch-charging-points-cause-injury-users/

http://wearabletechwatch.net
“Sunscreen melted my Nook”

- A tiny warning on the can reads it can damage some fabrics materials or surfaces.

http://bcove.me/hh5yfn26
I got a few smart watches and they worked so poorly that I just said, ‘UGH’, I did not really want this. It was not a good experience
How Do We Make Wearables Workable?
Wikipedia:
“...miniature electronic devices that are worn by the bearer under, with or on top of clothing.”

That’s It?!
An ‘always-available’ technology attached to the human body or clothing that allows the wearer to monitor, engage with, and control devices, themselves, or their social network.

*always-available means it must be always-workable!*
Is Your Wearable A Consumer Device...
### Family

<table>
<thead>
<tr>
<th>Family</th>
<th>Cumulative Failures</th>
<th>Duration (yrs)</th>
<th>Lifetime (yrs)</th>
<th>Units</th>
<th>Therapy Comprised</th>
<th>Therapy Uncomprised</th>
<th>Probability Device-Year (Hazard)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SecuraDR</td>
<td>0.0%</td>
<td>1</td>
<td>10</td>
<td>14000</td>
<td>0</td>
<td>0</td>
<td>0.00%</td>
</tr>
<tr>
<td>SecuraVR</td>
<td>0.0%</td>
<td>1</td>
<td>10</td>
<td>6000</td>
<td>0</td>
<td>0</td>
<td>0.00%</td>
</tr>
<tr>
<td>Maximo DR</td>
<td>0.1%</td>
<td>6</td>
<td>8</td>
<td>37000</td>
<td>8</td>
<td>26</td>
<td>0.02%</td>
</tr>
<tr>
<td>VirtuosoDR</td>
<td>0.1%</td>
<td>4</td>
<td>10</td>
<td>71000</td>
<td>19</td>
<td>15</td>
<td>0.03%</td>
</tr>
<tr>
<td>GEM III VR</td>
<td>0.3%</td>
<td>10</td>
<td>10</td>
<td>17000</td>
<td>9</td>
<td>27</td>
<td>0.03%</td>
</tr>
<tr>
<td>Intrinsic</td>
<td>0.2%</td>
<td>6</td>
<td>10</td>
<td>31000</td>
<td>7</td>
<td>36</td>
<td>0.03%</td>
</tr>
<tr>
<td>Maximo VR</td>
<td>0.2%</td>
<td>6</td>
<td>10</td>
<td>43000</td>
<td>12</td>
<td>33</td>
<td>0.03%</td>
</tr>
<tr>
<td>VirtuosoVR</td>
<td>0.1%</td>
<td>3</td>
<td>10</td>
<td>32000</td>
<td>9</td>
<td>4</td>
<td>0.03%</td>
</tr>
<tr>
<td>GEM III VR</td>
<td>0.3%</td>
<td>10</td>
<td>10</td>
<td>17000</td>
<td>9</td>
<td>27</td>
<td>0.03%</td>
</tr>
<tr>
<td>Marquis DR</td>
<td>0.4%</td>
<td>7</td>
<td>7</td>
<td>20000</td>
<td>11</td>
<td>27</td>
<td>0.04%</td>
</tr>
<tr>
<td>Marquis VR</td>
<td>0.3%</td>
<td>5</td>
<td>10</td>
<td>28000</td>
<td>6</td>
<td>37</td>
<td>0.06%</td>
</tr>
<tr>
<td>EntrustDR</td>
<td>0.3%</td>
<td>5</td>
<td>10</td>
<td>28000</td>
<td>6</td>
<td>37</td>
<td>0.06%</td>
</tr>
<tr>
<td>EntrustVR</td>
<td>0.3%</td>
<td>5</td>
<td>10</td>
<td>14000</td>
<td>5</td>
<td>21</td>
<td>0.06%</td>
</tr>
<tr>
<td>Marquis DR</td>
<td>0.8%</td>
<td>7</td>
<td>7</td>
<td>48000</td>
<td>100</td>
<td>79</td>
<td>0.11%</td>
</tr>
<tr>
<td>Onyx</td>
<td>0.5%</td>
<td>5</td>
<td>10</td>
<td>1000</td>
<td>1</td>
<td>3</td>
<td>0.10%</td>
</tr>
<tr>
<td>GEM</td>
<td>1.0%</td>
<td>10</td>
<td>10</td>
<td>22000</td>
<td>N/A</td>
<td>N/A</td>
<td>0.10%</td>
</tr>
<tr>
<td>GEM DR</td>
<td>1.2%</td>
<td>10</td>
<td>10</td>
<td>15000</td>
<td>N/A</td>
<td>N/A</td>
<td>0.12%</td>
</tr>
<tr>
<td>EntrustDR</td>
<td>2.8%</td>
<td>5</td>
<td>10</td>
<td>500</td>
<td>1</td>
<td>6</td>
<td>0.56%</td>
</tr>
<tr>
<td>VirtuosoDR (advisory)</td>
<td>28.3%</td>
<td>4</td>
<td>10</td>
<td>4000</td>
<td>2</td>
<td>490</td>
<td>7.08%</td>
</tr>
</tbody>
</table>
Why is Reliability a Challenge?

Figure 2. Power density trends of commercial and research systems and the Power Density Barriers.

**Everything is Hot**

![Power density trends graph]

- **3-phase AC-DC**
- **Isolated DC-DC**
- **Commercial**
- **Research**

**Figure 1. Equipment densities are rising even faster than once predicted.**

© 2009 ASHRAE TC 9.9 Datacom Equipment Power Trends & Cooling Applications

**Everything is Mobile**

![Mobile devices]

**Everything is Everywhere**

![M2M Technology diagram]

**M2M Technology**

- Satellite Communications
- Intermodal Communications
- Safety Systems
- Traffic Signals
- Passenger Information
- Travel Assistance
- Vehicle-to-Vehicle
- Connectivity

DfR Solutions
How Long Does a Wearable Need to Last?

- **IMPORTANT**: Not the same as a Warranty (marketing)

- **Rough equivalents**:
  - Clothes: ??
  - Running Shoes: 3 months to 5 years (600 miles)
  - Watches: 3 to 20 years
  - Glasses: 2 to 5 years
  - Cell phones: 12 to 36 months

- With a new technology, there is an opportunity to influence expectations
How Are Wearables Used?

The Use Case for Wearables Has Not Been Defined!

A Critical Action for the Wearable Tech Community
Where will they use it? How often?
Examples of Next Gen Technologies in Wearables

- Embedded components
- Ultra-small components (i.e., 01005 capacitors)
- New substrate materials
  - Polyethersulfone, polyethylene terephthalate (PET), polyethylene napthalate (PEN)
  - Polyimide is not a next gen technology
- Printed connections
  - Silver inks, copper inks, nanosolders, conductive polymers
- Organic displays
- Power Via Supercapacitors
Waiting on the Use Case: Define Failure Inducing Loads

- Temperature Cycling
  - Tmax, Tmin, dwell, ramp times
- Sustained Temperature
  - T and exposure time
- Humidity
  - Controlled, condensation
- Corrosion
  - Salt, corrosive gases (ie Cl₂)
- Power cycling
  - Duty cycles, power dissipation
- Electrical Loads
  - Voltage, current, current density
  - Moment, strain, electrical noise
- Mechanical Bending (Static and Cyclic)
  - Board-level strain
- Random Vibration
  - PSD, exposure time, kurtosis
- Harmonic Vibration
  - G and frequency
- Mechanical shock
  - G, waveform, # of events

And now we have to think about wear and wireless!
Field Environment: Body & Outdoor Temperatures

- Maximum temperatures likely not a significant concern
- Typically far below ratings

However, very cold temperatures (below -20°C) could be a challenge
- Especially in combination with a mechanical load

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>95°F (35°C)</td>
<td>0.375%</td>
<td>0.650%</td>
<td>11% (948)</td>
<td>13% (1,140)</td>
</tr>
<tr>
<td>105°F (40.46°C)</td>
<td>0.087%</td>
<td>0.050%</td>
<td>2.3% (198)</td>
<td>3.8% (331)</td>
</tr>
<tr>
<td>115°F (46.11°C)</td>
<td>0.008%</td>
<td>0.001%</td>
<td>0.02% (1.4)</td>
<td>0.1% (9)</td>
</tr>
</tbody>
</table>
Field Environment: Mechanical

- **Vibration**
  - Not typically affiliated with human body, but outliers can occur (especially with tools, transportation)
  - Examples: Jackhammer, reciprocating saw
  - Have induced failures in rigid medical devices

- **Mechanical Shock**
  - Drop loads can reach 1500g for mobile phone (some OEMs evaluate up to 10,000g)
  - Likely to be lower for lighter wearables, but could be repeated (i.e., affiliated with shoes)

Fig. 7. Typical acceleration and pressure patterns recorded while subject was running.
**Field Environment: Mechanical (cont.)**

- **Bending (Cyclic / Overstress)**
  - Often considered one of the biggest risks in regards to wearables
  - Certain human movements that induce bending (flexing of the knee) can occur over 1,000/day

- **Case Study**
  - There is indication that next-gen substrate materials experience a change in electrical properties after exposure to bending
  - Can be exacerbated by elevated temperature
Corrosion: Handling / Sweat

- Composition of dissolved salts in water
  - Can include other biological molecules.

- Main constituents, after the solvent (water),
  - Chloride, sodium, potassium, calcium, magnesium, lactate, and urea.

- Chloride and sodium dominate.
  - To a lesser but highly variable extent, iron, copper, urocanate (and the parent molecule histidine), and other metals, proteins, and enzymes are also present.

- Different constituents of sweat can attack different elements of the wearable technology (contacts, windows, straps, etc.)
Handling / Sweat (cont.)

<table>
<thead>
<tr>
<th>ID</th>
<th>Type of Exposure</th>
<th>F (µg/m²)</th>
<th>Cl (µg/m²)</th>
<th>NO₂ (µg/m²)</th>
<th>Br (µg/m²)</th>
<th>NO₃ (µg/m²)</th>
<th>PO₄ (µg/m²)</th>
<th>SO₄ (µg/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Raw stock aluminum</td>
<td>0.00</td>
<td>2.14</td>
<td>0.43</td>
<td>0.00</td>
<td>0.26</td>
<td>1.00</td>
<td>0.07</td>
</tr>
<tr>
<td>2</td>
<td>After polish and clean</td>
<td>0.00</td>
<td>0.47</td>
<td>0.45</td>
<td>0.00</td>
<td>0.21</td>
<td>1.07</td>
<td>0.09</td>
</tr>
<tr>
<td>3</td>
<td>Handling (office environment)</td>
<td>0.00</td>
<td>14.35</td>
<td>0.49</td>
<td>0.00</td>
<td>0.41</td>
<td>1.30</td>
<td>0.10</td>
</tr>
<tr>
<td>4</td>
<td>Handling (after exercise)</td>
<td>0.00</td>
<td>25.63</td>
<td>0.39</td>
<td>0.00</td>
<td>0.41</td>
<td>0.92</td>
<td>0.09</td>
</tr>
<tr>
<td>5</td>
<td>Handling (after wiping brow)</td>
<td>0.00</td>
<td>46.61</td>
<td>0.39</td>
<td>0.00</td>
<td>0.36</td>
<td>1.20</td>
<td>0.14</td>
</tr>
</tbody>
</table>

Contamination Extracted (µg)

- Chloride
- Sodium
- Potassium
- Calcium
- Magnesium
- Lactic acid

Type of Exposure

- Raw stock
- After Cleaning
- Handling (office)
- Handling (exercise)
- Handling (brow)
Examples of Sweat Formulation

- Defined by EN 1811 comprises 0.5% NaCl, 0.1% urea, 0.1% lactic acid and the pH adjusted to 6.6 with NH4OH.

- ISO standard ISO 3160-2 comprises 20 g/l NaCl, 17.5 g/l NH4Cl, 5 g/l acetic acid and 15 g/l d,l lactic acid with the pH adjusted to 4.7 by NaOH.

- Another mixture comprising 7.5 g/l NaCl, 1.2 g/l KH2PO4, 1 ml/l lactic acid, pH = 4.57.

- Another one used in Denmark comprises 4.5 g/l NaCl, 0.3 g/l KCl, 0.3 g/l Na2SO4, 0.4 g/l NH4Cl, 0.2 g/l urea.

- Other mixtures comprise 0.3% NaCl, 0.1% Na2SO4, 0.2% urea and 0.2% lactic acid, pH adjusted to 4.5.

- Japanese mixture 1 is 19.9 g/l NaCl, 1.7 g/l urea, 1.7 g/l lactic acid, 0.8 g/l Na2S, and 0.2 g/l NH4Cl

- Japanese mixture 2 is 17 g NaCl, 1500 ml CH3OH, 1 g urea, 4 g lactic acid made up to 1 liter by water.

Never Go Below pH of 4.5
Does Not Exist in the Real World
Rain & Water Immersion Challenges

- Issue of exposure to water & rain must be addressed for wearable electronics to survive

- Some cell phone manufacturers coat the product with either a conformal coating or a superhydrophobic coating to protect the electronics
Exposure to ultraviolet (UV) is typically not sufficient to induce degradation in electronic materials.

However, a combination of temperature, moisture, and UV can break polymeric chains.

- Exact combination, and specific portion of the UV spectrum, is not always well characterized.

It has been documented that stress corrosion cracking has been caused by sunscreen lotion.
### Annual UV Energy Calculations by City

<table>
<thead>
<tr>
<th>City</th>
<th>Latitude</th>
<th>Average Total Energy at 340nm (W(^{hr}/m^2/nm))</th>
<th>Average Annual Total Radiant Dose at 340nm (kJ/m^2/nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Singapore</td>
<td>1</td>
<td>426</td>
<td>1532</td>
</tr>
<tr>
<td>Paris, France</td>
<td>48</td>
<td>499</td>
<td>1796</td>
</tr>
<tr>
<td>Sao Paulo, Brazil</td>
<td>22</td>
<td>553</td>
<td>1991</td>
</tr>
<tr>
<td>Tokyo, Japan</td>
<td>35</td>
<td>570</td>
<td>2053</td>
</tr>
<tr>
<td>Guatemala</td>
<td>14</td>
<td>648</td>
<td>2334</td>
</tr>
<tr>
<td>Miami, FL</td>
<td>25</td>
<td>661</td>
<td>2380</td>
</tr>
<tr>
<td>New York NY</td>
<td>40</td>
<td>661</td>
<td>2381</td>
</tr>
<tr>
<td>Barcelona, Spain</td>
<td>41</td>
<td>662</td>
<td>2382</td>
</tr>
<tr>
<td>Brasilia, Brazil</td>
<td>15</td>
<td>662</td>
<td>2383</td>
</tr>
<tr>
<td>Melbourne, Australia</td>
<td>37</td>
<td>708</td>
<td>2549</td>
</tr>
<tr>
<td>Buenos Aires, Argentina</td>
<td>34</td>
<td>727</td>
<td>2618</td>
</tr>
<tr>
<td>Baghdad, Iraq</td>
<td>33</td>
<td>732</td>
<td>2634</td>
</tr>
<tr>
<td>Minneapolis, MN</td>
<td>44</td>
<td>735</td>
<td>2647</td>
</tr>
<tr>
<td>Townsville, Australia</td>
<td>19</td>
<td>743</td>
<td>2673</td>
</tr>
<tr>
<td>Madrid, Spain</td>
<td>40</td>
<td>748</td>
<td>2694</td>
</tr>
<tr>
<td>LA, CA</td>
<td>34</td>
<td>767</td>
<td>2761</td>
</tr>
<tr>
<td>Phoenix, AZ</td>
<td>33</td>
<td>869</td>
<td>3129</td>
</tr>
</tbody>
</table>

### Annual UV Intensity – Global Picture

**Enjoying the Sun Safely**

The sun’s rays:
- **Short-term:** Sunburn, suppression of the immune system, for instance, photosensitivity
- **Long-term:** Skin cancer, premature aging

The index describes the level of solar UV radiation at a particular moment, and the higher the index, the greater the damage to skin and eyes, and the more care needs to be taken in the sun. UV radiation varies according to the season.

http://www.drb-mattech.co.uk/uv%20map.html
Hardness of Skin and Hair Can Vary Widely (Ethnicity, Sex, Dryness)

<table>
<thead>
<tr>
<th></th>
<th>Cuticle(^a)</th>
<th>Cortex(^b)</th>
<th>Medulla(^b)</th>
<th>Cuticle(^a)</th>
<th>Cortex(^b)</th>
<th>Medulla(^b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Caucasian</td>
<td>0.32 ± 0.04</td>
<td>0.27 ± 0.02</td>
<td>~0.19</td>
<td>6.0 ± 0.4</td>
<td>6.5 ± 0.5</td>
<td>~5.5</td>
</tr>
<tr>
<td>Asian</td>
<td>0.39 ± 0.06</td>
<td>0.30 ± 0.02</td>
<td>~0.18</td>
<td>7.5 ± 0.8</td>
<td>6.7 ± 0.3</td>
<td>~5.8</td>
</tr>
<tr>
<td>African</td>
<td>0.24 ± 0.05</td>
<td>0.23 ± 0.06</td>
<td>~0.16</td>
<td>4.8 ± 0.6</td>
<td>5.8 ± 0.7</td>
<td>~5.0</td>
</tr>
</tbody>
</table>
Wireless

- How have we traditionally met reliability goals in wireless?
  - Margin, Margin, Margin
  - Testing, Testing, Testing

![Graph showing probability of link failure for S=6dB]
Reliability = Margin = Power

- Relationship between transmitted and received power
  \[ P_r = P_t \times G_t \times G_r \times \left( \frac{1}{4\pi \times f} \right)^2 \times \left( \frac{1}{d} \right)^n \]
  - G is gain, f is frequency, d is distance, and n is the path loss exponent (location dependent)

- Need greater reliability?
  - Higher power, Better antenna, Higher antenna
    - This is key for wearables!
    - Google Glass (head) has better transmission than Nike (foot)

<table>
<thead>
<tr>
<th>Location</th>
<th>n</th>
<th>σn</th>
</tr>
</thead>
<tbody>
<tr>
<td>Retail Store</td>
<td>2.2</td>
<td>8.7</td>
</tr>
<tr>
<td>Home</td>
<td>3</td>
<td>7</td>
</tr>
<tr>
<td>Office</td>
<td>2.6</td>
<td>14.1</td>
</tr>
<tr>
<td>Factory</td>
<td>3.3</td>
<td>6.8</td>
</tr>
</tbody>
</table>

What About Wearables?

The Path to Margin is Paved With Problems...

...Lower Battery Life, Higher Cost, Larger Design, FCC Violations, Slower Data Rates, etc.
Wireless – It is Not All About the Test

- Higher Reliability Applications (Military/Industrial) Rely on Lots and Lots and Lots of Field Testing
  - Is this Practical for Wearables?

- Everyone Else Relies on Standards (Compliance). But…
  - Compliance Is NOT Reliability
  - Wearables need to be more reliable than traditional Bluetooth/Wi-Fi/RFID (always available)
  - Cell Phones Buy Spectrum (no interference)
Simulate, Simulate, Simulate

Sophisticated tools (site-specific) are now available to perform Wireless Reliability predictions.
Other Challenging Environments for Wearables

- Washer / Dryer
- Cleaning fluids
- Mud / Dust / Water
If You Don’t Understand the Use Environment...

Is your iPhone 6 bent?
Here’s how to fix it.

Place it screen up into an oven heated to 350°F.
The heat will slightly soften the phone’s metal body temporarily, allowing it to return to its original flat shape.
After 10 minutes, remove from the oven.
Once cool, it should be like new.
Bringing it All Together

Reliability Expectations

Use Environment

= 

Appropriate Material and Technology Selection
Wearables and IoT are an Exciting Revolution!

There are Clear Risks
- Wearables use new technology that hasn’t been fully characterized
- They’ll be placed in environments not fully defined

Do Not Rely on ‘What Has Everyone Else Done’ or ‘Agile Development’ (Code Name: Customers as Guinea Pigs)
- Bring Knowledge and Simulation into the Design Process