The Quantum Technology Landscape, Quantum Sensing, and the Path to Maturity

Internet of Things (IoT) Summit at RWW2023

Prof. Dr. Niko Mohr
Quantum Technologies (QT) are comprised of three parts: Computing, Communications, and Sensing

Not exhaustive

Quantum computing (QC)
- 228¹
- $3.0 billion²
- $9 billion–$93 billion³

Quantum sensing (QS)
- 58¹
- $0.4 billion²
- $1 billion–$7 billion³

Quantum communications (QComms)
- 111¹
- $0.7 billion²
- $1 billion–$6 billion³

1. Includes start-ups and incumbents that develop or offer QT products
2. Based on public investments in start-ups recorded on Pitchbook and announced deals from 2001 to 2021. Actual investment is likely higher, excludes investments in internal QT departments or projects by incumbents.

Source: CapitalIQ; Crunchbase; PitchBook; press search; Quantum Computing Report; expert interviews
Overall, the QT ecosystem has seen a massive influx of capital in recent years.

Based on public investment data recorded in PitchBook; actual investment is likely higher.

1. Public announcements of major deals; actual investment is likely higher as for 7 out of 20 deals done in 2H2021 the deal size was not disclosed.

Source: PitchBook

Not exhaustive
While interest by investors in QS start-ups accelerates, unique to other QT, QS incumbents are important drivers of QS development.

**Activities re QS start-ups**

- **Cumulative Volume of raised funding, mnUSD**
  - 2003: 19
  - 2004: 22
  - 2005: 25
  - 2006: 28
  - 2007: 30
  - 2008: 32
  - 2009: 33
  - 2010: 99
  - 2011: 123
  - 2012: 149
  - 2013: 166
  - 2014: 256
  - 2015: 277
  - 2016: 347
  - 2017: 378

- **CAGR 2011-2021** 34%

**Funding**
- 2018: ~90 mnUSD
- 2020: ~70 mnUSD
- 2021: 347
- 2022: 378

**Corporate activities**

1. Measuring particle size, specific product surface and shape for quality check in plastics production, food industry etc.
2. Control of e.g., temperature and pH in bio reactors for improved quality and waste
3. Prediction of neurological conditions like Alzheimer’s and Parkinson’s
4. Prediction of magnetic fields generated by physiological processes
5. Tissue differentiation during surgery
6. Use cases for better resolution imaging in healthcare, MRI and CT scanning
7. Dark Ice project re navigation use cases: positioning of aircraft without GPS signal thanks to ultrasensitive magnetic field readings
8. Miniature quantum antennas to detect communication signals over very large portion of radiofrequency spectrum and long range for military purposes
9. 2021: Announced investment of 1 bnEUR annually in self-funded R&D for quantum tech
10. 2021: Announcement of Zeiss Quantum Challenge competition

**Not exhaustive**

Source: Pitchbook; McKinsey analysis

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QS is not just about sensors but an ecosystem incl. components, QS systems, orchestration layer, and applications and services layers

<table>
<thead>
<tr>
<th>Tech stack, incl. customer</th>
<th>Description</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sales</td>
<td>Market placement of the QS solution to customers</td>
<td>Integration of the underlying sensing technology into the application and service system such as navigation systems</td>
</tr>
<tr>
<td>Services</td>
<td>Services around QS solution, e.g., consulting, after-sales device care, product customization, etc.</td>
<td>Systems that extract data from each sensor and link with their physical position</td>
</tr>
<tr>
<td>Applications</td>
<td>Applications that use quantum sensing information, e.g., finding the best place to drill for oil, navigating a map without GPS signal, etc.</td>
<td></td>
</tr>
<tr>
<td>QS-BUS: Orchestration layer</td>
<td>Process to get useful information from the structured quantum sensor data, e.g., a map of brain activity, geological layer information, etc.</td>
<td>Systems that extract data from each sensor and link with their physical position</td>
</tr>
<tr>
<td>Data platform</td>
<td>Structuring of sensor data from both quantum and classical sensors into a form that is suitable for modeling later</td>
<td></td>
</tr>
<tr>
<td>Quantum sensing system</td>
<td>Overall packaging of the quantum sensor and the methods by which the data is read out of it</td>
<td>Interferometers, magnetometers; quantum atomic clocks; quantum radar</td>
</tr>
<tr>
<td>Sensor design</td>
<td>Low-level embedded software close to the sensor’s hardware that does basic signal processing and controls the sensors</td>
<td></td>
</tr>
<tr>
<td>Core sensor software</td>
<td>Finished element that can pick up a signal from the environment and transmit it further</td>
<td>Lasers; detectors; Cryostats; Specialized fibres; NV centre diamonds…</td>
</tr>
<tr>
<td>Core sensor hardware</td>
<td>Different parts of the sensor in their base form, e.g., chips, wiring, superconducting material, etc.</td>
<td></td>
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</table>
In this early stage of this ecosystem majority of funding and players are in the components segment

<table>
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<tr>
<th>Value Chain Segment</th>
<th>Number of Players</th>
<th>Share of Start-up Funding</th>
</tr>
</thead>
<tbody>
<tr>
<td>Component manufacturers</td>
<td>&gt;100¹</td>
<td>51%</td>
</tr>
<tr>
<td>Hardware manufacturers</td>
<td>16</td>
<td>21%</td>
</tr>
<tr>
<td>Applications, services &amp; Orchestration</td>
<td>13</td>
<td>28%</td>
</tr>
<tr>
<td>Total number</td>
<td>56</td>
<td></td>
</tr>
</tbody>
</table>

1. Includes start-ups and incumbents that develop or offer QT products; see methodology page for details
2. Based on public investments in start-ups recorded on Pitchbook and announced in the press. Includes announced deals for 2021; excludes investments in internal QT departments or projects by incumbents; actual investment is likely higher

Source: CapitalIQ; Crunchbase; Pitchbook; press search; Quantum Computing Report; expert interviews; McKinsey analysis

¹ Includes start-ups and incumbents that develop or offer QT products; see methodology page for details

² Based on public investments in start-ups recorded on Pitchbook and announced in the press. Includes announced deals for 2021; excludes investments in internal QT departments or projects by incumbents; actual investment is likely higher
Value pools and focus of the QS ecosystem is expected to shift up the stack over time

**Insights**

**Significant value pools move up the stack over time**
Historically, initially scarce components get commoditized, making the QS device the bottleneck; with time, value shifts towards analytics and applications.

**Most valuable plays involve platform approach**
Across industries, platform play are highly attractive given multiple monetization models, de-risking approaches and unavoidable role in ecosystem.

**Pull-through effect of software**
Software as critical element that drives decision for hardware in long-term.
### Tech stack, incl. customer

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<td>Applications</td>
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</table>

- **Analytics modules**
- **Data platform**

<table>
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<th>Bundle</th>
<th>Components</th>
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<tr>
<td>QS-BUS: Orchestration layer</td>
<td>Sensor design</td>
</tr>
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</table>

- Core sensor software
- Core sensor hardware

### Insights of the orchestration layer

- Is responsible for **the governance, control, and coordination** of data or applications, incl. (raw) data from sensors
- Ensures **data formatting** between separate services or applications, e.g., time relation between measurements from different sensors
- Optimizes **speed and data rates**
- Exists in cloud and manages interactions and interconnections between onsite and cloud components, incl. sensor data, edge layer and data lake
- May include **intelligence for communication between services** through API
## Solid state spins and neutral atoms are the most used hardware technologies for quantum sensing, so far

**Overview of quantum sensing technologies**

<table>
<thead>
<tr>
<th>Technology</th>
<th>Solid state spins</th>
<th>Neutral atoms</th>
<th>Superconducting circuits</th>
<th>Photonics</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Implementation type</strong></td>
<td>NV(^2) center in diamonds</td>
<td>Atomic vapor</td>
<td>SQUIDs(^3)</td>
<td>Interferometer(^4) Photon counter</td>
</tr>
<tr>
<td><strong>System description</strong></td>
<td>Spin of one electron localized in an insulator defect (e.g., NV center in diamond)</td>
<td>Atoms in the vapor cell sense changes in the environment</td>
<td>Difference in Cooper pairs between two islands of a Josephson tunnel junction</td>
<td>Photon interaction in a material that leads to measurable difference in the interference pattern</td>
</tr>
<tr>
<td><strong>Measured properties</strong></td>
<td>Magnetic field, electric field, temperature, pressure, rotation</td>
<td>Magnetic field, rotation, temperature, electric field, frequency, acceleration, rotation</td>
<td>Magnetic field, electric field</td>
<td>Temperature, distance, Refractive index, photon counts</td>
</tr>
<tr>
<td><strong>Example players</strong></td>
<td><a href="#">QOMI</a>, <a href="#">ODTI</a>, <a href="#">BOSCH</a></td>
<td><a href="#">NOMAD</a></td>
<td><a href="#">KRYBERG</a>, <a href="#">COLDQUANTA</a></td>
<td><a href="#">IDQ</a>, <a href="#">QLM</a></td>
</tr>
<tr>
<td><strong>Maturity</strong></td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
</tr>
</tbody>
</table>

1. Trapped ions are an additional technology at research state
2. Nitrogen Vacancy
3. Superconducting Quantum Interference Device
4. Miniaturization and precision has been improved; not a novel sensing principle

Source: Expert interviews
The advantages of QS are in enhanced sensitivity, increased reliable measurements and miniaturization

Key benefits of QS vs. classical sensors

<table>
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<th>Higher precision</th>
<th>Enhanced access</th>
</tr>
</thead>
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<tr>
<td>The enhanced sensitivity of quantum systems to the outside world can be leveraged to reach a higher precision</td>
<td>Quantum sensors provide <strong>new access</strong> to e.g., extremely small ranges in size, high resolution or inaccessible locations</td>
</tr>
</tbody>
</table>

Measured properties

- Magnetic field
- Temperature
- Time
- Rotation
- Force
- Pressure
- Electric field

Source: Expert interviews; McKinsey analysis
QS systems enable new applications in different industries with the potential to materialize in the next two to three years

Applications

Bio imaging, including brain scans, imaging of protein structures and real-time metabolic processes

Imaging of molecular structures (spectroscopy)

Signal receivers and amplifiers for radar communication

Calibration of electrical standards for new technologies (e.g., 5G, 6G)

Precise atomic clocks for high-accuracy GPS navigation

Navigation inside buildings and underground

Environmental monitoring: prediction of volcano outbursts

Fundamental research, e.g., High-Energy physics

Non-exhaustive

Next step: Identification of economically viable use cases vs. conventional alternatives

Quantum Sensing is the application of quantum metrology in practical settings.

“You have to do very accurate measurements to compare values, that’s metrology. When you then put this technique into instruments and place them in the field you build up a sensor.”

Professor of Quantum Communication, Computing & Measurement at Boston University

McKinsey & Company
Quantum sensing might be the first quantum technology to materialise, short-term

Quantum technology has the potential to revolutionise our everyday life and is receiving huge influx of funding (~$2.1bn) in recent years.

Unique to other QT, QS incumbents are important drivers of QS development in addition to QS start-ups.

QS is not just about sensors but an ecosystem incl. components, QS systems, orchestration layer, and applications and services layers.

As value pools and focus of the QS ecosystem is expected to shift up the stack over time, orchestration layer is becoming critical to the system.

Quantum Sensing systems enable new applications in different industries with the potential to materialize in the next two to three years.