

GMM-Fachbericht **109**



Energieautonome Sensorsysteme 2024

12. GMM-Fachtagung
19. – 20. März 2024 in Freiburg



EASS

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Vorwort

Wir leben in einer Ära, die von beispiellosen Fortschritten in der Technologie und einem wachsenden Schwerpunkt auf Nachhaltigkeit geprägt ist: Der Klimawandel bedroht unsere Ökosysteme, und die verfügbaren Ressourcen werden knapp. In diesem Zusammenhang stellt die Entwicklung energieautonomer Sensorsysteme einen entscheidenden Punkt dar. Diese Systeme haben die Fähigkeit, autonom durch die Energie aus ihrer Umgebung zu arbeiten. Daher versprechen Innovationen in diesem Bereich, verschiedene Bereiche zu transformieren: von Umweltüberwachung und Medizintechnik bis hin zur industriellen Automation und darüber hinaus. Die 12. EASS-Konferenz – Plattform für Wissenschaftler, Ingenieure und Forscher im Bereich energieautonomer Sensorsysteme Werden Sie Teil einer lebendigen Gemeinschaft, die sich der Weiterentwicklung der Grenzen der energieautonomen Sensortechnologie verschrieben hat! Nehmen Sie an der EASS 2024 teil, um Ihre wegweisende Arbeit zu präsentieren, Vertreter aus der akademischen und industriellen Welt kennenzulernen und sich mit Experten aus verschiedenen Disziplinen auszutauschen.

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Diese neue Edition der EASS bringt Sie nach Freiburg, in eine Stadt, die sich schon früh der Verwendung alternativer Energiequellen verschrieben hat. Forschungsaktiv, malerisch, kulinarisch-spannend: Freiburg im Breisgau – auch als Tagungsort Highlight unserer EASS Tagungen.

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Konferenz Chairman

Prof. Dr. Olivier Schecker
Leiter des GMM Fachausschusses
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Ein optisches Messsystem mit dynamisch einstellbarem Sichtfeld zu Messung des Leaf Area Index

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Kurzfassung

Der Leaf Area Index (LAI) ist ein entscheidender Parameter für die Modellierung und Überwachung des Kohlenstoff- und Wasseraustausch an der Schnittstelle zwischen dem Blätterdach und der Atmosphäre. Passive Instrumente zur Messung des LAI verwenden eine Photodiode, um den Anteil des durch das Blätterdach durchgelassenen Lichts zu bestimmen. Obwohl viele solcher Instrumente in der Industrie entwickelt wurden, gibt es eine große Einschränkung: sie benötigen fast immer einen Bediener. Da der LAI abhängig vom Blattneigungswinkel des jeweiligen Baumes ist, muss für eine genaue Bestimmung des LAI das einfallende Licht aus verschiedenen Zenitwinkeln gemessen werden. Was bisher manuell oder durch die Anordnung mehrerer Photodioden geschah, löst diese Arbeit nun mit einem kompakten und energiesparsamen Aufbau zur kontinuierlichen LAI-Messung mit einem dynamisch einstellbarem Sichtfeld. Das Messsystem besteht aus (1) einer 140° Linse, die das einfallende Licht sammelt, (2) einem Liquid Crystal Display (LCD), welches als optischer Shutter fungiert, darunter (3) einem Diffusor und (4) dem Multispektralsensor AS7341. Die Verwendung des LCDs als Shutter hat den Vorteil, weniger Energie zu verbrauchen als eine mechanische Lösung. Dies ermöglicht den zukünftigen Einsatz in energieautonomen Systemen. Zusätzlich erhöht das Fehlen von beweglichen Teilen die Robustheit und Langlebigkeit unter rauen Umwelteinflüssen.

1 Einleitung

Der Leaf Area Index (LAI) ist ein wichtiger Vegetationsparameter zur Modellierung des Kohlenstoff- und Wasseraustausch an der Schnittstelle zwischen dem Blätterdach und der Atmosphäre [1]. Er ist definiert als die Hälfte der gesamten Blattfläche pro Bodenoberfläche [2]. Der LAI kann durch destruktive und nicht-destruktive Methoden gemessen werden. Destruktive Methoden bestehen aus dem Pflücken der Pflanzenblätter und der Berechnung des LAI aus der Oberfläche oder dem Gewicht der gepflückten Blätter [3]. Diese Lösung ist zeitaufwändig, sehr invasiv für die Pflanze, die alle oder Teile ihrer Blätter verliert, und erlaubt keine kontinuierliche Überwachung des Parameters. Zu den zerstörungsfreien Methoden gehören die hemisphärische Fotografie, Light Detection and Ranging (LiDAR) und passive optische Instrumente [2]. Die hemisphärische Fotografie erfordert teure und energieintensive Fotoausrüstung [4], während LiDAR zeitaufwendig, arbeitsintensiv und kostspielig ist [5]. Passive optische Instrumente sind aufgrund ihres geringen Stromverbrauchs und ihrer geringen Komplexität ideal für die kontinuierliche drahtlose Überwachung. Diese Geräte messen die Bestrahlung mit einer oder mehreren Fotodioden. Die Genauigkeit der LAI-Messung ist jedoch abhängig vom Blattneigungswinkel [2]. Je nach Zenitwinkel wird mehr oder weniger Licht transmittiert, da der Weg durch die Baumkrone unterschiedlich ist. Handgeräte wie das LAI-2000/2200 (LICOR Inc., USA) lösen dieses Problem, indem fünf konzentrisch angeordnete Photodioden das Licht aus fünf verschiedenen Zenitwinkeln misst. Diese Geräte erfordern die Anwesenheit eines Bedieners, weshalb sie nicht für eine kontinuierliche drahtlose Überwachung eignen. Ein Sensorsystem, das in der Lage ist, Licht sowohl aus verschiedenen Zenitwinkeln, als auch Azimutwinkeln zu messen

und dabei die kontinuierliche Entwicklung der Baumkrone über die Jahreszeiten und Jahre hinweg berücksichtigt, ist nach Wissen der Autoren nicht verfügbar.

Um diese Probleme zu lösen, stellen wir eine neuartige optische Lösung mit geringem Stromverbrauch vor, die sich für einen langfristigen Einsatz eignet, um den LAI anhand des unter verschiedenen Zenitwinkeln gemessenen Lichts mit einem multispektralen Sensor zu bestimmen. Das System basiert auf einem zuvor entwickelten drahtlosen PAR-Sensorknoten [6]. Das Sensorsystem besteht aus (1) einer Linse, die das einfallende Licht aufnimmt, (2) einem Liquid Crystal Display (LCD), das als Shutter fungiert, (3) einem Diffusor, und (4) einem multispektralen Sensor. Die Verwendung des LCDs als Shutter hat den Vorteil, dass er weniger Energie verbraucht als eine mechanische Lösung. Außerdem erhöht das Fehlen von beweglichen Teilen die Robustheit und Langlebigkeit im Freien. Das in dieser Arbeit entwickelte Sensorsystem wird in Abschnitt 2 vorge-



Bild 1: In diesem Bild sieht man den Sensorknoten mit Linse, LCD und den darunter liegenden Sensor.

stellt und mit einem Labortestaufbau evaluiert. Die Ergebnisse der Evaluation werden in Abschnitt 3 vorgestellt und diskutiert. Schließlich wird die Arbeit in Abschnitt 4 zusammengefasst.

2 Material und Methoden

2.1 Sensor Design

Das Sensorsystem in Bild 1 besteht aus einer 140° M12 Linse (LN056, Arducam, Kowloon, Hong Kong), welche das Bild auf ein transparentes LCD überträgt. Als LCD wird das EA TFT015-22AI (Display Visions, Gilching, Germany) verwendet. Die Transparenz wurde erreicht, indem das Rücklicht des LCD entfernt wurde. Ein schwarzer Pixel blockiert das Licht, ein weißer Pixel transmittiert das Licht. Darunter befindet sich ein 3 mm dicker PMMA Diffusor, um eine möglichst gleichmäßige Lichtverteilung auf dem verwendeten Spektralsensor AS7341 (ams, Premstaetten, Austria) zu erreichen. Der Spektralsensor besitzt neben 8 Kanälen im sichtbaren Bereich auch einen Kanal im nahen Infrarot (NIR) Bereich. Das zu messende Umgebungslicht kann nun beliebig über die komplette Hemisphäre in sowohl dem Zenitwinkel θ und dem Azimutwinkel ϕ eingestellt werden. Dazu wird ein Muster des gewünschten Field of View (FOV) auf dem LCD mit weißen Pixeln eingestellt, der Rest bleibt schwarz. Bild 2 zeigt das entsprechende Muster auf dem LCD für einen Zenitwinkel θ von 23°-38° und einem Azimutwinkel ϕ von 360°.

2.2 Messaufbau

Um zu überprüfen, ob der Sensor tatsächlich Licht aus verschiedenen θ -Richtungen unterscheiden kann, wurde eine LED-Testkugel gebaut. Diese besteht aus 185 einzeln adressierbaren RGB-LEDs (SK6812), angebracht an der Außenseite einer diffus transparenten Kugel (24 cm Fado Tischlampe Lampe, IKEA, Schweden), sodass diese nach innen scheinen. Der Sensor wird dann innerhalb der Kugel platziert und blickt auf die LEDs. Bild 3(a) zeigt ein Bild des Messaufbaus, platziert in einer verdunkelten Kiste. Zur Überprüfung werden die LEDs der Testkugel nach denen in Bild 3(b) gezeigten Mustern angeschaltet. Für die Unterscheidung in der θ -Richtung, ist das Sichtfeld des Sensors auf eine dünne "Donut"-Form beschränkt (dünner als

in Bild 2). Der ϕ -Bereich [0°, 360°] bleibt konstant, der θ -Bereich wird in Schritten von 2,5° von [0°, 2,5°] bis [67,5°, 70°] durchlaufen.

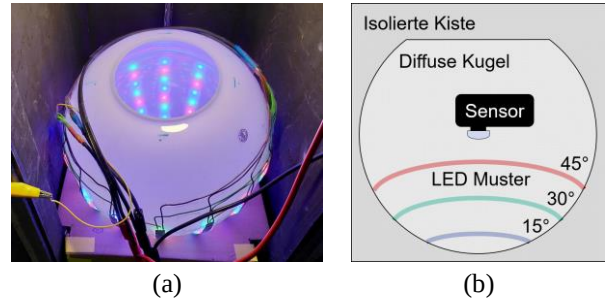


Bild 3: In (a) der Messaufbau bestehend aus den RGB LEDs und der diffus transparenten Kugel. In (b) das darin angelegte Muster zur Überprüfung der Funktion zur Differenzierung unterschiedlicher Zenitwinkel.

2.3 Leaf Area Index

Der LAI ist definiert als die Hälfte der gesamten Blattfläche pro Bodenoberfläche. Bild 4 zeigt exemplarisch die Aufreihung aller Blätter eines Baumes im Vergleich zu seiner Grundfläche. Die theoretische Grundlage der indirekten LAI-Messung ist das Lambert-beersche Gesetz. Hier beschreibt es die Lichtdämpfung in einer homogenen Baumkrone. Aufgrund des Blattneigungswinkels ist der Lichteinfall aber abhängig von dem Zenitwinkel.

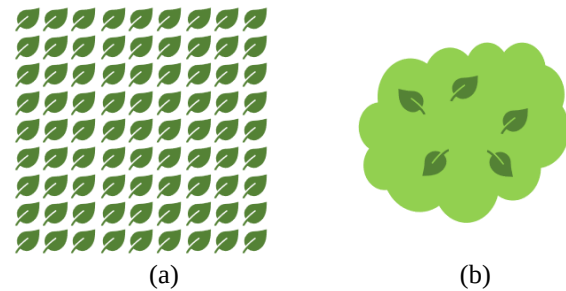


Bild 4: Visualisierung des LAI. In (a) sind alle Blätter des Baumes symbolisch aufgereiht. In (b) die dazu passende Baumfläche aus der Vogelperspektive.

Nach Yan et al. berechnet sich der LAI als Integral über den gesamten Zenitwinkel θ [2]:

$$LAI = 2 \int_0^{\pi/2} -\ln(P(\theta)) \cos(\theta) \sin(\theta) d\theta \quad (1)$$

$P(\theta)$ ist hier die Wahrscheinlichkeit mit der das Licht durch die Baumkrone gelangt:

$$P(\theta) = \frac{B(\theta)}{A(\theta)} \quad (2)$$

Wobei B für eine Messung unterhalb (below) der Baumkrone steht und A für eine Messung oberhalb (above) bzw. außerhalb der Baumkrone. Die Berechnung des LAI kann durch eine Diskretisierung des Integrals durch Messungen unter verschiedenen θ -Winkeln angenähert werden. Kommerzielle System wie das LAI-2000/2200 (LI-COR Inc.,

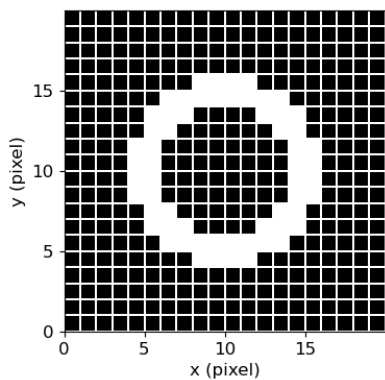


Bild 2: Dieses Bild zeigt das entsprechende Muster auf dem LCD für einen Zenitwinkel θ von 23°-38°. Weiße Pixel transmittieren das Licht, schwarze blockieren es.

USA) realisieren diese Annäherung durch fünf konzentrisch angeordnete Photodioden. In dieser Arbeit werden die verschiedenen θ -Winkel durch die entsprechenden Muster des LCDs erreicht.

3 Ergebnisse und Diskussion

Bild 5 zeigt die relativen Messwerte für den Kanal mit der passenden Wellenlänge des AS7341 für eingestellten Farben in dem Messaufbau (siehe Bild 3(b)) auf den jeweiligen θ -Winkel. Somit ist gezeigt, dass der Sensor zwischen Lichtquellen aus unterschiedlichen θ -Richtungen unterscheiden kann. Der Messbereich der blauen und grünen LEDs in θ sind breiter als die Breite des einzelnen Rings auf dem LCD. Diese Beobachtung lässt sich durch 2 Faktoren erklären: (1) eine zu ungenaue Positionierung der LEDs in der Testkugel und (2) die pixelige Beschaffenheit des LCD-Musters, das zur Begrenzung des FOV genutzt wird. Daher entspricht die "Donut"-Form nur annähernd einem Kreis.

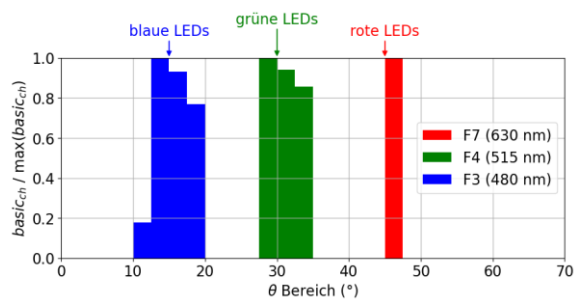


Bild 5: Positionen, in welchen die jeweilige Farbe gemessen wurde während der θ Bereich in 2,5° Schritten gescannt wurde.

Das in dieser Arbeit vorgestellte System ist somit in der Lage, Licht aus unterschiedlichen θ -Richtungen mit ausreichender Auflösung zu unterscheiden. Die gleichzeitige Verwendung von zwei Geräten (eines unterhalb und eines oberhalb der Baumkrone) ermöglicht dem System in einem weiteren Schritt die Bestimmung des LAI basierend auf Formel (1).

4 Zusammenfassung

Eine langfristige kontinuierliche Messung des LAI würde es ermöglichen ein besseres Verständnis der Vegetationsentwicklung und des Kohlenstoff- und Wasseraustauschs an der Schnittstelle zwischen dem Kronendach und der Atmosphäre. Indirekte optische Methoden werden zwar häufig für Messlösungen mit geringem Stromverbrauch verwendet, doch sind sie dadurch begrenzt, keine Unterscheidung von θ -Winkel vorzunehmen, welche für die korrekte Schätzung des LAI entscheidend ist.

Das in dieser Arbeit vorgestellte innovative System basierend auf (1) einer 140° Linse, (2) einem transparenten LCD, (3) einem Diffusor und (4) einer Photodiode ist in der Lage, Licht aus bestimmten und beliebig einstellbaren Richtungen zu messen. Dadurch lässt sich Leaf Area Index (LAI) von Bäumen mit homogen verteilten Baumkronen

zuverlässig bestimmen. Die matrixförmige Anordnung der Pixel des LCD lässt beliebige Muster zu, daher kann nicht nur nach Zenitwinkeln unterschieden werden, auch eine Unterscheidung in verschiedene Himmelsrichtungen (Azimutwinkel) ist möglich. Diese Eigenschaft kann eine Lösung sein, auch heterogene Baumkronen mit einer ungleichmäßigen Blattverteilung zuverlässig zu messen. Die Vermeidung von mechanischen Komponenten erhöht die Langlebigkeit unter rauen Umwelteinflüssen. Außerdem hat das LCD einen geringen Energieverbrauch im Vergleich zu einer mechanischen Lösung. Das macht dieses System so attraktiv für eine Anwendung in einem energieautonomen System. Die Validierung des LAI-Sensors in einer Feldkampagne wird Gegenstand zukünftiger Arbeiten sein.

5 Danksagung

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Konzeptualisierung eines energieautonomen mikrofluidischen Drucksensors mit Flüssigmetalltropfen

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Kurzfassung

Wir schlagen einen neuartigen Sensorikmechanismus vor, welcher auf einem mikrofluidischen Auslesesystem mit Flüssigmetall basiert und in weiche Materialien eingebettet werden kann. Ein segmentierter Strom von Flüssigmetalltropfen in einem strukturierten Mikrokanal wird hydraulisch von einer Zelle in die nächste verschoben, wenn eine Last auf das Material aufgebracht wird. Die Ausstattung der Zellen mit zwei koplanaren Elektroden ermöglicht es, die Flüssigmetalltropfen als Schalter zu verwenden. Die Struktur des Mikrokanals erlaubt es, die aktuelle Konfiguration der Tropfen bei Entlastung des Materials beizubehalten und zu speichern. Eine kontinuierliche Stromversorgung zur Speicherung von Informationen ist dadurch nicht mehr notwendig. Die Verschiebung der Tropfen kann direkt mit der Resonanzfrequenz eines im Material integrierten Schaltkreises korreliert werden. Wir schlagen eine Methode vor, um einen Mikrokanal mit integrierten Elektroden in einer Polydimethylsiloxan (PDMS)-Matrix herzustellen. Die Sensorkonzept bietet die Möglichkeit, flexible und weiche Materialien mit integrierter Sensorik auszustatten, welche über Speicher- und Löschfunktionen sowie drahtloser Auslesung verfügen. Mögliche Anwendungen umfassen weiche Robotik und geschlossene Regelkreise.

Abstract

We propose a novel sensing mechanism embedded in soft materials to provide by making use of a hydraulic readout system based on Gallium liquid metal microfluidics. A segmented stream of liquid metal droplets in a structured microchannel will be displaced hydraulically from one compartment to the next upon load application to the material. Equipping the compartments with two co-planar electrodes allows the liquid metal droplets to behave as a switch. The design of the microfluidic sensing system allows to keep the latest droplet configuration after load release and creates a memory function. A need for a continuous power supply to store information is no longer necessary. The displacement of the droplets can be directly correlated with the resonance frequency of the inner circuit. We propose a method to fabricate a microchannel with electrodes integrated in a polydimethylsiloxane (PDMS) matrix. The sensing method provides a unique opportunity to equip flexible and soft materials with a self-sensing mechanism with state memory, recovery and wireless readout. Possible applications include soft robotics and flexible closed loop systems.

1 Einleitung

Wenn ein physisches Material seine Umgebung wahrnehmen und sich entsprechend anpassen soll, muss es in der Lage sein, Informationen über seinen mechanischen Zustand abzufragen. Bei einer Wahrnehmung einer äußeren Belastung, kann es daraufhin reagieren, indem es seine physikalische oder chemische Struktur verändert und so seine Eigenschaften verstärkt oder anpasst. Diese Anpassung setzt die Fähigkeit voraus, dass eine Veränderung erkannt werden kann. Wenn ein sensorisches Material in der Lage ist, Änderungen des Lastzustands über geeignete Mechanismen zu melden, ermöglicht dies sowohl eine vollständig geschlossene Anpassung als auch eine Zustandsabfrage.

Wir schlagen ein Konzept für einen robusten und skalierbaren Ansatz zur Ermöglichung der Materialselbstwahrnehmung vor, welches ein hydraulisches Auslesesystem auf Basis von Gallium-Flüssigmetall-Mikrofluidik verwendet. Gallium-Indium-Zinn-Legierungen zeichnen sich

durch eine flüssige Phase bei Raumtemperatur, einer dynamischen Viskosität in der Größenordnung von Wasser und guter elektrischer Leitfähigkeit aus [1]. Ein strukturierter Mikrokanal, der mit einem segmentierten Strom aus Flüssigmetalltropfen gefüllt ist, wird bei Lasteinwirkung auf das Material hydraulisch verschoben. Diese Verschiebung ermöglicht die Überwachung des Lastfalls über das Öffnen und Schließen von Schaltern durch die leitfähigen Flüssigmetalltropfen. Die Zustandsmeldung wird über das drahtlose Auslesen der Resonanzfrequenz des im Material liegenden Schaltkreises durchgeführt. Das Konzept bereitet den Weg für einen energieautonomen, allgemein anwendbaren und vollständig geschlossen Regelkreis für Materialien mit integrierten sensorischen Fähigkeiten.

2 Konzept

Um den Zustand des Materials zuverlässig abfragen zu können, muss sich eine messbare physikalische Größe des Materials in Abhängigkeit von der Belastung ändern. Wir integrieren einen elektrischen Schaltkreis innerhalb eines

flexiblen Materials welcher mittels Elektroden mit dem Mikrokanal eine Einheit bildet und Zustandsabfragen über die Änderung der Kapazität C ermöglicht. Der Mikrokanal ist in einer Matrix aus PDMS eingebettet und in drei Abschnitte aufgeteilt, siehe **Abb. 1**: Reservoir, Zelle und Verbindungskanal. Die Zellen sind mit je zwei koplanaren Elektroden ausgestattet.

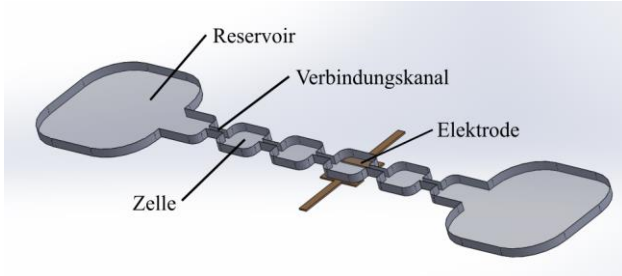


Abb. 1: Schema des Mikrokanals inklusive zweier koplanarer Elektroden. Der Kanal besteht aus zwei Reservoirs die mit einer variablen Anzahl an Zellen und Verbindungskanälen verbunden sind.

Der Kanal wird mit einer 1 M NaOH-Lösung und Galinstan (Strategic Elements, Deutschland) gefüllt. Die NaOH-Lösung verhindert die Bildung einer starren Oxidschicht auf der Oberfläche des Flüssigmetalls. Durch das Anlegen einer Spannung an beiden Enden des Kanals können die Tropfen generiert und in ihre Ausgangsposition verschoben werden [2, 3]. **Abb. 2** zeigt die antizipierten Lastfälle, welche auf den Mikrokanal wirken und somit den Zustand des Materials ändern. Beim Anlegen einer Last und dem Überschreiten des Schwellendrucks, gegeben durch die Geometrie der Verbindungskanäle [4], fließen die Flüssigmetalltropfen von einer Zelle in die nächste. Durch ihre elektrische Leitfähigkeit können die Tropfen die Brücke zwischen beiden koplanaren Elektroden der jeweiligen Zelle schließen und somit einen niederohmigen Stromfluss zwischen diesen ermöglichen. Wird die Last vom Material genommen, so verhindert die Geometrie der Verbindungskanäle einen Rückfluss und das Speichern der aktuellen Konfiguration der Tropfen im Mikrokanal. Die Tropfen können wieder in ihre Anfangskonfiguration verschoben werden,

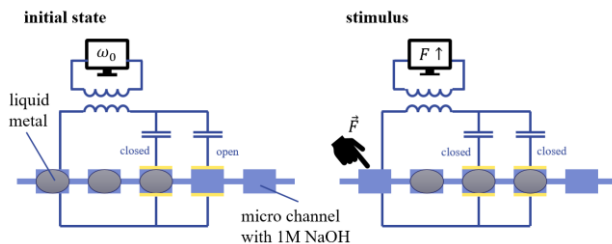


Abb. 2: Schema der erwarteten Lastfälle im Mikrokanal. Durch Hinzuschalten von Kapazitäten wird die Resonanzfrequenz geändert und dann drahtlos ausgelesen werden.

indem entweder eine Spannung an beiden Enden des Kanals angelegt wird [3] oder mechanisch der nötige Druck aufgebracht wird.

Die Information über die Position wird in eine elektrisch messbare Größe umgewandelt, indem jede Zelle in Reihe zu einer Kapazität geschaltet wird, siehe **Abb. 2**. Werden diese Kapazitäten parallel zueinander geschaltet, so kann

durch Wahl geeigneter Größen eine Kapazität C eindeutig einer Tropfenkonfiguration zugeordnet werden.

Um möglichst wenig starre elektronische Komponenten im Material integrieren zu müssen, soll der Zustand drahtlos ausgelesen werden können. Dazu wird der innere Schaltkreis des Materials als elektrischer Schwingkreis mit einer zusätzlichen konstanten Induktivität ausgelegt. Die Resonanzfrequenz kann anschließend durch Kopplung des Schaltkreises mit einer außen liegenden zweiten Induktivität ermittelt werden [5]. Das Konzept ermöglicht es, einen Sensor ohne konstante Stromversorgung in ein Material zu integrieren. Die Geometrie des Mikrokanals fungiert sowohl als diskreter Zähler für die Größe der aufgetragenen Kraft auf das Material, als auch als Speicher dieser. Die anschließend benötigte Energie zur Auslesung der Resonanzfrequenz ist abhängig von der Schrittgröße des Frequenzdurchlaufs des LCR-Meters und kann in der Größenordnung von $1\mu\text{J}$ bis 10 mJ pro Schritt erwartet werden [5, 6].

3 Herstellungsmethode

Die Herstellungsschritte der elektrischen Leiterbahnen und des Mikrokanals sind in **Abb. 3** dargestellt. Eine starre Trägerplatte (FR-4, glasfaserverstärkte Epoxid-Laminatplatte) dient dazu, die Kupferstruktur vorübergehend zu halten,

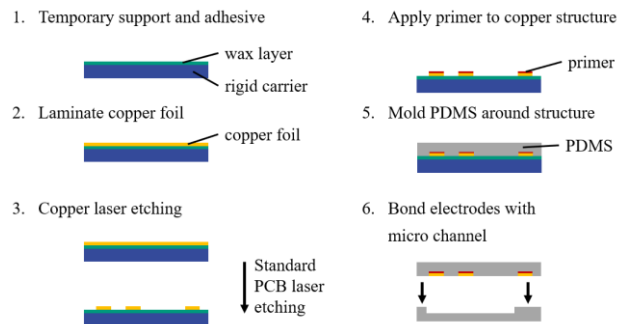


Abb. 3: Herstellungsschritte für mit Elektroden ausgestatteten Mikrokanal, eingebettet in PDMS

bis das PDMS um sie herum geformt wird. Zur temporären Adhäsion der Kupferfolie wird Montagewachs (EM-Tec TempStick 135C, Micro to Nano, Niederlande) verwendet, welches bei 100 °C auf die Trägerplatte geschmolzen wird und eine dünne Schicht bildet. Im geschmolzenen Zustand wird eine Kupferfolie ($35\mu\text{m}$ Dicke, Goettle Leiterplatten-technik, Deutschland) in den äußeren Abmessungen der gewünschten Struktur auf die Wachsschicht laminiert. Beim Abkühlen härtet das Wachs aus und hält die Kupferfolie. Anschließend wird die Struktur einem Standard-Leiterplattenherstellungsprozess mittels Laserätzung unterzogen. Die gewünschte Struktur wird mit einem $15\text{-}\mu\text{m}$ -Laserstrahl (ProtoLaser U4, LPKF, Schweiz) isoliert. Die überschüssige Kupferfolie ist anschließend von der Leiterplattenstruktur getrennt und kann von der Trägerplatte abgezogen werden. Auf diese Weise wird ein energie- und zeitaufwendiger Prozess der Abtragung mittels Laser vermieden und auf Herstellungszeiten von Sekunden bis Minuten reduziert werden.

Kupfer und PDMS gehen keine chemische Verbindung ein, wenn PDMS um Kupfer herum geformt und ausgehärtet wird. Die Adhäsion beruht in diesem Zustand ausschließlich auf van-der-Waals-Kräften. Um die Haftung zu verbessern, wird ein haftvermittelnder Primer (Primer G790, Wacker Chemie AG, Deutschland) auf die strukturierte Kupferoberfläche aufgetragen, welcher die Adhesion zwischen Kupfer und PDMS stark verbessert.

Nach der Grundierung wird PDMS (RT 601, Wacker Chemie AG, Deutschland) um die Kupferstruktur geformt und bei einer niedrigen Temperatur von maximal 70°C ausgehärtet, um eine übermäßige thermische Belastung der Strukturen und ein Schmelzen der Wachsschicht zu verhindern. Anschließend kann die Struktur auf eine Heizplatte gelegt und auf 100°C erhitzt werden. Durch das Schmelzen der temporären Wachsschicht lässt sich die Kupfer-PDMS-Struktur vom starren Träger lösen. Überschüssiges Wachs auf der Kupfer-PDMS-Struktur wird mithilfe von Aceton gereinigt. Das Resultat sind freiliegende in PDMS eingebettete leitfähige Bahnen, welche koplanar mit der PDMS-Oberfläche abschließen.

Die Struktur des Mikrokanals wird mithilfe eines SLS 3D-Druckers (Dilase 3D, KLOE SAS, Frankreich) auf einen Objektträger gedruckt. Durch das Gießen von PDMS über die Mikrokanalstruktur wird das Negativ dieser in die PDMS-Struktur eingebettet. Anschließend werden die Oberflächen der beiden Teilstücke in einer Plasmakammer einer Koronabehandlung zur Oberflächenmodifikation unterzogen. Durch das Ausrichten und Zusammenbringen beider Teile wird der Mikrokanal inklusive Elektroden geschlossen. **Abb. 4** zeigt die Draufsicht eines geschlossenen Mikrokanals mit zwei koplanaren Elektroden, welcher sich in einer transparenten PDMS-Matrix befinden. Durch das Stechen von jeweils einem Inlet und Outlet in den Reservoirs ist das Befüllen des Kanals mit 1 M NaOH sowie Galinstan möglich.

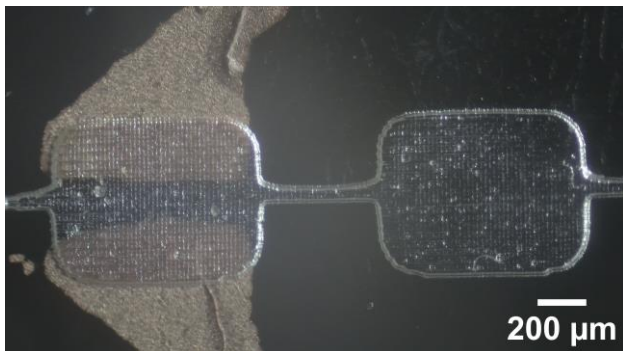


Abb. 4: Aufnahme eines Mikrokanals mit Elektroden, eingebettet in einer transparenten PDMS-Matrix.

4 Anwendungen

Durch die vollständige Integration der funktionalen Komponenten in eine PDMS-Matrix eröffnen sich vielfältige Anwendungsszenarien in Bereichen, wo starre Sensoren problematisch sind, weil diese sich nicht an inhomogene oder sich ändernde Geometrien anpassen können. Tragbare oder implantierbare Sensoren erfordern häufig eine nicht

flache Montage, da die Elektronik unregelmäßigen Formen folgen muss wie zum Beispiel in der der Soft Robotik, biomedizinischen Anwendungen, interaktiven Materialien [7]. Für weiche Materialien kann diese Art von Drucksensor eine energiesparende Lösung sein, Sensorik innerhalb des Materials zu verbauen, ohne auf komplexe Schaltkreise und ein Energiemanagement angewiesen zu sein. Zusammen mit einer Möglichkeit zur Aktuation bereitet es den Pfad für direkt im Material eingebettete geschlossene Regelkreise.

5 Zusammenfassung

Wir präsentierten ein Sensorkonzept samt Herstellungsmethode basierend auf in einem weichen Material eingebetteten Mikrokanal und Flüssigmetalltropfen, welche bei hydraulischem Verschieben zwischen Zellen Schalter eines elektrischen Schaltkreises öffnen bzw. schließen können. Durch die Änderung der Kapazität basierend auf der aktuellen Konfiguration der Tropfen kann eine direkte Korrelation zwischen Druck und Kapazität hergestellt werden. Eine kontinuierliche Stromversorgung zur Speicherung von Informationen ist nicht notwendig. Die Informationen können bei Bedarf über die Messung der Resonanzfrequenz drahtlos ausgelesen werden. Anwendungsmöglichkeiten liegen im Bereich der flexiblen Elektronik und interaktiven Materialien

6 Danksagung

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Integration kapazitiver Hochtemperatur-Drucksensoren in autonome Systeme: Demonstration in realen Anwendungen

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Kurzfassung

In dieser Arbeit demonstrieren wir die Stabilität, Genauigkeit, Reaktionszeit und den geringen Energieverbrauch der hergestellten kapazitiven Hochtemperatur-Drucksensoren, die eine bemerkenswerte thermische Stabilität von $-0,001\%$ FS (Full Scale) /K bei 350°C aufweisen, wie zuvor in [1, 2] gezeigt wurde. Um dies zu veranschaulichen, ist ein F2-Typ Sensor in zwei reale Anwendungen integriert, in denen er unter kontinuierlich anspruchsvollen Bedingungen wie höheren Temperaturen bis zu 120°C und widrigen Umgebungen wie heißem Wasser und Dampf betrieben wird. Ein Konzept für ein drahtloses Druckmesssystem, das während des Betriebs energieautark bleibt, indem es Abwärme effektiv nutzt und sich selbst mit elektrischer Energie versorgt, wurde zu diesem Zweck entwickelt.

Abstract

In this paper, we demonstrate the stability, accuracy, response time, and low energy consumption of the manufactured high-temperature capacitive shielded pressure sensors, which exhibit remarkable thermal stability of -0.001% FS (Full Scale) /K at 350°C , as previously shown in [1, 2]. To illustrate this, an F2-typ sensor is integrated into two real-world applications, where it operates under continuous challenging conditions such as higher temperatures up to 120°C and adverse environments like hot water and steam. A concept for a wireless pressure measurement system, designed to remain energy-autonomous during operation by effectively utilizing waste heat and self-powering with electrical energy, has been developed for this purpose.

1 Einführung

Hochtemperatur-Kraft- und Drucksensoren spielen eine entscheidende Rolle in zahlreichen Anwendungen, insbesondere in Umgebungen mit extremen Bedingungen. Die Hochtemperaturstabilität gewährleistet, dass Sensoren unter extremen Temperaturen genaue Messungen durchführen können, was in Branchen wie der Luft- und Raumfahrt, Energieerzeugung und Metallverarbeitung von entscheidender Bedeutung ist [3 - 5]. Gleichzeitig tragen Sensoren mit niedrigem Energieverbrauch dazu bei, die Betriebskosten zu senken und die Umweltauswirkungen zu reduzieren [6, 7]. Dies ist von besonderer Bedeutung in Bereichen wie drahtlosen Sensor-Netzwerken und IoT-Anwendungen. Durch ihre Energieeffizienz ermöglichen diese Sensoren eine längere Batterielebensdauer in tragbaren Geräten und tragen dazu bei, den Energieverbrauch in großen industriellen Anlagen zu optimieren.

In früheren Arbeiten haben wir erfolgreich abgeschirmte kapazitive relative und absolute Druck- und Kraftsensoren entwickelt und hergestellt, die ihre außergewöhnliche Leistungsfähigkeit mit präzisen Messungen und einer bemerkenswerten thermischen Stabilität von $0,001\%$ des Vollbereichs (FS) /K bei 350°C demonstrieren haben [1, 2]. Aufbauend auf diesem Erfolg zielt unsere aktuelle Forschung darauf ab, diese Sensoren in ein System zu integrieren, das kontinuierlich unter herausfordernden Bedingungen arbeitet. Das Hauptziel ist es, die Stabilität, Genauigkeit, Auflösung, Reaktionszeit und den geringen Energieverbrauch des Sensors in realen Anwendungen (Druckmessung im Schnellkochtopf und Stirlingmotor-Modell) zu demonstrieren. Wir präsentierten ein Konzept für ein drahtloses

Druckmesssystem, das während des Betriebs energieautark bleibt, indem es die Abwärme effektiv nutzt und sich selbst mit elektrischer Energie versorgt, um eine kontinuierliche und zuverlässige Leistung zu gewährleisten.

2 Herstellung und System Design

Für die vorliegende Anwendungen haben wir uns für einen relativen Drucksensor entschieden. Ein entscheidender Faktor bei dieser Auswahl ist seine Anwendbarkeit im Kontext eines Schnellkochtopfs. Da der Betrieb des Schnellkochtopfs auf erhöhtem Druck im Vergleich zum umgebenden Atmosphärendruck basiert, gewährleistet die Messung des Drucks auf relative Weise eine präzise Einschätzung des tatsächlichen Drucks im Inneren des Kochtopfs. Diese Überlegung spielt eine entscheidende Rolle für die Funktionalität und Sicherheit des Systems. Zu diesem Zweck haben wir einen relativen Drucksensor des Typs F2 ($3,8\text{ mm} \times 3\text{ mm} \times 0,58\text{ mm}$) [1] mit einer $50\text{ }\mu\text{m}$ dicken Membran hergestellt, der speziell darauf abgestimmt ist, den erwarteten maximalen Druck im Schnellkochtopf zu messen, der bis zu $1,7\text{ bar}$ erreichen kann. Eine ausführliche Beschreibung des Designs und des Herstellungsprozesses des Sensors ist in [1] präsentiert. Ein wesentlicher Unterschied besteht darin, dass im letzten Bearbeitungsschritt die obere Platte auf $50\text{ }\mu\text{m}$ geschliffen wird, anstatt die Membran zu ätzen. Da beide Sensorplatten aus reinem Silizium bestehen, treten keine durch unterschiedliche Temperaturkoeffizienten verursachten mechanischen Spannungen auf. Des Weiteren wird Silizium hier ausschließlich als mechanische Komponente und nicht als

Halbleiter verwendet, wodurch temperaturabhängige Halbleitereffekte vermieden werden. Das Ergebnis ist ein Sensor mit hoher mechanischer und thermischer Stabilität. Zusätzlich zeichnen sich diese Sensoren durch ihren geringen Energieverbrauch, ihre Langzeitstabilität, hohe Genauigkeit und Auflösung, gute chemische Beständigkeit sowie ihre Abschirmung gegen externe Störungen durch ihre integrierte Faradaysche Käfigstruktur aus.

Die Systemarchitektur **Bild 1** umfasst den kapazitiven Sensor, einen Kapazität-Digital-Wandler (CDC) für die Signalerfassung sowie einen Mikrocontroller, der für die Datenverarbeitung und die Übertragung über Bluetooth verantwortlich ist. Um eine kontinuierliche Stromversorgung zu gewährleisten, wird das gesamte System von einer Batterie betrieben, die effizient durch zwei thermoelektrische Generatoren (TEGs) aufgeladen wird, welche Abwärme in nutzbare elektrische Energie umwandeln.

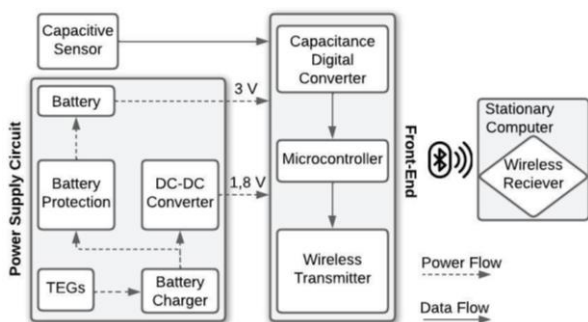


Bild 1 Hardware-Schaltplan Blockdiagramm

Die elektronische Schaltung gliedert sich in zwei Hauptabschnitte: Die Front-End-Schaltung und die Stromversorgungsschaltung. Das Front-End ist in drei Module unterteilt: den Kapazität-Digital-Wandler (CDC), den Mikrocontroller und die drahtlose Kommunikationseinheit. Für die Umwandlung des analogen Signals des kapazitiven Drucksensors in digitale Daten haben wir den PCAP04 CDC IC ausgewählt. Dieser IC bietet vielseitige Messmöglichkeiten mit verschiedenen Datenaufösungen und unterstützt Messfrequenzen von 1 Hz bis 9,32 kHz. Außerdem ermöglicht er gleichzeitige Messungen von bis zu drei Sensoren. Die Daten des PCAP04 werden im Mikrocontroller

verarbeitet, gespeichert und über das SPI-Protokoll übertragen. Als Mikrocontroller haben wir den STMicroelectronics STM32L433CCT6 gewählt. Dieser 32-Bit-Mikrocontroller basiert auf der ARM Cortex M4-Architektur und bietet neben dem geringen Stromverbrauch, ausreichend Speicherkapazität und vielseitige Peripheriegeräte. Für die drahtlose Kommunikation nutzen wir das STMicroelectronics BlueNRG-M2SA, ein Bluetooth Low Energy (BLE)-Modul. Dieses Modul integriert das BlueNRG-2 System-on-Chip mit einem Cortex ARM M0-Prozessor. Die Stromversorgung verwendet den Texas Instruments Power Management IC BQ25570 mit einem Boost-Konverter. Die Batterie wird durch Thermoelektrische Generatoren (TEGs) von Micropelt geladen. Der TGP-651 zeichnet sich durch eine Ausgangsspannung von 60 mV/K [8] aus. Das PCB-Design als 4-Lagen-PCB mit effizienter Stromverteilung und Signalintegrität verbessert die Gesamtleistung und Zuverlässigkeit der Schaltung.

3 Testaufbau und Ergebnisse

Für die Messaufbauten wird ein Stirlingmotor-Modell und ein konventioneller 6-Liter-Schnellkochtopf von Tefal, Modell Secure 5 P25307, ausgewählt. Für die praktische Evaluation ist der F2-Typ Drucksensor mittels elektrischen Schweißen verkabelt und nahtlos auf der Rückseite einer Leiterplatte (PCB) befestigt, wobei die Membranseite nach außen zeigt. Der Sensor ist an die entsprechenden Kontaktpads, die durch Durchkontaktierungen mit der Vorderseite verbunden sind, gelötet. Über zwei koaxiale Kabel und Steckverbinder ist das Sensor-PCB mit dem CDC-Auswertungsboard verbunden. Beim Stirlingmotor wird das Sensor-PCB seitlich verschraubt, wodurch der Sensor im Inneren des heißen Zylinders platziert wird, um den Druck durch die Expansion des Gases zu messen. Für die Messung im Schnellkochtopf ist das Sensor-PCB zusätzlich auf eine vorgefertigte M8-Messingschraube montiert, die ein durchgehendes M4-Loch aufweist. Dies ermöglicht es dem Sensor frei im Loch zu hängen und seine Membranseite später auf die Innenseite des Messsystems auszurichten. **Bild 2** zeigt die Messaufbauten und den F2-Typ Sensor mit der M8-Messingschraube.

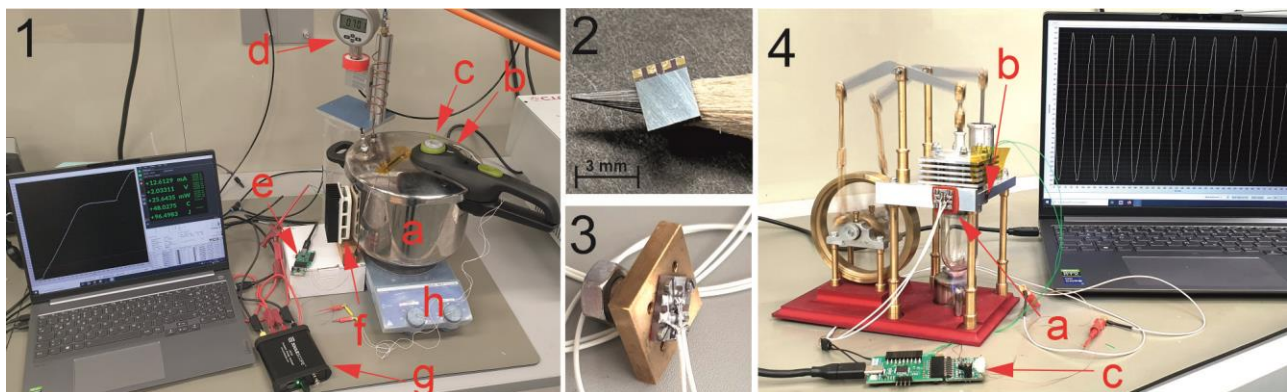


Bild 2 1 Schnellkochtopf-Testaufbau mit (a) Schnellkochtopf, (b) Messingschraube mit Drucksensor Typ F2, (c) mechanischem, zweistufigem Druckbegrenzungsventil, (d) Druckanzeige, (e) PicoProg LITE V1.0, (f) TGP (Thermogeneratoren), (g) Joulescope JS110 und (h) Heizplatte. 2 F2-Typ Drucksensor. 3 Messingschraube mit Sensor-PCB. 4 Stirlingmotor-Testaufbau mit (a) Sensor-PCB, (b) Pt-1000, (c) PicoProg LITE V1.0.

Der Deckel des Topfes ist mit einem mechanischen Zwei-stufen-Druckentlastungsventil ausgestattet. Laut Hersteller ist das Ventil für eine maximale Druckeinstellung von 1,7 bar (Stufe 2) ausgelegt. Der Deckel verfügt außerdem über zusätzliche Anschlüsse für Druckluft und Manometer. Die N-Seite der TGP's ist auf einem 5 mm dicken Aluminiumsubstrat mit silberleitfähigem Kleber montiert. Ein Aluminiumkühlkörper ist direkt an die P-Seite der TGP's mit einer 100 μm dicken Graphitfolie angebracht. Magneten sind auf der Unterseite des Aluminiumsubstrats eingebettet, um es während des Tests sicher an der Seite des Schnellkochtopfs zu befestigen, wobei sich auch Magneten an der Innenseite des Topfes an der entsprechenden Stelle befinden. Schließlich wird die Messingschraube direkt in den Deckel des Schnellkochtopfs geschraubt.

Da die entwickelte Auswertungs Elektronik nicht rechtzeitig hergestellt werden konnte, sind die Messungen mit dem PicoProg LITE V1.0 Evaluationskit mit integriertem PCAP04 durchgeführt. Zunächst wurde der Drucksensor bei Raumtemperatur mit Druckluft charakterisiert. Die Druckwerte sind mithilfe des Druckmessgeräts Digi-04 DM-04 2,5 bar mit einer Genauigkeit von 0,4% aufgenommen. Die Charakterisierung zeigt eine Nulllastkapazität des Sensors von 5,397 pF, eine Volllastkapazität von 10,8 pF bei 1,9 bar Überdruck und eine Nichtlinearität des kapazitiven Umkehrwertes gegenüber dem Druck von 0,002% des Vollbereichs (FS). Nach der Charakterisierung wurde die Druckmessung im Stirlingmotormodell durchgeführt. Das Arbeitsgas im Motor ist Luft und wird am Heißzylinder mit einer Ethanolf Flamme erhitzt. Der PicoProg bietet eine maximale Messrate von 274 Hz. Die Messung im **Bild 3** (2 Sekunden Abschnitt der gesamten Messung) zeigt eine präzise schnelle Ansprechzeit des Sensors und eine hohe Wiederholbarkeit. Die Expansion und Kompression des Gases erzeugen eine gesamte Druckänderung von etwa 270 mbar im Inneren des Stirlingmotormodells.

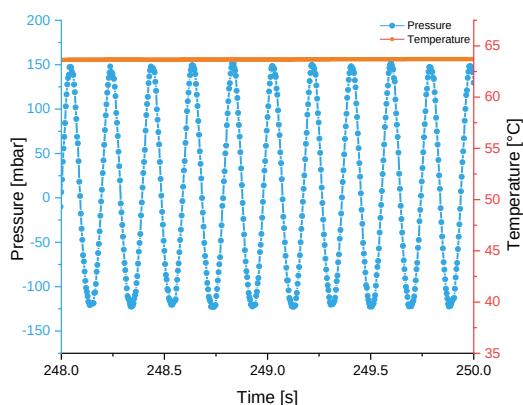


Bild 3 Druckverlaufsmessung eines F2-Typ-Drucksensors im Stirlingmotor.

Auch im Schnellkochtopf zeigt die Messung ein kontinuierliches und stabiles Verhalten des Sensors während des gesamten Kochvorgangs (**Bild 4**). Der Druckverlauf korreliert sehr gut mit dem Temperaturverlauf, der mit einem am Deckel angebrachten Pt-1000 gemessen wurde. Mit steigender Temperatur stieg der Druck bis zum Niveau von

Stufe 1 des Ventils an, wo ein Überdruck von 500 mbar gemessen wurde. Danach ist das Ventil auf Stufe 2 gestellt, woraufhin Druck und Temperatur weiter anstiegen, bis ein maximaler Überdruck von 710 mbar erreicht wurde. Auch bei der Entriegelung des Ventils zeigten die Messung die gleichen Werte.

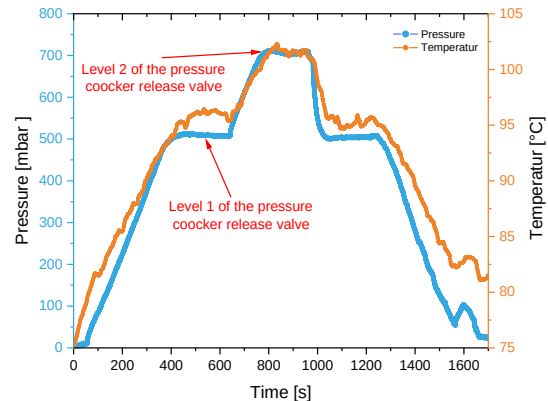


Bild 4 Druckverlaufsmessung eines F2-Typ-Drucksensors während eines Kochvorgangs.

Während des Kochvorgangs wurde die von den TEGs erzeugte Energie mit einem Energieanalyser, dem Joulescope JS110, gemessen. Im Durchschnitt lieferten die Thermogeneratoren eine kontinuierliche Leistung von etwa 18,3 mW während des gesamten Kochvorgangs. Auf Grundlage der Datenblätter des CDC-Chips, des Mikrocontrollers und des Bluetooth-Moduls ist ein maximaler Gesamtstromverbrauch pro Messzyklus, kombiniert aus Sensorbetrieb und Datenübertragung, von etwa 12,8 mW zu erwarten. Mit einer durchschnittlichen Leistung der TEGs von 18,3 mW deuten diese Zahlen darauf hin, dass die Energiequelle ausreicht, um kontinuierliche Messungen und regelmäßige Datenübertragungen zu unterstützen, mit einem Sicherheitspuffer, um einen stabilen Betrieb über längere Zeiträume zu gewährleisten. Außerdem wurde in dieser Studie keine Optimierung des Stromverbrauchs des Systems durchgeführt, was viel Raum für weitere Verbesserungen lässt.

4 Zusammenfassung

Dieser Beitrag demonstriert die Stabilität, Genauigkeit, Wiederholbarkeit und den geringen Energieverbrauch unseres innovativen kapazitiven Hochtemperatur-Drucksensors. Der Drucksensor wurde in zwei realen Anwendungen integriert, wo er seine Leistung unter anspruchsvollen Bedingungen wie heißem Wasser und Dampf unter Beweis gestellt hat. Weiterhin ist ein Konzept für ein drahtloses Druckmesssystem entwickelt worden, das während des Betriebs energieautark bleibt, indem es Abwärme effektiv nutzt und sich selbst mit elektrischer Energie versorgt. Darüber hinaus zeigen die Messungen eindeutig die geringen Energieanforderungen sowohl des Sensors als auch des gesamten Systems auf.

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A Portable Optical Sensor for Real-time Absorbance Characterization of Tunable Anthracene-Endoperoxides

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Abstract

Anthracene Endoperoxide (ANT-EPO) molecules exhibit a unique ability to selectively bind and release oxygen, making them promising candidates for energy storage applications. This work focuses on developing a sensing system to monitor the continuous binding and release of oxygen by ANT-EPO molecules, enabling efficient energy storage systems capable of releasing energy on demand. The sensing method involves an integrated optical sensor utilizing a 265 nm deep-UV light-emitting diode (LED) to stimulate ANT-EPO at its absorption peak, along with measuring and reference photodiodes for precise absorbance measurements. Experimental runs were focused on monitoring and tracking absorbance change over time, providing valuable data on the dynamics of oxygen release and laying the foundation for the innovative optical detection system. By focusing on real-time measurements and calibration procedures, this research aims to contribute to a better understanding of ANT-EPO behaviour and its potential applications in energy storage systems. The developed sensor opens possibilities for advancing adaptable energy technologies, enabling systems to adjust their reactions based on available energy. This paves the way towards future applications in materials systems, where state changes are triggered only when sufficient energy is available.

Keywords: Optical sensing, Absorbance detection, Anthracene endoperoxide, Energy storage, Deep-UV

1 Introduction

In the pursuit of innovative solutions for energy storage, this study proposes a novel approach leveraging water-soluble Anthracene Endoperoxide (ANT-EPO) molecules. These molecules possess the unique ability to selectively bind and release oxygen and are therefore the perfect candidate to develop energy storage, capable of releasing energy in the form of oxygen triggered by light [1]. The potential applications of such energy storage range from powering portable devices to enabling advancements in soft robotics. To achieve precise control over the oxygen binding process, an integrated sensing system is proposed. Recent developments in materials science have enabled progress in energy storage, facilitating informed decisions and adaptive responses based on energy status. By enabling responsive systems to adjust their reactions based on available energy, a more efficient approach to energy utilization is achieved. This is possible through an innovative optical sensor for monitoring the released oxygen of ANT-EPO. Optical detection technology emerges as a promising approach for sensing the amount of oxygen trapped and released.

Optical detection technologies offer high sensitivity and specificity in terms of detection limits and accuracy. However, conventional Ultraviolet-visible (UV-VIS) spectrophotometers are often complex, large, and expensive. Recent advancements have led to the development of more compact and cost-effective solutions. Light-emitting diode (LED) based devices emerge as promising alternatives due to their portability, and reliable spectral analysis [2]. UV LEDs offer several advantages over conventional light sources, including instant operation, low response time, and accurate control with constant current drivers [3].

Therefore, in this paper, an optical sensing system is proposed, that utilizes a modular setup to quantify the amount of oxygen release through the amount of light absorbed by ANT-EPO. The designed optical sensing unit integrates (1) a 265 nm deep-UV LED that stimulates ANT-EPO at its absorbance peak, (2) a measuring and (3) reference photodiode to measure the transmitted light proportional to their output voltages, and (4) beam splitter with target wavelength filter. Analysing absorbance over time provides insights into the concentration of the molecule during the reaction progress. Integrating an LED, with detectors in a closed channel has advantages, in minimizing background scattering from the light source ensuring high sensitivity during measurements. This compact sensing solution has the potential to deliver results comparable to a commercial spectrophotometer in terms of linearity and precision while offering low power consumption, and a modular setup. Additionally, to tune the bandwidth at which the sensing system must work, a standard spectrometer was used to identify the ANT-EPO and ANT molecule's absorption. By focusing on characterizing the absorption properties of the molecules and laying the groundwork for the development of the sensing system, this research sets the stage for further advancements in energy storage technology.

2 Background

2.1 Chemical and Reagents

For initial testing, a variant of ANT-EPO with an extended half-life and high oxygen yield was synthesized [1], as mentioned in Table 1. The synthesis involved mixing ANT with a Photosensitizer (PS), which, upon light activation, releases singlet oxygen (SO), that reacts with the ANT to form ANT-EPO as illustrated in Figure 1. An appropriate

light source aligned with the absorption properties of the molecules was selected, for the absorbance and concentration determination using the Beer-Lambert Law [4]. Figure 2 illustrates that ANT has an absorption peak at 400 nm and for wavelength lower than 270 nm, while ANT-EPO peaks at around 262 nm.

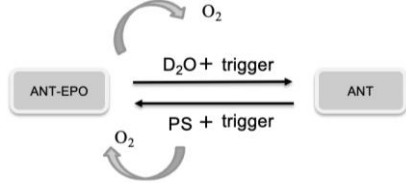


Figure 1. Reaction flow of Anthracene-Endoperoxide (ANT-EPO)-left, and anthracene (ANT)-right.

Requirements	Test compound, ANT-EPO
Oxygen release at room temperature	$t_{1/2} = 4.7$ hrs at 37 °C
Long half-life	
High O ₂	100 % O ₂ yield

Table 1. Requirements and characteristics of chosen ANT-EPO synthesized from ANT scaffold.

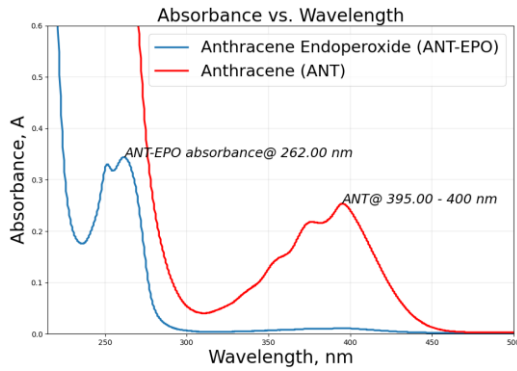


Figure 2. Absorbance peaks of Anthracene (ANT)-red and Anthracene Endoperoxide (ANT-EPO)-blue.

2.2 Principle of Absorbance

Absorbance, A , establishes a direct relationship between light intensities (i_o & i) before and after passing through the sample [5]. The photodetectors do not provide absorbance value directly but provide information as voltages (V_{ref} & V_{sample}). The detector shows a linear relationship between incident light and the voltage ratio. The absorbance is then given by:

$$A = \log \frac{i_o}{i} = \log \frac{V_{ref}}{V_{sample}}$$

It is noteworthy that the Beer-Lambert Law is typically applicable to monochromatic light radiation. However, the light emitted by LEDs, typically has non-monochromatic radiation due to slightly broader bandwidth, introducing challenges related to spectral distortion. Therefore, a modification is considered to account for variations in the intensity of the LED, I_o , the sensitivity of the detector, S , and the molar absorptivity, ϵ , across the bandwidth of the LED, mentioned as [6]:

$$A = \log \frac{i_o}{i} = \log \frac{\int_{\lambda_o}^{\lambda} S(\lambda) I_o(\lambda) d\lambda}{\int_{\lambda_o}^{\lambda} S(\lambda) I_o(\lambda) 10^{-\epsilon(\lambda)bc} d\lambda}$$

3 Absorbance Analysis

Preliminary measurements and calibrations conducted with a Shimadzu spectrophotometer provided significant absorbance data. ANT demonstrated a distinguished absorbance peak within the 395-400 nm range, while ANT-EPO has high absorbance maxima at 262 nm. Further analysis, including quantum yield assessment on ANT scaffold, revealed absorbance of 72.231 % at 325 nm excitation and 92.655 % at 360-400 nm excitation. These precise findings provided crucial data for the design of the sensing system. It is important to note the potential challenge in distinguishing between the absorbance peaks of ANT-EPO and the ANT, which also exhibits absorbance in 262 nm as shown in Figure 2. To address this, parallel setups will be used at both 262 nm and 400 nm wavelengths. Initially, only ANT-EPO is present, resulting in a distinct peak at 262 nm. As the reaction progresses, traces of anthracene begin to appear, leading to an increasing absorption on both 400 nm and 260 nm. To disentangle the absorption peaks at 260 nm, due to both ANT and ANT-EPO, a parallel measurement on 400 nm and 260 nm will be used. A normalization factor will be sought, which by considering the increase of ANT measurable at 400 nm, compensate for the unwanted increase in absorbance at 260 nm due to ANT. The determined wavelength bandwidth from this analysis supports the sensor design, facilitating reliable measurements with the sensing system in subsequent experiments.

4 System Design and Integration

4.1 LED and Photodetector Selection

Choosing a high-power LED is essential for a strong signal, that matches the photodiode's sensitivity and the concentration of ANT-EPO molecules. Higher power LEDs improve signal-to-noise ratio (SNR) and increase measurement accuracy [5]. The objective is to employ a high-intensity, stable light source emitting wavelengths aligned with the absorption maxima of the molecules. A deep-UV-LED of 265 nm is the preferred option to align with the absorption properties. The emission spectrum of the chosen 265 nm LED, depicted in Figure 3, has a high intensity around 262 nm, complementing its peak at 265 nm.

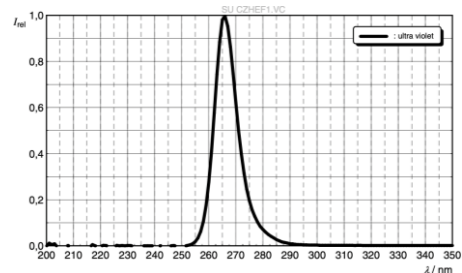


Figure 3. Emission spectrum of 265 nm deep-UV LED.

The chosen photodetectors capture absorption spectrum at specific peaks for ANT-EPO, providing higher bandwidth, and optimal wavelength sensitivity. In addition, the photodetectors are integrated with an amplifier inside the TO5 housing which provides a strong output signal. Sensitivity at 262 nm is typically one magnitude lower than at 300 nm, highlighting the need for specialized photodetectors designed for deep-UV (~262 nm) testing. Equipped with optical filters designed to block higher wavelengths, these detectors ensure precise measurements within the targeted wavelength range of 262 nm and 400 nm.

4.2 Instrumentation & Prototype

Two UVC Photodetectors, Tocon_C9, from sglux, serve as both signal and reference detectors, securely mounted on PCBs. A high-power surface-mounted LED, Osron UV-6060 at 265 nm/100 mW, sourced from Osram, mounted to the PCB. A precision beam splitter BSW20R, from Thorlabs, directs light within the range of 250-450 nm. These components were housed and aligned with a custom 3D housing designed and fabricated by Formlabs form3 printer, mounting the optical components and sample cuvette as depicted in Figure 4.

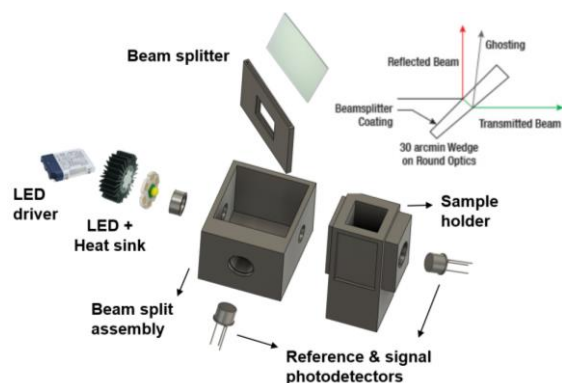


Figure 4. Prototype design

Signal amplification was achieved through integrated amplifiers within the photodetectors. The log ratio of the reference and sample voltages, obtained via the data acquisition unit, established a relationship between detector output voltage and absorbance as shown in Figure 5. The LED and signal photodetector were positioned on opposite sides of the optical path and the reference detector was placed at 90° to compute absorption measurements in real-time.

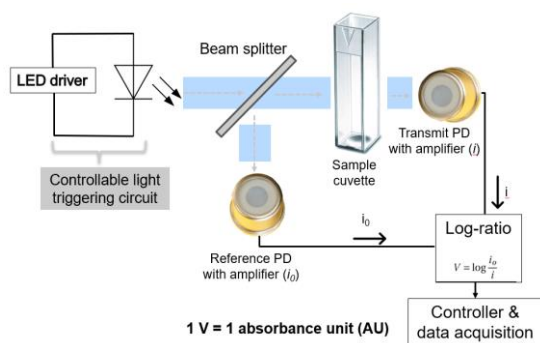


Figure 5. Circuit layout

5 Conclusion

Herein, a novel portable optical sensor has been proposed to monitor oxygen release and binding in ANT-EPO molecules. Preliminary measurements were conducted with a Shimadzu spectrophotometer, which demonstrated an absorbance peak within 395-400 nm range of ANT, while ANT-EPO exhibited high absorbance maxima at 262 nm. These measurements represent the basis for the development of a compact and cheaper sensing solution, which is presented in this article. These properties position the described sensing system as a compelling choice for future development towards intelligent materials that are self-aware of their energy status.

Acknowledgements

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Water-based galvanic cell for powering of wireless sensors

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Abstract

This article deals with the energy supply of wireless sensor nodes using a galvanic cell in which water (e.g. tap water or rainwater) is used as an electrolyte. The electrodes of the developed galvanic cell consist of a gold surface and a zinc foil, which are placed on the reverse side of the sensor board. In case of contact with water, a voltage of several 100 mV is generated between the electrodes. The self-discharge of a battery does not limit the service life of such a galvanic cell, so maintenance-free installation directly under the screed in the floor or roof area is possible. The developed sensor can be used as a wireless water leakage sensor in different building parts. An additional RF power supply is being implemented to test the sensor in its installed state to activate the sensor electronics.

1 Introduction

Energy harvesting technologies are widely used to power wireless sensors, especially in industrial applications. Techniques such as photovoltaic cells and thermoelectric generators are widely available on the market, but there is always a need for new ideas for energy harvesting solutions. The Sensor Technology Group at the University of Paderborn is directly developing a power supply system based on a galvanic cell with a water-based electrolyte (lake, rain or tap water) [1-3].

The wireless sensors powered by the developed electrochemical cell can be used, e.g., to detect water leaks in roofs or wall structures of industrial and private buildings. Such sensors integrated into building structures can be activated by encountering water caused by leaking. This water acts as an electrolyte for the galvanic cell, providing the electrical energy for the sensor electronics. The main advantage of this approach is the long lifetime of the sensor in the non-activated state, which is much longer than most of the batteries currently available on the market (usually up to 10 years).

2 Implementation of a galvanic cell

The output voltage of the galvanic cell is defined by the standard potential of the chosen electrode metals [4].

Several combinations of electrode materials were compared and tested during the experimental measurements. Although platinum and zinc electrodes show the highest output power value, a combination of zinc and gold metals has been selected for the developed galvanic cell, because gold finish is a standard coating technique in producing printed circuit boards (PCB). A 100-200 nm gold plating is typically used to protect PCB from corrosion and facilitate soldering [5]. Such gold thickness allows the stable operation of the implemented galvanic cell. The zinc electrode is made from zinc foil placed manually on the reverse side of the sensor board.

The load curve of the gold-zinc galvanic cell is shown in Figure 1. The maximal output power achieves up to 44 μ W.

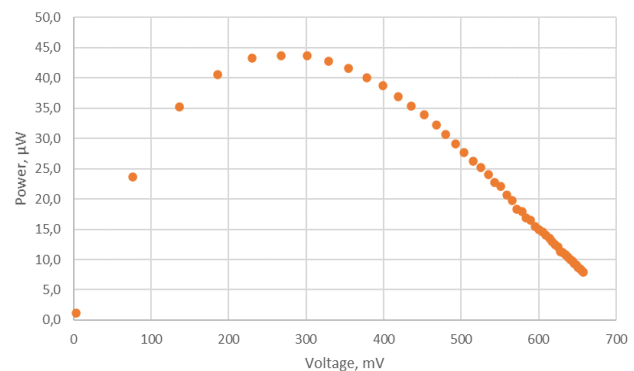


Figure 1 – The output power of the implemented galvanic cell [3]

3 Sensor board design

The output current of the developed galvanic cell is between 50 to 100 μ A (short-circuit current), much lower than the current consumption of wireless transmitter ICs (10 to 15 mA). The output voltage of the galvanic cell is also lower than the typical supply voltage (1.8V to 3.3V). For this reason, a step-up voltage converter circuit was implemented to boost the output cell voltage. The output voltage charges a capacitor, whereas its capacitance is calculated to power the sensor circuit for the required operating time (0.2 to 0.5 seconds).

3.1 Sensor block diagram

The block diagram of the developed sensor board, powered by a galvanic cell, is shown in Figure 2.

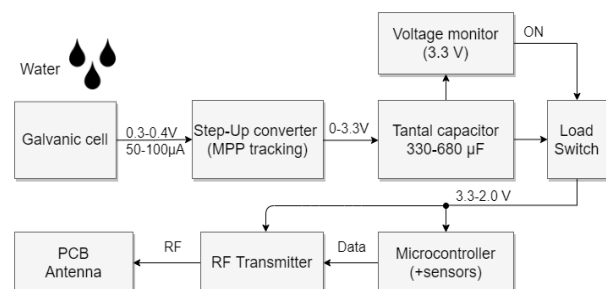


Figure 2 – Block diagram of the developed sensor board

After activating the galvanic cell, the output voltage supplies a step-up voltage converter with Maximal Power Point (MPP) tracking. The supply circuit is implemented with ADP5091 by Analog Devices. Two 330 μ F tantalum capacitors at the output of the voltage converter operate as the energy storage. After charging the output capacitors up to 3.3 V, the load switch will connect the output voltage to the sensor circuit. During operation, the capacitors discharge to the minimal voltage of 1.8V and the load switch will be closed. The whole process will be repeated.

3.2 Wireless data transmission

The developed sensor does not measure any physical value; it only sends its unique ID number. Using the ID, the sensor as water leakage detector allows the localization of the occurred leakage. To minimize the data transmission time and the required energy, the packet length of the transmitted data (shown in Table 1) is chosen as short as possible. The developed sensor operates in the 868 MHz frequency range. The consumed energy is 0.7 mJ for the first transmitted data packet and 0.3 mJ for the following packets. The energy storage with the capacitance of $2 \times 330 \mu\text{F}$ allows sending 3 to 4 data packets, with 200 ms time intervals between packets. The single data transmission takes about 60 ms.

Byte 1	Byte 2	Byte 3	Byte 4	Byte 5	Byte 6	Byte 7	Byte 8
Preamble	Preamble	ID-1	ID-2	ID-3	ID-4	CRC-16	CRC-16

Table 1 – Transmitted data packet

3.3 Additional RFID power supply

The patented design of the gold electrode in the antenna coil allows the use of the gold electrode for an additional power supply from an RF power source [6]. A resonance capacitor parallel to the antenna coil enables a parallel resonance oscillator at 125 kHz. This frequency range is compatible with 125 kHz RFID technology. A diode rectifies the RF voltage induced in the coil antenna and serves as the input of the voltage converter.

The feature of the additional RF powering allows the regular functionality test for embedded sensors (in roofs or floors). Using an RFID transmitter antenna with a diameter of 14 cm allows a sensor activation from a distance of up to 20 cm (sensor activation time of 5 seconds).

3.4 Sensor PCB

The final design of the sensor PCB is shown in Figure 3. The RF antenna for data communication (in 868 MHz range) covers the right part of the sensor PCB. The power supply circuit and the sensor electronics are placed in the middle of the sensor PCB. The left side of the PCB is reserved for the RFID antenna (also used as the positive gold electrode for the galvanic cell). Electronic components are not placed above the antenna area to prevent shielding of the magnetic field in the antenna.

Zinc and gold (RFID coil) electrodes are on the bottom. The white material dots at two edges of the zinc were used

to seal the zinc electrode connections and protect the top side of the PCB from water.

The sensor circuit includes the EFM8 low-power MCU and the wireless transmitter Si4012, both from Silicon Labs.

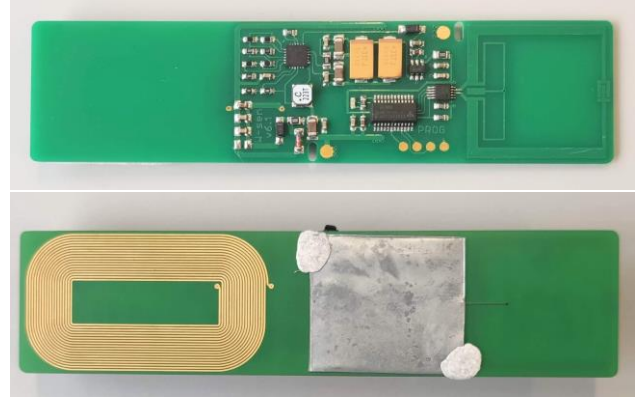


Figure 3 – Top and bottom side of the sensor PCB

4 Practical results

4.1 Activation time and live time

The activation time of the developed sensor depends on the temperature and the water conductivity. It is typically between 4 to 8 minutes. This time should be fast enough to achieve a quick reaction to the water leakage. Quicker activation time is also possible; some improvements are discussed below.

The ambient temperature also affects the sensor charging time. The sensor charging time at 30°C is about 50% shorter than at 10°C.

The live time of the sensor in the activated state is between two to three months. At the end of the live time, the activation time will continuously increase from 4 to 15 minutes.

4.2 Data transmission range

The tested data transmission range is about 100 to 150 meters. Sending multiple packets during a single activation increases the redundancy of data transmission. Data transmission consists of 3 to 4 data packets, with 200 ms time intervals between packets.

The developed receiver module supports the sensor data protocol and allows transmitting the received data to the PC via a USB interface.

4.3 Sensor activation over RFID or QI

The tested activating distance over RFID technology with an RF loop antenna of 14 cm diameter is about 20-24 cm (sensor activation time about 5 seconds).

It is also possible to make the activation of the sensor by using the QI technology (typically used for wireless charging of mobile phones or headsets). The QI devices operating in the frequency range from 100 kHz to 200 kHz are also compatible with the sensor RFID antenna circuit. The

sensor placed over the Qi charger pad or the power bank with a Qi interface (Figure 4) will be activated in a few seconds. Mobile phones with a Qi reverse charging feature were also tested for activating the sensor circuit. This quick activation can be used during the sensors' installation to check the installed sensors' ID number. For multiple sensor placement over a large area like industry roofs, saving the sensor IDs in the mapping software makes sense for further quick leakage localization.

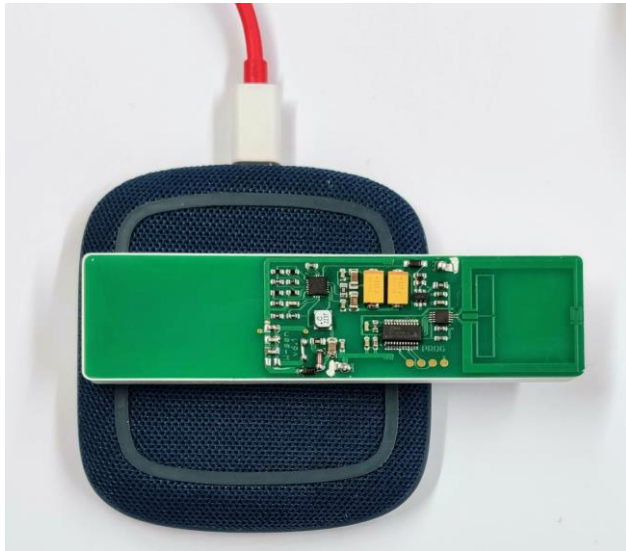


Figure 4 – Sensor placed over the Qi charger pad

4.4 Improving the galvanic cell

The output power of the galvanic cell depends on the electrode material chosen, the electrode size, and the electrolyte used. The chosen electrode metals (gold and zinc) allow the reliable operation of the galvanic cell with low production costs. Using other materials like platinum instead of gold will slightly increase the output power but increase the production costs disproportionately.

A bigger size of the electrodes affects the resulting size of the sensor PCB and the sensor costs. Reducing the electrode size will reduce the sensor PCB size and increase the charging time for sensor electronics.

By using the electrolyte, additional materials increasing the conductivity will increase the output power of the galvanic cell and thus decrease the sensor activation time. Salts or acids in low concentration will give 100% to 200% more output power. Organic materials like soil or dirt minimally affect the sensor activation time.

The water caused by a water leakage typically cannot be influenced by its conductivity. Nevertheless, applying some additional material to the sensor electrodes is possible before installing the sensors. Some experiments with sodium chloride (salt) and citric acid were implemented. These materials were applied on a water-soluble film placed over the electrodes (Figure 5). In this case, the resulting activation time can decrease by 40% to 50%.



Figure 5 – Natrium chloride applied on the water-soluble film and placed over the zinc electrode

5 Outlook

The developed sensors can be used for water leakage detection and other purposes, like water quality control or flooding areas [7]. Including them in some emergency kit for boats or ships is also possible.

Other wireless technologies can be investigated for operation with the developed galvanic cell. Currently, wireless communication in 2.4 GHz range and wireless communication using LoRa (Long Range) technology by 868 MHz are being investigated by Sensor Technology Group of Paderborn University.

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Temperature enhanced Lithium-Ion-Batteries for Small-Scale Sensor Systems

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Abstract

The limited installation space of small-scale sensor systems requires the dimensions of installed components to be reduced. In the case of energy storage devices such as capacitors or batteries, this reduction in volume has a direct effect on the amount of energy that can be stored. By integrating batteries into substrates or sensor housings, these can be expanded to include the property of energy storage and thus lead to a more efficient utilization of the space. Due to the instability of the cell chemistry at temperatures above 80°C, conventional lithium-ion batteries cannot withstand the demands placed on batteries during the manufacture of such sensor systems - especially when used as printed circuit boards.

This work deals with lithium-ion batteries whose thermal resistance enables integration into structural elements of space-constrained sensor systems. In particular, it deals with the construction of lithium iron phosphate (LFP) graphite batteries with an electrolyte of lithium bis(oxalato)borate (LiBOB) in γ -butyrolactone (GBL) and ethylene carbonate (EC), as well as the behaviour with regard to thermal loads at temperatures between 200°C and 220°C.

The electrochemical characterization of the cell was carried out using galvanostatic measurements. The effects of heating the cells were investigated by comparing thermally stressed cells with unstressed cells of identical design. The cell temperature was measured inside the battery housing in the immediate vicinity of the cell stack. This ensures that the electrodes and electrolyte were exposed to the specified thermal loads.

It was found that the batteries tested continued to function even after thermal stress and were therefore suitable in principle for integration into structural elements.

1 Introduction

In an increasingly networked and automated world, energy-autonomous sensor systems are gaining in importance. These systems enable a wide range of applications, from environmental monitoring to industrial automation, without having to rely on conventional power sources. A central concern in the development of such systems is to guarantee their function in the event of a temporary failure of the main energy source - such as missing sunlight at night or short-term shading in the case of solar cells. Although the use of energy storage devices such as capacitors or batteries enables buffering, their design and size impose limits, especially in small-scale sensor systems. The idea of integrating the battery into areas that give the sensor stability, such as housings or circuit boards, is therefore a promising solution.

The integration of lithium-ion batteries in structural elements opens up new possibilities for the development of energy-autonomous systems. However, before this integration can take place, the batteries must meet the specific requirements associated with the integration. Particularly when embedded in printed circuit boards, robustness is required, especially with regard to high temperatures.

During soldering, for example, local temperatures of over 200°C can occur. Even if the battery is not being actively used at the time, choosing the right material combination is here crucial.

The cathode material lithium iron phosphate (LFP) provides a good thermal stability as it starts to decompose at

245°C [1]. It also has a high resistance to deep discharge due to its crystal structure and is considered a long-lasting material with over 1000 charging cycles [2]. These properties are particularly important as it may not be possible to replace the integrated batteries during the product life cycle.

Studies show that decomposition of the materials in uncharged LFP-Graphite Batteries occurs in absence of thermal runaway until 250°C.

From a state of charge (SOC) of 25% on, slight exothermic reactions occur, but these are not sufficient for thermal runaway. This is only to be expected from a temperature of over 140°C and a SOC greater than 50%. In case of overcharged cells these exothermal reactions start already at 80°C. Irrespective of this, destruction of the batteries occurs due to the decomposition of the electrolyte produces gas increasing the pressure inside the cell [2].

A frequently used electrolyte consisting of 1M LiPF₆ in ethylene carbonate (EC): Diethyl carbonate (DEC): Dimethyl carbonate (DMC) (2:1:2 v/v/v) begins to decompose at temperatures of 140°C and above. Exothermic reactions also occur at temperatures above 200°C [3]. One of the elements leading to a reaction and thus to the reduced temperature stability is the LiPF₆ lithium-salt used.

While pure LiPF₆ already shows the first signs of thermal decomposition at temperatures of 91°C, it reaches the peak of these decomposition reactions at around 200°C. A salt that can be used in electrolytes and that is more stable is lithium bis(oxalato)borate (LiBOB), with decomposition beginning at 295°C [4]. In addition, LiBOB can also be

dissolved in solvents with higher temperature stability such as gamma-butyrolactone (GBL) (boiling point 204°C) with EC (boiling point 248°C [4]. As GBL has a high dielectric constant it can also dissolve low solubility salts like LiBOB and depresses gassing of EC [5].

The separators of the cell, which avoid a short circuit between the anode and cathode and are generally made of polypropylene (PP) and polyethylene PE, do not show sufficient resistance at melting temperatures of around 130°C or 160°C [2].

In this work, cells with LFP cathodes, graphite anodes, a glass fiber separator and an electrolyte made of LiBOB in EC and GBL are investigated. In addition to high cycle stability, the electrode material also exhibits good resistance to temperatures in the temperature range relevant for integration. To avoid exothermic reactions in the cell, the cells are heated in an uncharged state and only then cycled. The individual components of the electrolyte also have a high temperature resistance due to the absence of linear carbonates and the use of LiBOB. The use of a glass fiber separator instead of PE and PP separators prevents melting and thus also the destruction of the cell.

2 Electrochemical measurements

2.1 Experimental

All measurements for electrochemical characterization were performed in Swagelok-type T-cells. Instead of a reference electrode a PT1000 temperature sensor was inserted to determine the temperature inside the cell. The sensor is molded into a thin-walled stainless steel sleeve filled with indium to avoid an insulating air gap.

Graphite was used as the anode material and lithium-iron-phosphate (LFP) as the cathode material. Both electrode materials were purchased from Customcells. A Whatman GF glass fiber filter was used as separator. The electrolyte was a mixture (1:1) of EC and GBL with 1 M (LiBOB). All electrolyte components were purchased from Sigma Aldrich.

The cells were assembled in an argon-filled glovebox with less than 0.5ppm oxygen.

After setting up the cells, they rested for 3 hours. They were then heated in an oven until the target temperature of 200°C and 220°C was reached inside the cell, removed from the oven, and cooled to room temperature. This was followed by a further 3-hour rest phase, followed by a charging/discharging cycle with a C/10 constant current, whereby the OCP was measured for one hour after the end-of-charge voltage was reached. The cells were then charged and discharged with a constant current of C/5 over 4 halfcycles, with a 1-hour OCP measurement following each half cycle.

In the case of the unheated reference cell, the heating step was omitted.

Both the measurement of the temperature and the cycling of the cells were carried out using USB-controlled potentiostats/galvanostats as described by Dobbelaere et al in [6]. The original software was adapted for this purpose.

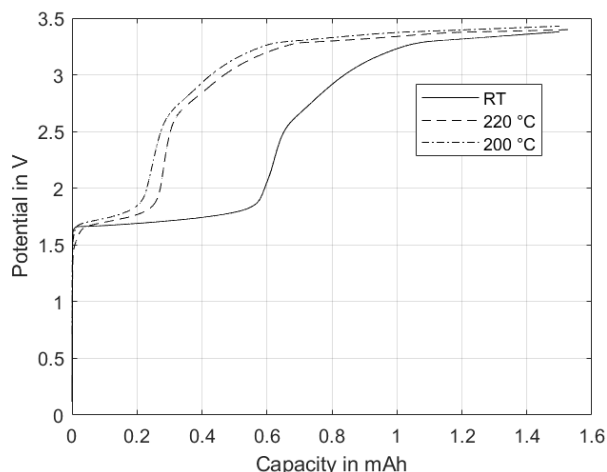


Figure 1 Potential of the first charging cycle at a current of 0.1C. The solid line represents the unheated reference cell, dashed-dotted line the cell heated to 200°C and the dashed line the cell heated to 220°C.

2.2 Results and Discussion

The first charging of the cells with a current of 0.1C shows a significant shoulder at a potential of 1.67 V for the electrolyte used (**Figure 1**). According to Xu, this can be attributed to production residues in the LiBOB and will only appear during the first cycle. In the case of the heated cells, this shoulder is less pronounced than in the case of the reference cell. Despite from this in all cases the voltage plateau at around 3.4 V is reached and stable.

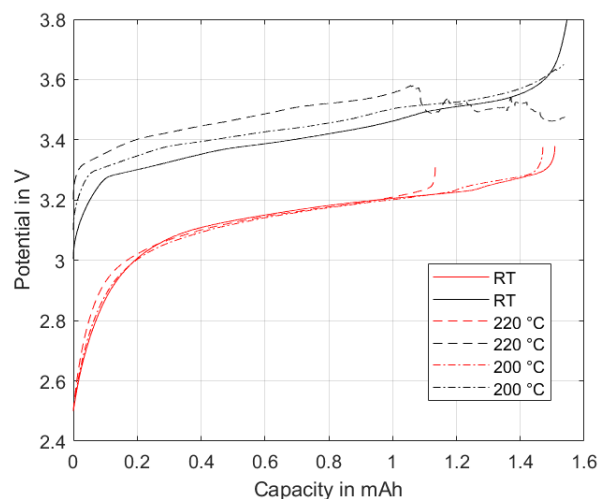


Figure 2 Potential of the second charging (black) and discharging process (red) cycle at a current of 0.2C. The solid line represents the unheated reference cell, the dashed-dotted line the cell heated to 200°C and the dashed line represents the cell heated to 220°C.

The comparison of the potential curves over the capacities (**Figure 2**) achieved when the cells are cycled at a current of 0.2C shows that the reference cell and the cell heated to 200°C have approximately the same discharge capacity,

while that of the cell heated to 220°C is significantly lower at 1.12 mAh. As the cells heated to 200°C could not reach the final charging voltage of 3.8V in our tests, this was reduced to 3.65V. In the case of the cell heated to 220°C, this limit voltage could no longer be reached in the second charging cycle, but collapsed after reaching a voltage of 3.58 V.

In addition to the measurement of the voltage curves over the capacitance of the cell, the subsequent monitoring of the OCP during the relaxation of the cell also shows a significant difference (**Figure 3**). All the cells show a stable voltage after the charging process. In case of the unheated reference cell and the cell heated to 200°C this potential is even the same and stabilizes at 3.4V. It is also noticeable that the potential difference between the heated and reference cells is much more pronounced after discharging.

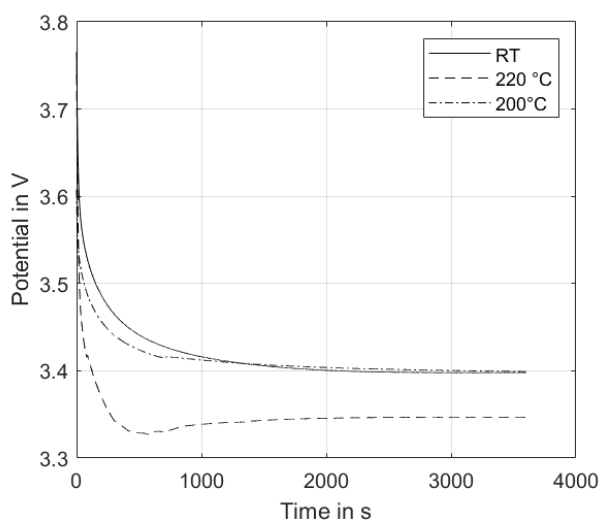


Figure 3 OCP after the 2nd charging with a current of 0.2C. The solid line represents the unheated reference cell, the dashed-dotted line the cell heated to 200°C and the dashed line represents the cell heated to 220°C.

Both the curve of the voltages over the capacity and the potential curve after charging show that the cell heated to 200°C behaves identically to the reference cell except for reaching the end-of-charge voltage. The cell heated to 220°C is also functional in principle, although the first temperature-related changes occur here, such as not reaching the final charging voltage and stabilisation at a slightly lower potential after charging.

3 Conclusion

We were able to show that lithium-ion batteries with LFP and graphite electrodes, a glass fiber separator and an electrolyte of 1M LiBOB in a 1:1 mixture of GBL and EC remain in principal functional even after heating up to 220°C. Up to a temperature of 200°C, the behaviour remains the same as for the unheated reference cell. Further investigations into long-term stability are subject of future studies.

4 Literature

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Auf der richtigen Frequenz – LoRaWAN als Zukunft der Füllstands- und Pegelüberwachung

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Nachhaltige Innovation – ein Begriff, der aus Unternehmenssicht mehrere Dimensionen besitzt: Umfasst er einerseits positive ökologische Auswirkungen eines Produkts oder einer Lösung, so sollte im Idealfall auch ein signifikantes wirtschaftliches Potenzial vorhanden sein. Um eine Innovation, die tatsächlich beide Aspekte erfolgreich in sich vereint, handelt es sich bei Pepperl+Fuchs' WILSEN.sonic.level bzw. „WILSEN“: Hinter diesem markanten Namen (kurz für Wireless Sensor Node) verbirgt sich ein funkbasierter LoRaWAN-Ultraschallsensor, der deutschlandweit auf reges Interesse stößt und sich auf bestem Wege befindet, zu einer Standardlösung im Bereich Entsorgungsmanagement zu werden. Doch auch über die Abfallwirtschaft hinaus kann dieser IoT-Füllstandssensor ein breites Einsatzspektrum abdecken – und dabei sogar zum potenziellen Lebensretter werden.

1 Beginn einer Erfolgsgeschichte

Wie bei vielen erfolgreichen Produktentwicklungen war die wirtschaftliche Nachhaltigkeit auch beim WILSEN kein Selbstläufer, wie Daniel Möst, New Business Development Manager bei Pepperl+Fuchs, im Gespräch berichtet: „Der heutige WILSEN ist das Resultat kontinuierlicher Weiterentwicklung. Immer wieder haben wir die von uns gesammelten Erfahrungen und das Feedback von Kunden aufgegriffen und in das Produkt einfließen lassen, bis die heute serienmäßig erhältliche Lösung entstanden ist.“ Tatsächlich erprobten die Mannheimer Spezialisten für Automatisierungstechnik bereits 2014 funkgestützte Ultraschallsensorik im Feld, damals als Teil eines Smart-City-Projekts in Barcelona. „Seinerzeit zeichnete sich schon ab, welche Relevanz das Thema Nachhaltigkeit global einmal einnehmen würde. Dieser Trend hat sich in den darauffolgenden Jahren weiter verstärkt und wir konnten eine ganze Reihe von Folgeprojekten an anderen Orten umsetzen“, skizziert Möst die Ursprünge des WILSEN.

Die erfolgreichen Testläufe zeigten, dass Pepperl+Fuchs hier im Begriff war, ein Produkt mit großem Potenzial zur Serienreife zu bringen: Was zu dieser Zeit noch unter dem nüchternen Arbeitstitel „IoT-Sensor“ in den sprichwörtlichen Kinderschuhen steckte, erreichte wenig später unter dem einprägsamen Namen „WILSEN“ den breiten Markt der öffentlichen Versorger und Entsorger.



2 Von Barcelona nach Heidelberg

Eines dieser Folgeprojekte spielte sich unweit des Mannheimer Pepperl+Fuchs Hauptsitzes ab und sollte einen weiteren Meilenstein auf dem Weg zum Serienprodukt markieren: Im Verbund mit der Digital-Agentur Heidelberg, SAP und Smart City Solutions konzipierte Pepperl+Fuchs im Jahr 2018 eine Lösung, um Füllstände von Entsorgungsbehältern im Heidelberger Stadtgebiet mittels funkbasierter Sensoren via LoRaWAN an eine IoT-Plattform zu übermitteln. „Dafür kapselten wir einen Ultraschallsensor, dessen Wandler mit einer PTFE-Schutzfolie überzogen ist, gemeinsam mit einem Funkmodul und einer Batterieeinheit in einem speziellen IP66/67-Gehäuse“, berichtet Möst. „So war die Sensorik für die widrigen Umgebungsbedingungen in Entsorgungscontainern entsprechend robust ausgelegt.“

3 Freiburg entsorgt intelligent

Heute, einige Jahre später, ist der WILSEN zu einem unverzichtbaren Bestandteil einer stetig wachsenden Anzahl von Entsorgungsbehältern in ganz Deutschland geworden. In die Liste der Städte und Gemeinden, die den batteriebetriebenen Ultraschallsensor aus dem Hause Pepperl+Fuchs für sich entdeckt haben, reiht sich auch Freiburg im Breisgau ein. Rund 350 Glascontainer warten hier im gesamten Stadtgebiet auf regelmäßige Abholung und Entleerung durch die Abfallwirtschaft und Stadtreinigung Freiburg (ASF).

Um dabei möglichst effizient und nachhaltig agieren zu können, vertraut die ASF seit mehreren Jahren auf die Unterstützung der badenovaNETZE. Als Tochter der badenova begleitet sie Kommunen und Dienstleister wie die ASF bei der Realisierung von IoT-Lösungen und hat dabei ein hohes Know-how und Qualitätsverständnis im Bereich

Sensorik aufgebaut. Aus diesem Grunde setzt sie auch in Freiburg auf den WILSEN von Pepperl+Fuchs: 2020 gingen 50 der funkbasierten Ultraschallsensoren in den örtlichen Glascontainern in Betrieb, nun folgten weitere 50 Stück. „Jeder zusätzliche Container, den wir mit Sensoren von Pepperl+Fuchs bestücken, hilft uns dabei, die Datenbasis für eine Mustererkennung und -interpretation weiter zu verbessern“, erklärt Sascha Dachtler, zuständig für Vertrieb und Projektentwicklung bei badenovaNETZE. Bereits heute sei die ASF so in der Lage, saisonale Tendenzen in der Containerauslastung zu erkennen und dank der durch die WILSEN-Sensoren übermittelten GPS-Daten die manuelle Tourenplanung zu verbessern.



4 Weniger Emissionen dank optimierter Routen

Insbesondere in den schwächer frequentierten Außenbezirken, die für Entsorgungsfahrzeuge nur nach längeren Fahrtwegen zu erreichen seien, versprechen die zusätzlichen intelligenten Container großes Potenzial für weitere Routenoptimierungen. „In erster Linie profitieren natürlich die Freiburger Bürger von den smarten Containern. Perspektivisch wollen wir gemeinsam mit der ASF eine vollständig automatisierte Routenplanung realisieren. So lassen sich Emissionen und Verkehrsbehinderungen im Stadtgebiet reduzieren. Aber auch dem Ärgernis überquellender Behälter können wir mit den smarten Containern effektiv entgegenwirken“, kündigt Dachtler an. Aufgrund des innovativen Charakters sei dieses Vorhaben auch Teil des Reallabor-Projekts „Smart Region Südbaden“ der badenovaNETZE und ihres Kooperationspartners Thüga AG. Im Rahmen dieses Projekts wurden in der Vergangenheit bereits diverse Smart-City-Anwendungsbeispiele aus den Bereichen Mobilität, Gebäude, Umweltschutz und technische Betriebe für verschiedene Kommunen entwickelt. „So haben wir die Möglichkeit, den Mehrwert von Smart-City-Anwendungsfällen für die teilnehmenden Kommunen erlebbar zu machen und den Erkenntnisaustausch untereinander zu fördern“, hebt Dachtler hervor.

Dass die Wahl in Freiburg auf den WILSEN fiel, war einem Tipp durch einen ehemaligen Projektpartner zu verdanken: Dieser hatte schon gute Erfahrungen mit dem Ultraschallsensor gemacht und ihn badenovaNETZE weiterempfohlen. „Wir waren auf der Suche nach einem wirklich

robusten Sensor, der die von uns bevorzugte, weltweit standardisierte LoRaWAN-Technologie nutzt und gleichzeitig auch bei variierenden Umgebungsbedingungen zuverlässig Füllstandsdaten übermittelt; der auch mal dreckig und nass werden darf. Der WILSEN versprach hier eine tragfähige Lösung“, beschreibt Dachtler die Erwägungen bei der Sensorauswahl.



Und tatsächlich überzeugte der WILSEN in der Praxis, wie von badenovaNETZE und ASF erhofft: „Jeder Sensor ist ab Werk auf einer Montageplatte aufgebracht, sodass sich die Geräte rüttelsicher im Inneren der Container verschrauben lassen. So können wir Problemen bei Entleerungsvorgängen vorbeugen. Inbetriebnahme und Anmeldung im LoRa-Netzwerk erfolgen ganz einfach via Bluetooth über eine App von Pepperl+Fuchs. Hat der Sensor seine Arbeit aufgenommen, ist er in der Lage, trotz Verschattungen durch Gebäude oder Vegetation kilometerweit Messdaten via LoRaWAN zu übertragen – und das bei einem sehr geringen Batterieverbrauch“, umreißt Dachtler die technischen Vorteile des WILSEN. Zudem sei auch die Unterstützung durch Pepperl+Fuchs ein Faktor bei der Sensorauswahl gewesen: „Uns war wichtig zu wissen, dass wir im Supportfall nicht mit einer Hotline verbunden werden, sondern dass der Techniker bei Bedarf kurzfristig bei uns vor Ort ist. Bereits die Betreuung in der Implementierungsphase hat uns gezeigt, dass wir mit all diesen Anforderungen bei Pepperl+Fuchs genau richtig sind.“

5 Existenzielle Bedrohung am Wupperufer

Doch auch abseits der Entsorgungswirtschaft ist es dem WILSEN gelungen, sich eine hochzufriedene Anwendergruppe zu erschließen – so zum Beispiel bei der Berger Gruppe in Wuppertal. Die Umstände, die hier zum Einsatz des Sensors führten, gestalteten sich bei den Spezialisten für CNC-Roboter-Schleif- und Poliertechnik jedoch deutlich dramatischer als in Freiburg: In der Nacht vom 14. auf den 15. Juli 2021 hatte sich die Wupper nach stundenlangen Starkregenfällen in einen reißenden Strom verwandelt und überflutete auch das unweit des Flussufers gelegene Firmengelände der Berger Gruppe. „Ich hatte riesige Angst, dass wir die Firma verlieren. Diese Ereignisse gehen mir bis heute nach“, erinnert sich Geschäftsführer Dr. Andreas Groß mit Schrecken an die Flutnacht zurück.

„Von 8 000 m² Firmenfläche standen 7 000 m² unter Wasser. Das betraf auch 30 Roboter, die gerade auf Auslieferung zum Kunden warteten. Da uns aufgrund der problematischen Lage des Gebäudes eine Versicherung gegen Flutschäden immer verwehrt worden ist, mussten wir letztlich einen Schaden von fast einer Million Euro selbst abfedern“, skizziert Groß die Tragweite der Katastrophe.

6 Wille zur Eigeninitiative

Die zum Zeitpunkt der Überflutung gegebenen öffentlichen Überwachungs- und Schutzmaßnahmen sieht der promovierte Ingenieur rückblickend kritisch: „Einige wenige, nicht miteinander vernetzte Sensoren und ein lückenhaftes Netz von Sirenen können im Zeitalter von Digitalisierung und Klimawandel nicht der Anspruch an ein verlässliches Hochwasserwarnsystem sein“, konstatiert Groß. Und so reifte – noch während der kräftezehrenden Aufräumarbeiten – innerhalb der Berger Gruppe der Plan, ein technisches Konzept zu erarbeiten, um Menschen und Gebäude entlang der Wupper und ihren Zuflüssen künftig effektiver vor Hochwasserereignissen zu schützen: „Sich lediglich über das Schicksal zu beklagen, war für uns keine Option. Stattdessen überlegten wir, welche Impulse wir als Unternehmen mit technologischem Know-how für die Allgemeinheit liefern können.“

Tatsächlich kann die Berger Gruppe auf eine umfangreiche Expertise rund um die Themen Sensorik, Steuerungstechnik und adaptives Lernen zurückgreifen. Davon zeugen 950 Roboterautomationen, die das Unternehmen im Laufe der Jahre für seine Kunden realisiert hat. Dieses Wissen floss nun auch in die Entwicklung des initialen technischen Anforderungsprofils für ein Monitoring- und Analysesystem, mit dem Pegelstände und Regenmengen entlang der Wupper und ihren Bächen und anderen Zuläufen zuverlässig überwacht werden sollen.

7 Passgenau abgestimmte Sensorik

Einen zentralen Punkt in dem Konzept stellte natürlich die zu verwendende Sensorik dar: „Die Wahl einer geeigneten Sensorlösung war ein Teilthema, um das ich mich selbst gekümmert habe. Bei der Recherche bin ich auf den Ultraschallsensor WILSEN von Pepperl+Fuchs aufmerksam geworden, der bereits viele der von uns geforderten Kriterien abdeckte“, erläutert Groß. Einer der Aspekte, die ihn überzeugten, waren die einstellbaren Übertragungsintervalle: „Wir können jetzt softwareseitig das Sendeverhalten des Sensors mit den aktuellen Wetterdaten synchronisieren. Das bedeutet, dass der WILSEN im Falle gemeldeter Niederschläge häufiger Füllstände über das LoRa-Netzwerk an unseren Server sendet als bei Schönwetterlage. Dadurch lässt sich die Laufzeit der Hochleistungsbatterien noch weiter verlängern“, schildert Groß.

Dennoch hatten er und seine Mitstreiter noch einen speziellen Anpassungswunsch an Pepperl+Fuchs: „Der standardmäßige Erfassungsbereich des WILSEN ist zur Überwachung eines Entsorgungscontainers sicherlich völlig ausreichend. Da wir die Sensoren in unserem Anwendungsfall allerdings häufig an bzw. unter Brücken montieren und diese unterschiedliche Höhen haben, wollten wir

keinerlei Risiken eingehen, dass die Distanz zwischen Brücke und Flussbett in Einzelfällen zu groß für den Sensor sein könnte. Wir haben das mit Pepperl+Fuchs diskutiert und tatsächlich ist man unserem Wunsch nachgekommen und hat die Reichweite des Sensors noch mal deutlich erhöht. Das hat uns beeindruckt und war für uns ein Zeichen, dass wir hier auf den richtigen Partner für die Ultraschallsensorik setzen.“



8 Sensordaten als Basis für adaptives Lernen

Seitdem hat das Projekt an der Wupper weiter an Fahrt aufgenommen: Neben der Berger Gruppe unterstützen auch die Stadtwerke Wuppertal, die Technischen Betriebe Solingen, die Bergische Gesellschaft sowie die Uni Wuppertal und das ihr angeschlossene IZMD (Interdisziplinäres Zentrum Machine Learning and Data Analytics) das ehrgeizige Vorhaben. Rund 60 WILSEN sowie zusätzliche Drucksensoren verrichten mittlerweile entlang der 116 Kilometer langen Gewässerstrecke ihren Dienst. „Mit Sensoren Pegelstände zu überwachen, ist an sich kein Neuland. Womit wir mit unserem Projekt aber weiter gehen als bisher: Wir nutzen die Messdaten, um das datenbasierte, adaptive Lernsystem des IZMD zu speisen und weiterzuentwickeln. In zwei bis drei Jahren werden wir damit in der Lage sein, mittels eines Algorithmus hochpräzise Vorhersagen zur Pegelentwicklung zu treffen. Die Kombination aus funkgestützter Sensorik und künstlicher Intelligenz, mit der wir hier arbeiten, passt dafür wie die Faust aufs Auge“, zeigt sich Groß optimistisch.

Zudem hoffen er und die weiteren Unterstützer darauf, dass ihre prototypische Entwicklung als Leuchtturmprojekt in das KI-Spitzencluster des Landes Nordrhein-Westfalen aufgenommen wird. „Das würde unserem Projekt natürlich noch mal großen Vorschub leisten. Perspektivisch möchten wir ein skalierbares und niedrigschwelliges Hochwasserwarnsystem nach Open-Source-Prinzip bereitstellen, von dem nicht nur die Anwohner der Wupper, sondern auch die breitere Öffentlichkeit profitieren“, skizziert Groß die langfristigen Ziele. Die Aufmerksamkeit ebendieser Öffentlichkeit habe das Projekt indes bereits längst auf sich gezogen. Dafür spreche die Tatsache, dass Groß kürzlich sogar eine interessierte Anfrage aus dem mit Überflutungen sehr vertrauten US-Bundesstaat Mississippi erreicht habe.

9 Übertragbares Prinzip

Währenddessen zeigt man sich auch bei Pepperl+Fuchs umtriebig in Bezug auf die Zukunft des WILSEN. So entdeckten nun immer mehr Industriekunden den WILSEN für sich, wie Daniel Möst von Pepperl+Fuchs schildert. „Aktuell implementieren wir den WILSEN beispielsweise bei einem großen süddeutschen Automobilhersteller. Hier verbirgt sich durch die Überwachung von IBC-Tanks oder Wertstoffbehältern auf dem Werksgelände ebenfalls ein beachtliches Optimierungspotenzial, das sich mit relativ geringem Aufwand heben lässt. Die funkbasierte Ultraschallsensorik hat sich mittlerweile als eine ideale Lösung für verschiedene Anwendungen im Kontext von Nachhaltigkeit und Smart City sowie der Industrie bewiesen.“

Darüber hinaus spinne das Unternehmen auf Basis all der gesammelten Projekterfahrungen den Grundgedanken kontinuierlich weiter: „Im nächsten Schritt werden wir auch andere sensorische Wirkprinzipien als nur Ultraschall mit Funkübertragung kombinieren. Unsere Kunden und Anwender dürfen sich schon jetzt auf eine weitere Variante des WILSEN freuen: Mit dem WILSEN. valve planen wir den Markteintritt mit einem batteriegestützten LoRa-Sensor zur Ventilstellungsüberwachung. Auch hier sehen wir einen großen Bedarf und sind davon überzeugt, zeitnah eine passgenaue Lösung bieten zu können“, verspricht Möst abschließend.

On the Right Frequency—LoRaWAN as the Future of Fill Level and Water Level Monitoring

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Sustainable innovation is a term that has several dimensions from a company's perspective—it encompasses the positive environmental impacts of a product or solution, so ideally there should also be significant economic potential. The WILSEN.sonic.level or "WILSEN" from Pepperl+Fuchs is an innovation that successfully combines both of these aspects. Behind this distinctive name (short for Wireless Sensor Node) is a radio-based LoRaWAN ultrasonic sensor that is attracting great interest throughout Germany and is on the way to becoming a standard solution in the field of waste management. But this IoT level sensor can also cover a wide range of applications beyond waste management—and even become a potential lifesaver.

1 Start of a Success Story

As with many successful product developments, economic sustainability was not a sure-fire success with WILSEN, as Daniel Möst, New Business Development Manager at Pepperl+Fuchs, explains: "Today's WILSEN is the result of continuous development. We have continuously gathered experience and feedback from customers and worked this into the product to create the solution that is available as standard today." In fact, the Mannheim-based specialists in automation technology already tested radio-based ultrasonic sensors in the field in 2014, as part of a smart city project in Barcelona. "At the time, it was already clear that the topic of sustainability would assume great global relevance one day. This trend has intensified further in subsequent years, and we have been able to implement a whole series of follow-up projects in other locations," says Möst, outlining the origins of WILSEN.

2 From Barcelona to Heidelberg

One of these follow-up projects took place near the Pepperl+Fuchs headquarters in Mannheim, marking another milestone on the way to series production. In conjunction with the Digital-Agentur Heidelberg, SAP, and Smart City Solutions, Pepperl+Fuchs designed a solution in 2018 for transmitting the fill levels of waste disposal containers in Heidelberg's metropolitan area to an IoT platform via LoRaWAN using radio-based sensors. "For this purpose, we encapsulated an ultrasonic sensor—the transducer of which is coated with a PTFE protective film—together with a radio module and a battery unit in a special IP66/67 housing," says Möst. "This meant that the sensor technology had a robust design for the adverse ambient conditions in the waste disposal containers."

The successful test runs showed that Pepperl+Fuchs was about to bring a product with great potential to series production maturity. What was still in its infancy under the simple working title "IoT sensor" at the time, reached the

wider market of public utilities and waste disposal companies shortly afterward with the catchy name "WILSEN."



3 Intelligent Waste Disposal in Freiburg

Today, several years later, WILSEN has become an indispensable part of an ever-growing number of waste disposal containers throughout Germany. Freiburg im Breisgau is also part of the list of cities and municipalities that have discovered the battery-operated ultrasonic sensor from Pepperl+Fuchs. Around 350 glass containers throughout the entire metropolitan area require regular collection and emptying by ASF (Abfallwirtschaft und Stadtreinigung Freiburg—Freiburg's waste management and city cleaning service provider).

To be able to act as efficiently and sustainably as possible, ASF has been relying on the support of badenovaNETZE for several years. As a subsidiary of badenova, it supports municipalities and service providers such as ASF in implementing IoT solutions, and has established a high level of expertise and understanding of quality in the field of sensor technology. For this reason, in Freiburg they also rely on WILSEN from Pepperl+Fuchs: In 2020, 50 of the radio-based ultrasonic sensors went into operation in the local glass containers, followed by another 50 units. "Each addi-

tional container that we equip with sensors from Pepperl+Fuchs helps us to further improve the database for pattern recognition and interpretation," explains Sascha Dachtler, responsible for sales and project development at badenovaNETZE. ASF is already able to detect seasonal trends in container utilization and, thanks to the GPS data transmitted by the WILSEN sensors, to improve manual route planning.



4 Reduced Emissions Thanks to Optimized Routes

The additional smart containers promise great potential for further route optimization, especially in the less frequented suburbs that can only be reached by disposal vehicles driving longer distances. "Of course, the citizens of Freiburg are the ones who will primarily benefit from the smart containers. In the future, we want to implement fully automated route planning together with ASF. In this way, emissions and traffic obstructions in the metropolitan area can be reduced, and we can effectively counteract the annoyance caused by overflowing containers with the smart containers," says Dachtler. Due to its innovative character, this is also part of the "Smart Region Südbaden" living lab project by badenovaNETZE and its cooperation partner Thüga AG. As part of this project, various smart city application examples have already been developed for various municipalities in the areas of mobility, buildings, environmental protection, and technical operations. "This gives us the opportunity to experience the added value of smart city applications for the participating municipalities and to promote the exchange of knowledge," emphasizes Dachtler.

WILSEN was chosen in Freiburg thanks to a tip from a former project partner who had already had a positive experience with the ultrasonic sensor and recommended it to badenovaNETZE. "We were looking for a truly robust sensor that uses our preferred, globally standardized LoRaWAN technology, reliably transmits fill level data even in varying ambient conditions, and can get dirty and wet from time to time. WILSEN promised to be a viable solution here," says Dachtler, describing the considerations made when choosing a sensor.

WILSEN also impressed in practice, as hoped by badenovaNETZE and ASF: "Each sensor is attached to a mounting base at the factory so that the devices can be screwed into the inside of the containers and be resistant to vibrations.

This will help to prevent problems during emptying operations. Commissioning and logging into the LoRa network can be carried out easily via Bluetooth using an app from Pepperl+Fuchs. Once the sensor has started working, it is able to transmit measurement data over several kilometers via LoRaWAN despite shadowing from buildings or vegetation—all with very low battery consumption," says Dachtler, describing the technical advantages of WILSEN. The support provided by Pepperl+Fuchs was an additional factor when selecting the sensors: "It was important for us to know that, if support was needed, we would not be connected to a hotline, but that the technician would be on-site at short notice. The support we received during the implementation phase showed us that with all these requirements, we had made the right choice with Pepperl+Fuchs."



5 Existential Threat on the Banks of the Wupper

But WILSEN has also managed to tap into a highly satisfied user group away from the waste management industry—for example, at the Berger Gruppe in Wuppertal. However, the circumstances that led to the specialists for CNC robot grinding and polishing technology using the sensor were much more dramatic than in Freiburg. During the night of July 14 to 15, 2021, the Wupper River turned into a raging torrent after hours of heavy rainfall, flooding the Berger Gruppe's company premises located not far from the river bank. "I was afraid that we would lose the company. The events still haunt me to this day," says Managing Director Dr. Andreas Groß, remembering the night of the flood with horror. "Our company premises spans 8000 m², of which 7000 m² were under water. This also affected 30 robots, which were awaiting outbound delivery to customers. Because we have always been denied insurance against flood damage due to the problematic location of the building, we ultimately had to cushion a loss of almost a million euro ourselves," says Groß, outlining the scope of the disaster.

6 Willingness to Take the Initiative

In retrospect, the PhD engineer is critical of the public monitoring and protective measures at the time of the flooding: "In the age of digitalization and climate change, a few sensors that are not networked with each other and an incomplete network of sirens cannot be the requirement

for a reliable flood warning system," says Groß. And so—even during the debilitating cleanup work—a plan formed within the Berger Gruppe to develop a technical concept to protect people and buildings along the Wupper River and its tributaries more effectively from flood events in the future: "Simply complaining about fate was not an option for us. Instead, we considered what impetus we could provide to the general public as a company with technological expertise."

The Berger Gruppe can draw on extensive expertise in the fields of sensor technology, control technology, and adaptive learning. This is evidenced by the 950 robot automations that the company has realized for its customers over the years. This knowledge has now also been incorporated into the development of the initial technical requirements profile for a monitoring and analysis system, with which water and rainfall levels along the Wupper, its streams, and other inlets can be reliably monitored.

7 Precisely Matched Sensor Technology

A key aspect of the concept was, of course, the sensor technology to be used: "Choosing a suitable sensor solution was a subtopic that I took care of myself. During my research, I became aware of the WILSEN ultrasonic sensor from Pepperl+Fuchs, which already covered many of our required criteria," explains Groß. One of the aspects that convinced him was the adjustable transmission intervals: "In the software, we can now synchronize the transmission behavior of the sensor with the current weather data. This means that in the event of reported rainfall, WILSEN transmits fill level data to our server more frequently via the LoRa network than in fair weather conditions. This allows the runtime of the high-power batteries to be extended even further," explains Groß.

Nevertheless, Groß and his colleagues had a special adaptation request for Pepperl+Fuchs: "The standard sensing range of WILSEN is certainly completely sufficient for monitoring a waste disposal container. However, since we often mount the sensors on or under bridges and these have varying heights, we did not want to risk the distance between the bridge and river bed being too large for the sensor in some cases. We discussed this with Pepperl+Fuchs and they fulfilled our request, and the detection range of the sensor has been significantly increased. This really impressed us and showed us that we are relying on the right partner for ultrasonic sensors."

8 Sensor Data as the Basis for Adaptive Learning

Since then, the project on the river Wupper has continued to gain momentum—in addition to the Berger Gruppe, Stadtwerke Wuppertal, Technische Betriebe Solingen, Bergische Gesellschaft, the University of Wuppertal, and the associated IZMD (Interdisciplinary Center for Machine Learning and Data Analytics) are also supporting the ambitious project. Around 60 WILSEN and additional pressure sensors are now operating along the 116-kilometer-

long stretch of water. "Monitoring water levels with sensors is not uncharted territory, but what we are doing with our project is going further than before. We are using the measurement data to feed and further develop the data-based, adaptive learning system of the IZMD. In two to three years, we will be able to make highly accurate predictions regarding the development of water levels using an algorithm. The combination of radio-based sensor technology and artificial intelligence that we work with here is a perfect match for this," says Groß optimistically.

Furthermore, Groß and the other supporters hope that their prototype development will be included as a flagship project in the top AI cluster in North Rhine-Westphalia. "That would of course give our project a big boost. In the future, we would like to provide a scalable and low-threshold flood warning system based on an open source principle, from which not only the residents of Wupper, but also the wider public can benefit," says Groß, outlining the long-term goals. The project has long since attracted the attention of this very public. This is supported by the fact that Groß recently even received an interest request from the US state of Mississippi, which is very familiar with floods.



9 Transferable Principle

Meanwhile, Pepperl+Fuchs is also busy with regard to the future of WILSEN. More and more industrial customers have now discovered WILSEN for themselves, as Daniel Möst from Pepperl+Fuchs describes: "We are currently implementing WILSEN at a major car manufacturer in South Germany, for example. Monitoring IBC tanks or recycling containers on the plant premises harbors considerable potential for optimization that can be leveraged with relatively little effort. Radio-based ultrasonic sensors have now proven to be an ideal solution for various applications in the context of sustainability, smart city applications, and in industry."

Furthermore, on the basis of all the project experience gathered, the company continues to develop the basic idea: "Next, we will also combine sensing principles other than just ultrasound with radio transmission. Our customers and users can already look forward to another version of WILSEN—with the WILSEN.valve we are planning to enter the market with a battery-powered LoRa sensor for valve position monitoring. We see a great need in this area and we are convinced that we will be able to offer a tailor-made solution in the near future," concludes Möst.

Ultrasonic Wake-Up Receiver for An Ultra-Low Power Communication Platform

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Abstract

This paper presents an ultrasonic receiver that implements a wake-up functionality to save energy. A small form factor allows flexible use in a variety of systems. The presented ultrasonic communication platform uses piezo crystals as transducers with a resonant frequency of 2 MHz, which couple sound waves into a steel bar. Due to high acoustic damping, a weak signal of -50 dBm is received after 1 meter. A demonstrator is built and tested using off-the-shelf components.

1 Motivation

Integrated sensor systems in metallic cavities, such as machine elements, face challenges when data needs to be transmitted from inside a metal enclosure. This encapsulation is mandatory in this application and prevents an electromagnetic transmission [1]. An ultrasonic communication platform solves this problem, as these waves can penetrate metal [2]. To optimize the power consumption and therefore enable a lifetime of the battery-powered device for multiple years with a single button cell battery, the communication module turns off most of the time. Since system availability must be ensured, a wake-up receiver is needed to wake up the sensor platform, therefore the receiver turns on periodically.

The characteristic of the acoustic channel is unknown because it is highly dependent on the physical design of the platform's environment. To compensate for these variables, the receiver provides a high dynamic range and adapts to varying signal strengths at its input.

The concept of a wake-up receiver is well known in the field of classical electromagnetic radiofrequency (RF) [3]. These concepts can be adapted and implemented in the ultrasonic domain.

2 Physical Setup

2.1 System Overview

The system consists of two asymmetric parts, a base station and one or more nodes. These nodes are integrated with the sensors and act as a communication interface. Due to the low power availability within the sensor system, the ultrasonic transmitter and receiver must be as energy efficient as possible. To optimize power consumption, the nodes are in a sleep mode most of the time while they are still individually addressable. The data to be transmitted is not time critical and a delay of multiple seconds can be accepted. Only small data packets of a few bytes are expected for transmission. A small form factor must also be achieved to allow integration with a variety of sensors. A circular PCB design with the same diameter as a 12 mm CR1220 button cell battery is targeted.

The base station, on the other hand, has no size or power constraints. OOK (On-Off-Keying) was chosen as the modulation scheme because it can be decoded with little hardware effort.

2.2 Transmission Channel

B. Wang et al. [4] have shown that it is generally possible to transmit data over an ultrasonic channel. They propose a directed transducer design that can improve the transmission quality. For the intended use case with an unknown placement of the sensors and the base station, a directed wave cannot be expected. Due to these limitations, a piezo crystal is clamped to a steel bar. According to [4] this will generate waves that are ideal to just penetrate the metal and have the receiver on the opposite side. Due to reflections, a small fraction of the signal energy is expected to propagate through the steel bar. The setup is shown in Figure 1. Measurements have shown that the signal is received with an amplitude between 1 mV and 10 mV after 1 m of transmission.

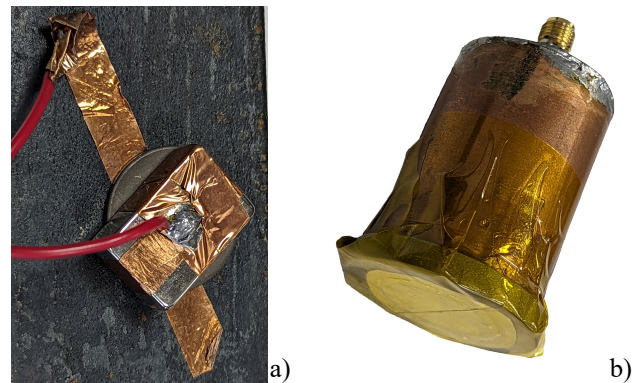


Figure 1 The physical setup of the system. A piezo crystal is clamped onto steel bar using a magnet (a). Another one is added with a distance of 1 m. One piezo transmits, the other receives. The receiving one is connected to the wake-up receiver. To reduce influences of electromagnetic couplings on the measurements, the setup is encapsulated in a metal enclosure (b).

3 Hardware Receiver

The receiver is built around a low power microcontroller in the form of an STM32L072 by STMicroelectronics. The controller is responsible for powering up the receiver circuitry and processing the received signals.

3.1 Design

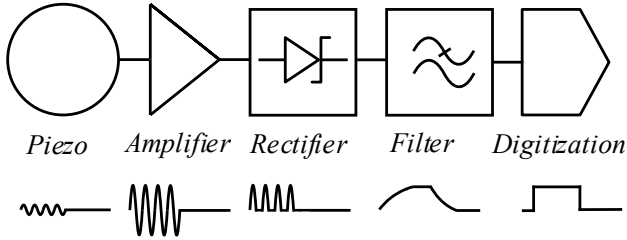


Figure 2 The block diagram of the proposed receiver design. The received signal is amplified and filtered. For demodulation, the amplified signal is then rectified using a Schottky diode [5]. The rectified signal is low pass filtered and digitized by a comparator.

The general design of the receiver is shown in Figure 2. The comparator is integrated with the microcontroller, this optimizes power consumption and required area. Discrete off-the-shelf components are used for all other elements. The microcontroller has an ultra-low power sleep mode in which it only consumes $0.85 \mu\text{A}$ at 3 V. A power switch, controlled by the microcontroller, turns the analog front end off to save power.

The receiver is integrated within other components onto a circular printed circuit board (PCB) with a diameter of 20 mm and shown in Figure 3. The physical size could be decreased further by selecting smaller packages of the individual components.

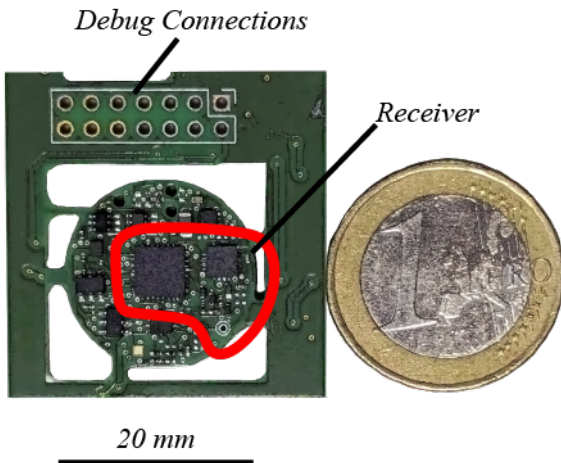


Figure 3 The receiver design is implemented onto a circular PCB with a diameter of 20 mm. The receiver circuit is marked in red.

3.2 Amplification

We selected an AD8338 from Analog Devices as a variable low noise amplifier (LNA). With a gain of up to 80 dB, the weak input signal can be amplified to a peak-to-peak voltage of 1 V for further processing. The variable gain allows adaptation to variations within the physical transmission channel. Since the power consumption of the amplifier depends on the gain setting, a gain as low as possible and as high as necessary must be found. This is done during an initial calibration process. Therefore, a continuous signal is transmitted from the base station so that the receiver can calibrate to it.

3.3 Digitization

The capacitor after the rectifying diode is selected based on the desired data rate. A trade-off must be made between transmission speed and reliability. Figure 4 shows a 1 nF capacitor with a 1 kHz modulated signal. The cutoff frequency of the demodulating low pass filter is designed to be between the carrier frequency and the modulation frequency. A smaller capacitor tends to show a too high cutoff frequency and does not smooth the analog signal enough to fully restore the digital signal. In comparison, a larger capacitor will limit the data rate as charging and discharging the capacitor takes longer. A comparator digitizes the received signal. The smoothed analog signal is fed as an input and compared with an analog voltage provided by the microcontroller's digital to analog converter (DAC). This allows the threshold voltage to be adjusted to compensate for signal strength.

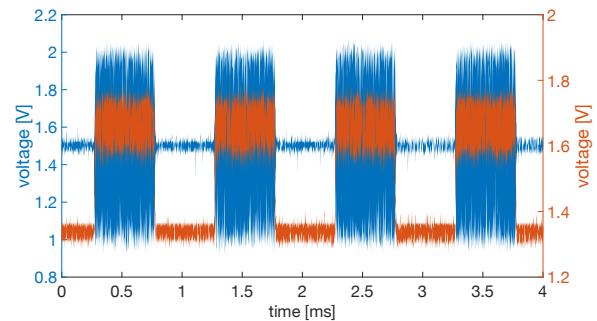


Figure 4 The amplified signal (blue) and the filtered signal at the capacitor (orange). A capacitance of 1 nF is used to filter a 1 kHz OOK modulated signal. The low pass filter is designed so that the cutoff frequency is between the carrier frequency and the modulation frequency to generate an input for the following comparator.

4 Wake-Up and Receive

The concept of low power wake-up receivers in a classical RF environment has been described in the past and is now to be adapted to the ultrasonic domain [3].

To keep the power consumption as low as possible, the analog frontend is turned off most of the time and the controller is put into a standby mode. The built-in real-time clock (RTC) allows for periodic wake-ups of the controller to check for incoming data.

4.1 Wake-Up

To initiate a wake-up, the base station will first broadcast a continuous carrier signal. This broadcast must be long enough to be picked up by the node twice during its sensing periods to assure a reliable wake-up call and reduce the chance of a false positive detection due to a noisy signal.

The wake-up call continues with a zero modulation followed by another one modulation for synchronization. If the node detects a one modulated signal after the sensing frequency is increased, it can sleep for the duration of the zero modulated signal. Once the synchronization rise is detected, the sensing frequency can be reduced to the base station transmit frequency.

The base station starts each data package with the address of the target node. After the address is transmitted and received by the node it can be compared to the programmed address. If the received address matches the node's address, the node will listen for the actual data transmission. If the address does not match, the node can return to sleep mode and reduce the scanning frequency again.

The wake-up and data transmission scheme is shown in Figure 5.

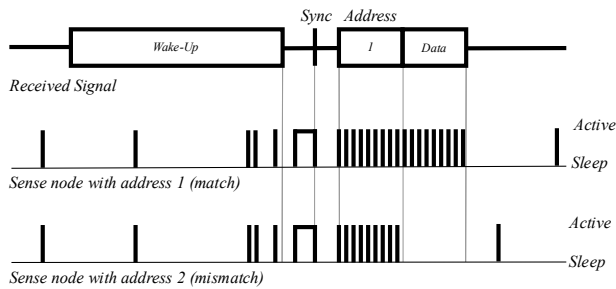


Figure 5 The node will increase its scanning frequency after the carrier signal is detected twice. After a synchronization scheme, the base station will transmit the address of the destination node. The individual node compares the received address with its own and listens for incoming data or returns to sleep.

4.2 Transmission Speed and Data Rate

The maximum possible transmission speed of the node with the weakest transmission quality will limit the data rate for the address transmission during wake-up for all nodes. Based on the maximum possible packet length, the worst time to send a packet can be calculated.

If a node detects a different address during the wake-up process it can go back to sleep mode. To prevent a false wake-up by detecting parts of the still ongoing transmission, the node must sleep at least until the transmission with the other node is done. To further improve energy efficiency, the sleep time can be increased.

5 Evaluation

In sleep mode the microcontroller with its running RTC consumes 0.85 μA at 3 V. In sensing mode, the power consumption is determined by the required gain of the amplifier. At 40 dB the circuit requires 3 mA. This results in a power consumption of less than 2.6 μW in standby and approx. 9 mW in sense mode. The average power consumption will highly depend on the systems usage and the desired response time. For example, at a 1 s response time the average power consumption is 12 μW , with 10 s it is reduced to 3.5 μW .

During transmission, electromagnetic couplings were observed that drastically improved the transmission quality. Metallic encapsulation was used to eliminate these effects. The receiver was successfully tested to receive data of up to 20 kBaud through the ultrasonic channel.

6 Summary and Outlook

A prototype of a wake-up receiver in an ultrasonic communication platform has been developed, implemented, and successfully tested. Concepts from classical RF receivers can be adapted to the ultrasonic platform. It was shown that the system can be implemented in a way that it is compatible in power consumption and size with a CR1220 button cell battery.

In future work, both the base station and the physical transmission channel can be further improved. Overall, it is confirmed that ultrasonic communication is a promising alternative to electromagnetic transmission when connecting integrated sensors.

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An Improved Architecture for a Fully Digital UHF RFID PIE-Stream Data Recovery Circuit

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Abstract

In UHF RFID systems conforming to the EPC-Gen2 standard, data from reader to tag is sent in a pulse-interval encoded (PIE) manner. Recovery of this data is an important first step towards establishing communication. A data frame may be sent at any time after a completed startup, and, hence, the receiver must be continuously active. Traditionally, an analog or digital circuit samples the incoming signal and performs the decoding by measuring the times between received pulses. In this contribution, we propose an improved method that relies on a partly asynchronous architecture. Decoding and pulse-interval measurements are performed by an emulated JK-FlipFlop that enables or disables a counter, and symbol decoding is realized by thresholding the counter values. This procedure results in a bitstream that can be further processed by an attached shift register for the following command processing.

We evaluated our new architecture with an FPGA-based prototype of a UHF-RFID-based sensor system comprising a protocol processor and additional control logic. We show that our new structure can be used with a reduced clock frequency compared to a conventional sampling-based decoder. Also, the new structure allows for better integration with approaches such as On-Demand Clocking since it may start its own clock at the start of the data frame. The new decoder circuit was integrated into an ASIC with a conventional automated synthesis process. The functionality has been shown in a post-layout simulation.

1 Introduction

In context of passive UHF RFID systems, the reduction of the energy demand of circuits is a major challenge [1,2]. Every component is to be optimized for low power. Consider the system shown in Fig. 1 where a transponder IC is used to realize a UHF RFID sensor system. The chip handles the communication and the energy management and may control external circuitry. It comprises analog and digital components. Low-power design for analog circuits is a well-explored topic [3]. In the digital part of the system, the energy is often reduced via clock gating [4] or reduction of the clock frequency itself. The clock frequency, however, can only be reduced to the point where the communication with a reader device can be established. Therefore, a focus point of these considerations are the units handling the signals from the outside. In the regarded system, this targets the encoder and decoder blocks. We focus here on a purely digital implementation of the PIE decoder, which recovers timing and data information from the incoming pulse-interval encoded (PIE) signal. By using a JK-FlipFlop-based structure, we reduce the minimum clock frequency needed for bit decoding.

This contribution is structured as follows: In a first section, we show the principles of PIE decoding. We proceed to present our improved PIE decoder structure along with a sketch of the implementation. Finally, we present our verification based on digital simulation and FPGA prototyping with a discrete RF frontend.

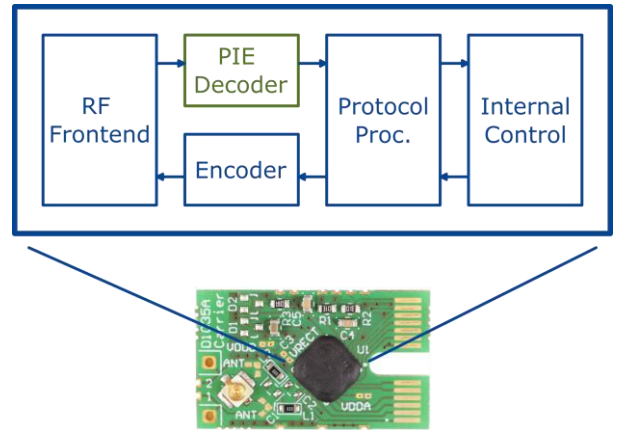


Figure 1. System overview of our passive UHF RFID transponder prototype. Our IC has been bonded to a test PCB for interfacing the characterization environment.

2 PIE-Stream Decoding

The incoming data signal for the RFID transponder is encoded using pulse intervals. As the name *pulse interval encoding* indicates, the data values are defined by the distance between incoming rising edges on a given signal. The structure of a data frame is shown in Fig. 2.

The begin of a frame is indicated by a delimiter phase of a fixed width. It is followed by a Data-0 symbol for calibrating the fundamental time unit used in all further symbol, the Tari [1]. Before the actual payload data is transmitted, the RTCAL and TRCAL (optional) symbols are sent.

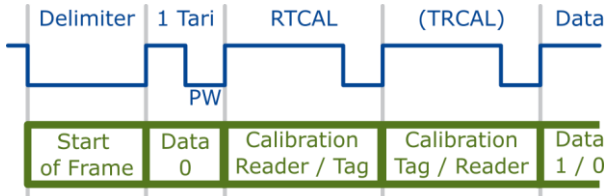


Figure 2. Frame structure of an incoming signal according to the EPC-Gen2 Standard [1] whereas Tari represents the time base of the transmission and PW the pulse-width. RTCAL and TRCAL determine the communication parameters.

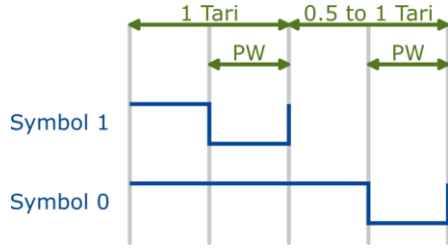


Figure 3. Encoding of data symbols in the PIE stream as defined by [1].

RTCAL defines the reader-to-tag communication by representing the duration of a data-1 and data-0 symbol. TRCAL calibrates the tag-to-reader transmission and is used to calculate the backscatter link frequency and thereby the data rate. The TRCAL phase is optional may be omitted by the reader after the first frame.

The payload data is encoded as shown in Fig. 3 by encoding the data value in the distance between the begin of the symbol and the first low pulse. This leads to the conclusion that the decoder is inherently bounded by the accuracy of the utilized time measurement which is directly related to the used clock frequency.

3 Decoder Architecture

The interface of our PIE decoder is shown in Fig. 4. The output is designed to provide the recovered values along with signals indicating that a new value arrived. In this sense, the *new_frame* signal indicates new RTCAL and TRCAL value and *new_bit* shows that a new bit is to be processed by the following unit.

The incoming PIE signal is generated by an analog component and is therefore asynchronous to the internal clock. For measuring timings between edges on this signal, an edge detector based on standard D-FlipFlops can be used. Still, this leads to the effect that due to time discretization the delay measurement may be offset by up to two clock cycles, i.e. one clock cycle at the beginning and the end of a pulse.

Note that pulses are never measured being too long with this method, since the time quantization may only miss a cycle but never add an additional cycle.

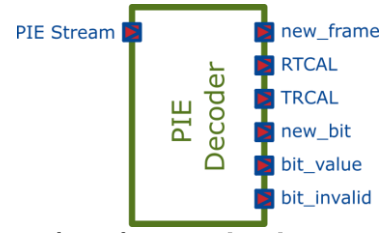


Figure 4. Interface of our PIE decoder circuit.

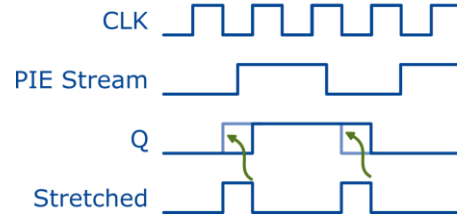
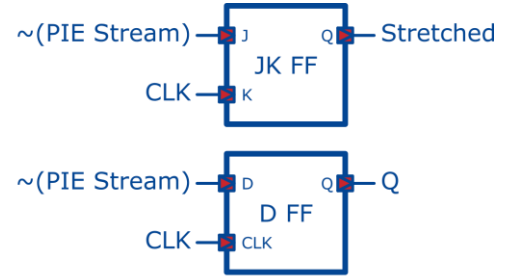


Figure 5. Basic idea of our PIE decoding scheme. By using a JK-FlipFlop, we correct the time measurement executed by a standard timer realized with D-FlipFlops.

The effect is shown in Fig. 5: For a standard D-FlipFlop based sampling of an additional signal, the output signal Q may be a cycle shorter. This may compromise the decision between 0 and 1 symbols and can only be mitigated by increasing the clock frequency to a value, where the error is neglectable. By using an JK-FlipFlop-based detector, we can correct the measurement since we can detect, whether the incoming pulse was compromised. The concept is shown with the *Stretched* signal that indicates the *implicit rounding* due to the discretization (indicated by the green arrows). For simplicity, only a single JK-FlipFlop is shown. Our decoder utilizes two of these structures to detect changes of the incoming signal in both clock phases. The timer in our PIE decoder then decodes the symbol based on a corrected measurement. This results in the time measurement to be more precise than the compared standard solution. Therefore, the overall clock frequency may be reduced while still maintaining a correct decoding. While we designed this structure in synthesizable Verilog, the actual synthesis yields additional challenges due to timing constraints and the availability of standard cells. We have observed that for an FPGA prototype, a straightforward implementation of the JK-FlipFlop may be used. For an ASIC, the implementation had to be changed to a Latch-based JK-FlipFlop realization.

4 Verification in Simulation

For verifying our PIE decoder within the simulation, our approach is two-fold: A simulation on block-level realizes a set of parameter combinations for an input signal for the single function block. These parameters include extreme cases and intermediate values for Tari, RTCAL, TRCAL, PW and different clock frequencies. Our testbench exercises the system by transferring randomized data frames. We verify that our encoder is recovering the data and calibration parameters correctly from the input signal. On this level, we evaluated both a D-FlipFlop-based decoder and our proposed architecture by means of minimum operating frequency. The conventional decoder was functional with a minimum frequency of 2 MHz. Our proposed decoder could recover data and timings correctly even at a system clock frequency of 1.4 MHz.

To validate the integration in the overall system, we included the PIE decoder into a digital top-level simulation and executed a set of representative RFID commands. This simulation was extended to also include the analog frontend in a mixed-signal simulation.

After layout of the full digital part, simulation with extracted timings over the technology corners were conducted. Again, a set of RFID commands was executed to verify the system's functionality. Still, the introduction of our JK-FlipFlop demanded for additional treatment of a possible metastability at the input. This was also avoided by the previously mentioned latch-based realization.

5 FPGA Prototyping

For improving the verification coverage and ruling out possible mismatches between our testbench and a real environment, we created a discrete RF frontend shown in Fig. 6. This frontend resembles the functionality of the input circuit of our ASIC. It is connected to an FPGA that implements the full digital part of our RFID system and hence, also our proposed decoder. In this way, we tested our system with a conformance tester and a commercial RFID reader by executing different command sequences. This prototyping also indicates that the post-layout timing and metastability issues were covered correctly since the system did show deterministic behavior with non-synchronized clocks between tag and reader.

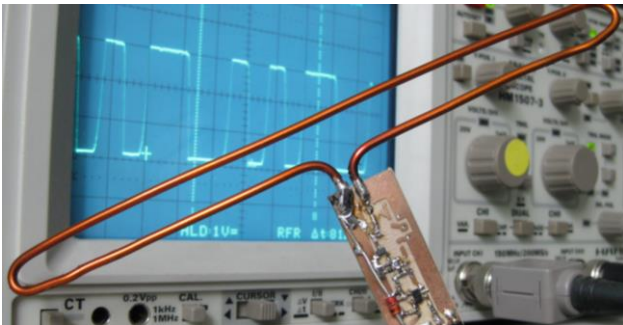


Figure 6. Prototype RF frontend for verifying our RFID protocol processor in an FPGA in combination with a commercial reader system.

6 Conclusions

In this contribution we have proposed an improved architecture for PIE-stream decoding as used in UHF RFID systems. Our system utilizes a JK-FlipFlop emulated by a latch-based structure for correcting a time measurement of an asynchronous signal. This correction allows for a lower system clock frequency resulting in a decrease in power consumption of the overall system.

Our system has been verified both in simulation and in an FPGA prototype and is implemented in an ASIC.

Still, this architecture can be improved by means of power by using On-Demand-Clocking as shown in [4]. It is also possible to enhance the time estimation even further by utilizing a dual-edge scheme for the decoder which also yields new challenges for defining the timing constraints for the utilized components.

7 Acknowledgements

This work was carried out in the project StorAIge, which has received funding from the ECSEL Joint Undertaking (JU) under grant agreement No. 101007321. The JU receives support from the European Union's Horizon 2020 research and innovation program and France, Belgium, Czech Republic, Germany, Italy, Sweden, Switzerland, Turkey.

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SAYA („Safe As You Are“) – smarter Ring zur Vermeidung sexueller Übergriffe

SAYA („Safe As You Are“) – Smart Ring to Prevent Sexual Assault

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Kurzfassung

Im Projekt Safe As You Are (SAYA) wird zusammen mit der SAYA UG Düsseldorf eine persönliche Sicherheitslösung als Lifestyle-Produkt entwickelt, in dem Schmuck und Design mit smarter Technik und hoher Funktionalität verbunden wird. Daraus entstand ein modischer Smart Ring, der es der Trägerin bzw. dem Träger ermöglicht einen lauten Alarm auszulösen und per Bluetooth-Low-Energy-Verbindung zu einem Smartphone Standortdaten sowie Notrufe an Dritte weiterzuleiten. Der Vorteil der Integration in einem Ring im Vergleich zu aktuell existierenden Produkten ist, dass der Alarm in fast jeder Situation, selbst mit fixierten Händen auslösbar ist. SAYA richtet sich an eine junge Zielgruppe und soll beim Ausgehen getragen werden. Das Sicherheitssystem SAYA besteht neben dem eigentlichen smarten Ring aus der Schatulle und einer auf dem Smartphone installierten Sicherheits-App. Bei Nichtbenutzung und zur induktiven Nachladung wird der Ring ins die Schatulle eingelegt. Zusätzlich sendet der in der Schatulle integrierte Signalgeber im Alarmfall einen markanten Ton aus. Dadurch wird die akustische Reichweite erheblich erweitert und ist vom Aggressor nicht gleich zu orten. Hahn-Schickard entwickelt zum System SAYA die Elektronik für den Smart Ring und für die Schatulle. Zentrale Funktion des smarten Rings ist die sichere Erkennung der Auslösung bei Betätigung des Tasters, bei möglichst geringer Anzahl von Fehlauflösungen. Die Kernaufgabe besteht – neben der eigentlichen Hardware- und Firmware-Entwicklung – in der Integration des Systems in einem anwendungsbedingt sehr begrenzten Bauraum unter Einhaltung konstruktiver modischer Designvorgaben.

Abstract

In the Safe As You Are (SAYA) project, a personal safety solution is being developed as a lifestyle product together with SAYA UG Düsseldorf, combining jewelry and design with smart technology and high functionality. The result is a fashionable smart ring that enables the wearer to trigger a loud alarm and transmit location data and emergency calls to third parties via a Bluetooth low-energy connection to a smartphone. The advantage of integration in a ring compared to existing products is that the alarm can be triggered in almost any situation, even with fixed hands. SAYA is aimed at a young target group and is intended to be worn when going out. In addition to the actual smart ring, the SAYA security system consists of the box and a security app installed on the smartphone. When not in use and for inductive recharging, the ring is placed in the casket. In addition, the integrated signaling device in the casket emits a distinctive sound in the event of an alarm. This considerably extends the acoustic range and means that the aggressor cannot be located immediately. Hahn-Schickard is developing the electronics for the smart ring and the casket for the SAYA system. The central function of the smart ring is the reliable detection of triggering when the button is pressed, with the lowest possible number of false triggers. The core task - in addition to the actual hardware and firmware development - is to integrate the system into a very limited installation space due to the application, while adhering to constructive, modular design requirements.

1 SAYA-Konzeptionsphase

1.1 Konzeptentwicklung

Die Konzeptphase diente der Definition des Systems SAYA, in der neben dem eigentlichen Ring als Schmuckstück die weiteren funktionellen Elemente (Schatulle, Smartphone-App) und ihr Zusammenspiel definiert wurden.

Die Nachladung des im Schmuckstück integrierten Akkus erfolgt über eine attraktive Schatulle, in die es eingelegt

wird. Zur Signalisierung eines Notfalles kann sie einen markanten Alarmton abgeben, der vom Aggressor nicht direkt mit dem Ring in Verbindung gebracht wird. Eine auf dem Mobiltelefon der Anwender*in installierten App leitet bei Auslösen des Alarms diesen an bestimmte vorher definierte Kontaktpersonen weiter.

Ursprünglich war die Integration des Signalgebers direkt im Ring angedacht. Dazu wurden mehrere integrierbare Miniatur-Signalgeber akustisch vermessen. Es zeigte sich jedoch, dass die erreichbaren Schalldrücke nicht den Erwartungen an das Alarmsystem entsprachen. Daher wurde

entschieden, einen größeren und dadurch lauterem Schallgeber in die Schatulle zu integrieren. Die Alltagstauglichkeit wird hierdurch voraussichtlich nicht signifikant eingeschränkt, da die Schatulle in der Regel in der Handtasche der Träger*innen mitgeführt wird.

Die Verbindung der einzelnen Systemkomponenten, SAYA-Ring, Schatulle und Mobiltelefon erfolgt über Bluetooth Low Energy (BLE). In **Bild 1** sind die zum Notrufsystem SAYA benötigten Komponenten dargestellt.



Bild 1 Übersicht, Systemkomponenten der Sicherheitslösung SAYA („Safe As You Are“), nicht maßstabsgetreu

1.2 Abgrenzung zum Stand der Technik

Kommerziell erhältliche smarte Ringe (z. B. von Oura oder RINGLY) zielen meist darauf ab, Health-Fitness-Informationen oder Nutzungsdaten zu sammeln sowie Smartphone-Komfortfunktionen oder NFC-Zahldienste bereitzustellen (z. B. KAKAKE Orii Magic Smart Ring). Der SAYA-Ring sammelt keine Nutzerdaten, sondern agiert als Alarmsystem und nur bei Auslösung. Es gibt derzeit weltweit keinen Ring, der einen Alarm auslösen kann.

2 Entwicklung SAYA-Ring

Zu Beginn des Projektes galt es Komponenten zu identifizieren, welche technisch und in den Abmessungen für die Anwendung geeignet sind. Die Entwicklung spezieller ASIC-Lösungen oder Chip-on-Board-Technologien waren im Rahmen des Projektbudgets nicht möglich.

Für die zentrale Funktion der Alarmauslösung wurden verschiedene Mechanismen und Prinzipien betrachtet. Die Anforderungen waren wie folgt:

- Auslösung mit nur einer Hand
- Intuitiv einfache Handhabung
- Vermeidung von Fehlalarmen
- Anwendbar rechts/links, an Mittel- und Ringfinger
- Tolerant gegenüber Nässe, Fette und Verschmutzung

Für die Realisierung des Auslöse-Elements wurden zunächst einfache SMD-/Folientaster, kapazitive und resistive Touch-Sensoren, optische Prinzipien, sowie Drehraten- und Beschleunigungssensoren betrachtet. Nach Abwägung der Vor- und Nachteile fiel die Entscheidung letztendlich auf den Folientaster.

Ein anwendungsspezifischer Folientaster in der Ringschiene ermöglicht die Auslösung selbst bei fixierten Handgelenken. Zudem ist er auf Grund des weichen, gummiartigen Materials selbstdichtend gegenüber Feuchte und Schmutz. Die Gefahr der Fehlaktivierung konnte durch konstruktive Maßnahmen (z. B. Formgebung der Auslösefläche) zur Einstellung des Druckpunkts und der Betätigungskraft minimiert werden.

Für die Anerkennung als hochwertiges Schmuckstück sind neben dem Design auch Materialien, Robustheit und Farbgebung von entscheidender Bedeutung. Das gewählte Fertigungsverfahren erlaubt die Verwendung verschiedener edler Grundmaterialien (z. B. Silber, Platin, Gold), sowie Nicht-Edelmetallen (z. B. Edelstahl). Das Verschlusselement (die Ringtafel) bildet ein Schmuckstein, der attraktive Gestaltungsmöglichkeiten bietet. Für die korrekte Funktionalität ist wichtig, dass ein Material mit guter Durchdringung für die Funkwellen gewählt wird.

Die Firmware des Rings stellt die grundlegenden Funktionen sicher sowie das Update Over The Air, da das Öffnen von der Nutzerin oder dem Nutzer nicht vorgesehen ist. Gesteuert wird neben der Alarmfunktion das Energie-Management und die Ladefunktion. **Bild 2** zeigt die Integration der Komponenten im Ring. Als Mikrocontroller wird ein stromsparender EFR32BG22 Series 2 Bluetooth Wireless SoC von Silicon Labs verwendet. Dieser Mikrocontroller basiert auf einer ARM Cortex-M33-CPU, welcher im Schlafmodus weniger als 2 μ A verbraucht. Als wiederaufladbarer Akkumulator kommt eine Lithium-Ionen-Knopfzelle mit 3,6 V und 18 mAh (LIR1040 von JBCCELL) zum Einsatz.



Bild 2 Komponenten des Rings (1) Ringschiene, (2) Leiterplatte, (3) Akku, (4) Ladespule, (5) Schalter mit Flexkabel, (6) Ringtafel.

3 Entwicklung SAYA-Schatulle und akustische Messungen

Die in der Schatulle integrierte Elektronik mit eigenem Energiespeicher ermöglicht die induktive autonome Nachladung des SAYA-Rings. Mit Hilfe eines USB-C-Kabels lässt sich der eigene interne Akku nachladen. Sie ist mit einem eigenen Alarmgeber sowie einer BLE-Schnittstelle ausgestattet.

Als Schallgeber wird der Baustein AT-3050-TT-R von PUI Audio verwendet. Es handelt sich hierbei um einen piezoelektrischen Lautsprecher mit einem maximalen Schalldruck im Bereich zwischen 4 kHz und 6 kHz. Dies konnte durch eigenen Messungen verifiziert werden. **Bild 3** zeigt den Messplatz, mit dem die in **Bild 4** dargestellte Messkurve aufgenommen wurde.

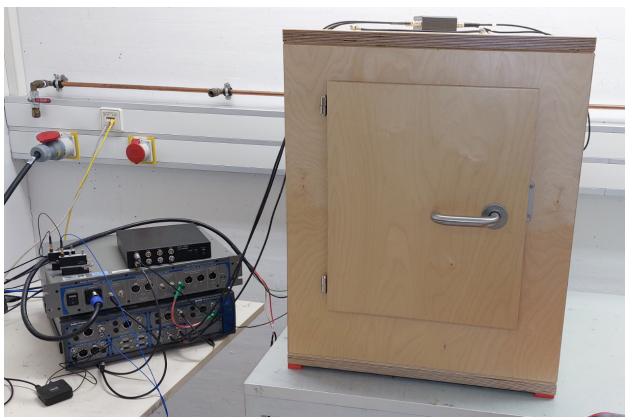


Bild 3 Messplatz zur Bestimmung des Schalldruckpegels, bestehend aus APx1701 Verstärker, APx525 Audioanalyser (beide von Audio Precision) sowie einer Messkammer mit Testmikrofon und dem Schallgeber (nicht zu sehen).



Bild 4 Messung des Schalldruckpegels (Sound Pressure Level) zwischen 1 kHz und 10 kHz bei einer Anregung von 3,6 V.

Die Firmware der Schatulle und des Rings steuern gemeinsam den induktiven Ladevorgang des Ring-Akkus. Bei eingehender Alarmierung wird die Alarminformation auch

von der Schatulle über BLE versendet, wodurch die Reichweite zwischen Ring und Smartphone vergrößert wird. Verwendet wird das Bluetooth-Emergency-Profil, welches prinzipiell von allen Smartphones in Reichweite empfangen werden kann. Bei installierter SAYA-Smartphone-App und entsprechender Freigabe ist die Auslösung eines Gruppenalarms möglich. Analog zur Firmware des Rings besitzt die Firmware der Schatulle die Möglichkeit zum Update-over-the-Air.

Die Schatulle soll, wie der Ring selbst, als hochwertiges Element wiedererkannt werden. Als Material ist ein geeigneter Kunststoff vorgesehen, der sich in der Farbgebung sowie der Oberfläche vielseitig gestalten lässt.

4 Entwicklung SAYA-Smartphone-Anwendung und Testergebnisse

Die im Smartphone integrierte BLE-Schnittstelle empfängt die Alarmmeldung vom Ring und/oder von der Schatulle. Das bedeutet, dass die Alarmmeldung sowohl vom Ring direkt als auch über die Schatulle ans Smartphone weitergeleitet wird. Die Schatulle arbeitet dann als Repeater, um die Reichweite zu erhöhen. Die Oberfläche der Anwendungs-Software (**Bild 5**) kann von dem/der Nutzer*in individuell gestaltet werden. Die Notrufanforderung wird vom Smartphone an voreingestellte Nummern weitergeleitet. Die Anwendung wird zukünftig in den gängigen App-Stores von Android (Google Play Store) und iOS (Apple App Store) angeboten.

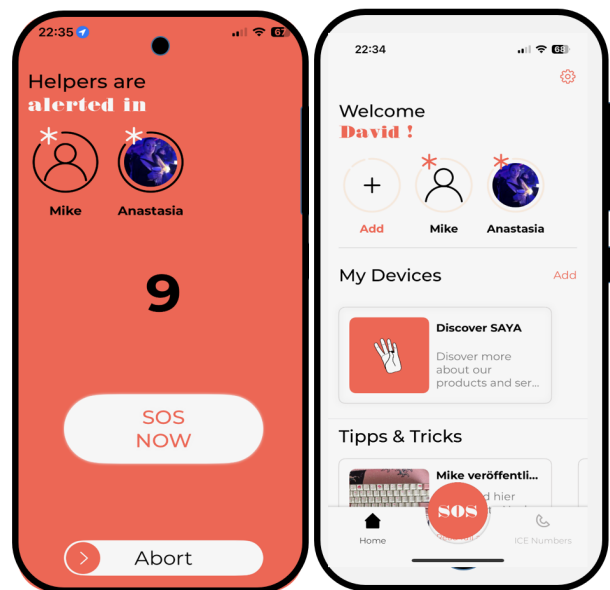


Bild 5 Zwei Beispiele der individuellen Gestaltungsmöglichkeiten der Benutzeroberfläche.

Durch das effektive Energiemanagement konnte die Betriebsdauer des Rings mit einer Akkuladung (18 mAh) auf über mehr als eine Woche gesteigert werden. Die Bluetooth-Reichweite beträgt ca. 5 Meter, wobei die Schatulle als Repeater fungieren kann und so die Reichweite zum Smartphone erhöhen kann.

Evaluation of LPWAN technologies for pest monitoring

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Abstract

The choice of wireless technology for a pest monitoring setup is crucial for energy efficiency and reliability. We analysed 48 different modules with regards to bitwise energy consumption theoretically and evaluated the best modules in real-life scenarios. It was found that the choice of module can be inferred from a thorough market analysis and Narrowband Internet of things (NB-IoT) and Long Range (LoRa) are the most promising candidates for deployment in industrial environments. Regarding the tested site NB-IoT showed a coverage of over 97 % with good signal quality. For LoRa a calculation of the coverage percentage is not reasonable, as it strongly depends on the amount and location of the gateways. It was determined that one gateway can cover more than 10,000 m².

The results indicate that NB-IoT is suitable for wireless transmission in industrial environments and that LoRa with an individual gateway setup is ideal as a backup solution.

1 Introduction

Detection and monitoring pest in the food processing industry is crucial for providing high quality and hygienically safe products that follow the “Hazard Analysis and Critical Control Point” principles [1]. To this date, traps that are controlled monthly by humans are the main source for pest detection. This is labour-intensive and suitable for automation. By using Low Power Wide Area Network (LPWAN) radio technologies, the pest infestation can be transmitted immediately to a reporting centre. This enables faster intervention through countermeasures and therefore can reduce the use of harmful pesticides. Since the traps are intended to operate for a long time without maintenance intervals, energy efficiency plays a major role.

2 Methods

First, ten different LPWAN technologies were theoretically evaluated using data from 48 different modules. Second, the bitwise energy consumption per day of each module was calculated and compared.

Finally, a coverage analysis at a typical industry building was done.

2.1 Theoretical energy analysis

The energy consumption of radio modules is a sum of the energy in active mode E_{Idle} , the energy when sending data E_{Tx} and the energy when receiving data E_{Rx} . For the rest of the day, the module remains in sleep mode E_{Sleep} .

$$E_{day} = E_{Tx} + E_{Rx} + E_{Idle} + E_{Sleep}$$

This theoretical evaluation was calculated for various Uplink (UL) scenarios with different payloads and amounts of connections per day. The scenarios consider the varying requirements for different sensor signals with different data sizes and measurement intervals:

- Uplinks: 1 – 200
- Data per day: 12B – 44.1 kB

All common modules available on the market (as of 05/23) were analysed based on the energy consumption data provided in their data sheets.

2.2 Practical energy analysis

The LoRa and NB-IoT modules selected from the theoretical analysis were characterised with a power meter (Power Profiler II, Nordic Semiconductors, Trondheim, Norway), considering technology-specific transmission parameters.

- LoRa: MWX1ZZABZ (Murata Manufacturing Company, Kyoto, Japan)
- NB-IoT: Adrastea-I (Würth GmbH, Künzelsau, Germany)

Coverage Enhancement Level (NB-IoT) and Spreading Factor (LoRa)

NB-IoT uses Coverage Enhancement (CE) levels for reliable and deep-penetrating communication by repeating information, especially in poorly covered areas. The CE level is selected based on the existing signal quality and requires more energy to send the message at higher levels (CE0-CE2) [3].

The Spreading Factor (SF) is a key parameter in LoRa technology and determines how widely the signal is spread over the transmission time window (SF7-SF12). An increasing SF enables a higher sensitivity and therefore a better range of the module. Due to the lower bit rate and therefore longer transmission time, more energy is consumed per message as the SF increases [4].

2.3 Coverage Analysis

2.3.1 In-field measurements

A detailed evaluation of both technologies was carried out at a large bakery site, with typical dimensions (approx. 90 m x 120 m) and design of the facility. At this site 125 trap locations were evaluated. Both wireless measurement devices were triggered at the trap locations to provide spatial

information on the signal quality specific for the wireless technology.

2.3.2 LoRa measurement device

With LoRa, the range can be extended at any time by adding gateways. To evaluate the range of LoRa sensors a central gateway was set up and then all trap locations were tested. An existing LoRa network, consisting of FMLR-61-STM (STMicroelectronics N.V., Plan-les-Ouates, Schweiz) LoRa nodes and the UG65 (Milesight, Xiamen, Fujian, China) gateway was used. By using one gateway, the indoor coverage per gateway can be estimated more precisely, and thus the total number of gateways required to cover the entire site. Each measurement contained the SF, Signal-to-noise ratio (SNR), Received Signal Strength Indicator (RSSI) and the trap location.

$$SNR = \frac{P_s [W]}{P_N [W]}$$

The SNR is the ratio of the power of the signal (P_s) to the power of the background noise (P_N). The RSSI is a value to determine the received field strength and contains the noise and the interference. Both values are used to quantify the signal quality. The assessment of the signal qualities was done according to T. Petric et al. [7].

2.3.3 NB-IoT measurement device

The Adrastea-I was used in a mobile measuring device. Informations such as Reverence Signal Received Quality (RSRQ), CE level, trap location and the selected radio tower were taken. If there was no coverage at the location, the measured values were saved on the local device and sent at a later point.

$$RSRQ = N \times \frac{RSRP [W]}{RSSI [W]}$$

The RSRQ is a value defining the connection quality. It consists of the RSSI and the Reference Signal Received Power (RSRP) which is defined as the mean receiving power per resource block (N). The assessment of the connection qualities was done according to 3GPP Release 13 [6].

3 Results

3.1 Energy analysis

To determine a suitable energy-saving radio technology for this application, ten technologies were first analysed theoretically. The energy consumption per transmitted bit was calculated to allow a comparison between the modules as shown in **Figure 1** and more detailed analysis of the best modules in **Figure 2**.

Through this theoretical evaluation and the consideration of additional parameters (market analysis, range, penetration, regulations), NB-IoT and LoRa were selected for this specific use case and the further analysis.

Both technologies are designed to provide energy-efficient and wide-area networking for many IoT devices [2].

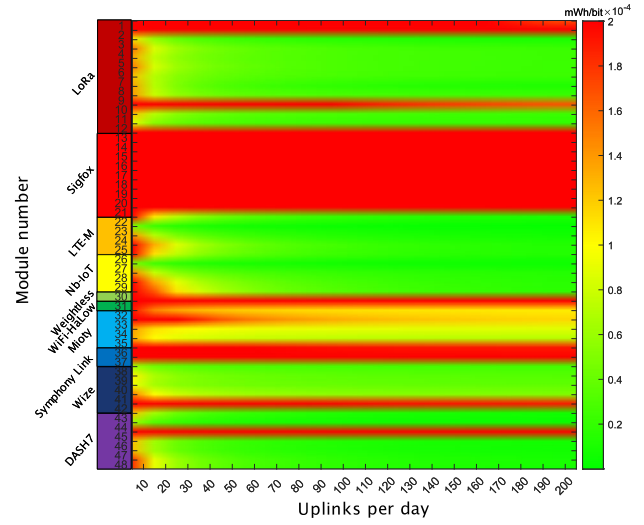


Figure 1 Theoretical evaluation of 48 modules in relation to energy per transmitted bit at 12 byte payload and overhead for each technology.

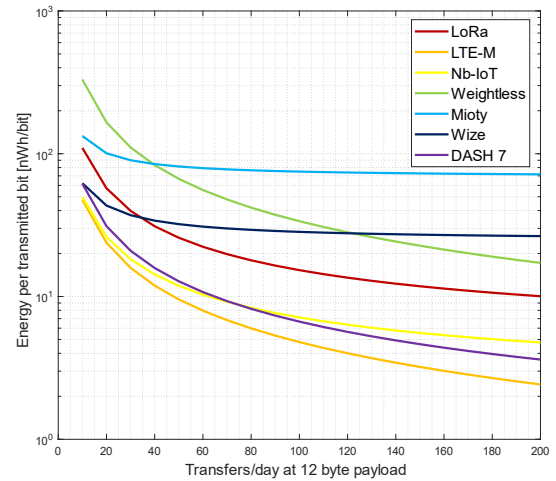


Figure 2 Comparison of the best module per technology. Depending on the bit rate, sleep current and transmit current, the consumption profile changes with a varying number of transmissions per day with a 12-byte payload.

3.2 Module comparison

An increasing CE-Level at NB-IoT connections results in increasing energy consumption and transmission time. Analogue, with increasing SF at LoRa connections, the uplink T_x slot, transmission time and thus the energy consumption per uplink increases significantly.

A direct comparison (**Figure 5**) shows the change in power consumption for each selected SF or CE level. The energy consumption for NB-IoT varies by a factor of 25 between CE0-CE2 and for LoRa between SF7-SF12 by a factor of 13. The location of the trap in relation to the nearest radio tower or gateway therefore has a significant impact on the expected battery life and maintenance interval of the trap.

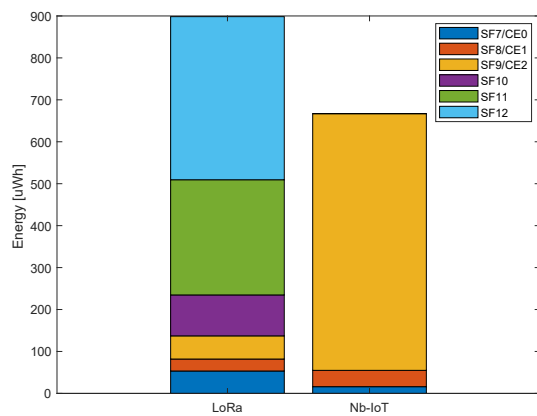


Figure 5 Comparison of the power consumption profiles of both, LoRa and NB-IoT modules as a function of the SF and CE levels at a total of 256 bytes of transmitted uplink data.

4 Evaluation under real conditions

4.1 Measurements at field sites

By documenting the individual data readings of the NB-IoT monitoring station, these can be assigned to the individual trap locations of the respective field site (**Figure 6**).



Figure 6 Analysed NB-IoT signal readings from the mobile monitoring station on the ground floor of a large bakery.

This location would be well suited for the use of NB-IoT, as almost all readings (>97 %) are sent at energy-saving CE level 0 due to the nearby radio tower (approx. 250 m line of sight), and more than 75 % of the measurements have good to very good signal quality. Poor readings are mainly found at traps, which are difficult to access for every wireless technology due to the path losses (red area).

The same can be done with LoRa (**Figure 7**). With one gateway and fixed Spreading Factor 7 settings, almost two thirds of the total trap locations on the ground floor could be covered (blue area). With two gateways or higher SF of the nodes, an entire floor of the company site can be covered.

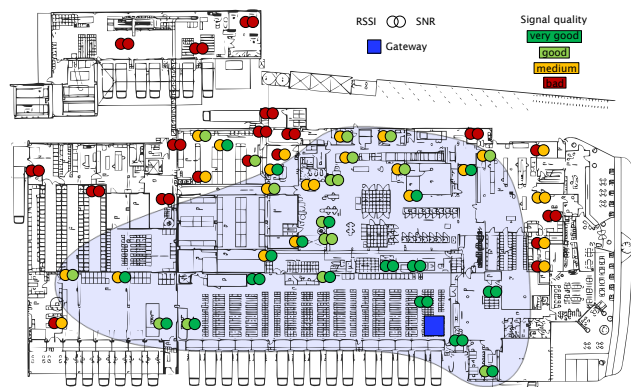


Figure 7 Analysed LoRa signal readings from the ground floor of the industrial bakery. Failed uplinks are marked with two red circles.

5 Conclusion

Several wireless modules were compared theoretically with regards to energy efficiency. Two modules were evaluated in hardware and tested under real conditions. It was shown that NB-IoT is suitable for application in an industrial environment while LoRa is a good alternative for areas with poor radio tower coverage.

The wireless demonstrator has to be paired with the sensor system to evaluate its suitability in the intended application. This involves different pest trap layouts, battery concepts, and sensor data processing methods. The radio interface will be kept flexible to evaluate both LoRa and NB-IoT.

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Optimizing Energy Efficiency: A Comprehensive Analysis of Microcontroller Platforms for Ultra-Low-Power Environmental Wireless Sensor Networks in Climate Change Monitoring

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Kurzfassung

Weltweit werden Ökosysteme durch den Klimawandel bedroht. Dies unterstreicht den Bedarf von zuverlässigen wartungsfreien Sensorsystemen, die einen sehr niedrigen Stromverbrauch aufweisen. Maßgebend für die Optimierung des Energieverbrauches ist die Wahl des Mikrocontrollers. Es werden in dieser Veröffentlichung Plattformen basierend auf dem MSP430FR5994 und dem Ambiq Apollo 3 verglichen und auf ihre Eignung hinsichtlich verschiedener Sensor-komplexitäten untersucht. Es wird festgestellt, dass der MSP430FR5994 besser für einfache drahtlose Sensorknoten geeignet ist, während der Apollo 3 für komplexe Anwendungsszenarien mit aufwendigen Rechenaufgaben besser abschneidet. Diese Veröffentlichung bietet Einblicke zur Auswahl des bestgeeigneten Mikrocontrollers für Umweltbeobachtungs-Wireless-Sensor-Netzwerke.

Abstract

Ecosystems around the world are threatened by climate change. This underlines the need for reliable maintenance-free sensor systems with very low power consumption. The choice of microcontroller is crucial for optimizing energy consumption. In this publication, platforms based on the MSP430FR5994 and the Ambiq Apollo 3 are compared and examined for their suitability with regard to different sensor complexities. It is found that the MSP430FR5994 is better suited for simple wireless sensor nodes, while the Apollo 3 performs better for complex application scenarios with elaborate computational tasks. This paper provides insights for selecting the most suitable microcontroller for environmental monitoring wireless sensor networks.

1 Einführung

Ökosysteme weltweit sind durch den globalen Klimawandel bedroht [1]. Durch die Überwachung der Auswirkungen mittels verteilter Umweltsensorsysteme kann ein tieferes Verständnis der Ursache-Wirkungs-Ketten gewonnen werden, das als Grundlage für die Entwicklung von Strategien zur Schadensbegrenzung dienen kann. Die Positionierung dieser Sensoren variiert von unter der Erde bis hoch in das Blätterdach. In tiefen und dichten Wäldern ist der Zugang zum Stromnetz schwierig oder nicht gegeben. Für Sensoren, die mit Batterie betrieben werden, sind professionelle Kletterer erforderlich, um die Aufstellung und Wartung der Sensoren durchzuführen [4]. Somit ist die energieautarke Stromversorgung mittels Energy Harvesting die praktikabelste Lösung mit dem Vorteil eines wartungsfreien Betriebs an exponierten oder schwer zugänglichen Standorten. Um jedoch eine zuverlässige Funktionalität der Sensorknoten allein durch lokal erzeugte Energie zu garantieren, sollte die Elektronik so wenig Energie wie möglich verbrauchen.

Der Mikrocontroller ist das Herzstück eines energieautarken drahtlosen Sensornetzwerks (WSN) und ist ein entscheidender Faktor für seine Energieeffizienz. Die Wahl des Mikrocontrollers hängt im Wesentlichen von der Komplexität der Anwendung, der erforderlichen Rechenleistung und des Energiebudgets ab. Die Auswahl eines geeigneten Mikrocontroller ist daher eine komplexe Aufgabe, da ein Kompromiss zwischen Stromverbrauch und Leistungsfähigkeit gefunden werden muss.

Für ein WSN können die Mikrocontroller-Funktionalitäten in zwei Hauptkategorien unterteilt werden. In der ersten Kategorie ist das WSN ausschließlich für die Erfassung von Sensordaten und deren drahtlose Übertragung ohne Durchführung komplexer Algorithmen verantwortlich. Als Beispiel für diesen Typen wird ein Körpersensornetzwerk angeführt, das darauf abzielt, Elektrokardiographie- (EKG) und Elektromyographie- (EMG) Signale zu überwachen [5]. Die Autoren wählten einen MSP430F2274 von Texas Instruments (TI) als Mikrocontroller, da er die Anforderungen an Datenerfassung und -verarbeitung unterstützt, die für die meisten biomedizinischen Anwendungen erforderlich sind.

In der zweiten Kategorie erfordert die Anwendung leistungsstarke Sensorknoten im WSN, von denen erwartet wird komplexe Daten in Echtzeit zu verarbeiten und/oder Vorhersagealgorithmen basierend auf Sensordaten auszuführen. Ähnliche Arbeiten werden in [6] beschrieben, in der die Autoren eine drahtlose Plattform für komplexe Sensoreinsätze in Smart Cities entwickelt haben. Unter Verwendung des STM32F407, einem ARM Cortex M4-basierten Mikrocontroller von ST, wurden Machine-Learning-Algorithmen für die Überwachung von blitzartigen Flutungen, Verkehrsüberwachung oder Vorhersage der Fahrzeugbewegung implementiert. Dieses System ist so konzipiert, dass es von 8 W-Solarmodulen und einem 8-Ah-Akku betrieben wird, der oben auf einer Straßenlaterne installiert ist.

Die zuvor genannten Anwendungsbereiche präsentieren den aktuellen Stand der Technik und haben keine strikte Begrenzung hinsichtlich ihrer Dimensionierung des

Energy Harvesting Moduls und Energiespeichereinheit. Im Falle der Umweltsensorik spielen Größe und Gewicht des energieautonomen WSN eine wichtige Rolle. Der Knoten muss kompakt sein, damit er an dünnen Zweigen befestigt werden kann. Daher ist die Oberfläche der Solarmodule begrenzt. Darüber hinaus hängt die Menge der erzeugten Energie stark vom Standort des Sensorsystems ab. Im Wald wird die Effizienz der solar erzeugten Energie aufgrund der teilweisen Beschattung der in der Baumkrone oder in der Nähe der Bodenoberfläche installierten Solarmodule reduziert. Zusätzliche Einschränkungen ergeben sich aus den Außenbedingungen, sodass die Solarmodule verschmutzen können und somit ihre Effizienz negativ beeinflusst wird. Daher bleibt für die Umweltsensorik das Problem der begrenzten zur Verfügung stehenden Energie bestehen, was die Notwendigkeit zur Untersuchung der von äußerst Energiesparsamen Mikrocontrollern für Umwelt-WSNs hervorruft.

Eine Analyse von Mikrocontrollern die sich auf ihren Energieverbrauch bei verschiedenen Aufgaben bezieht, existiert bereits im Bereich des IoT, der Smart Cities und biomedizinischer Anwendungen, jedoch nach Kenntnis der Autoren nicht im Bereich der Umweltsensorik. Daher liefert diese Veröffentlichung eine Studie über die Energieverbräuche verschiedener Mikrocontroller-Plattformen mit Unterschiedlichen Architekturen um die an der besten geeigneten Lösung für Umwelt-WSNs mit niedriger und hoher Leistung zu identifizieren. Die Plattformen basieren auf dem bereits vorhandenen Messaufbau zur Bestimmung der Chlorophyll-Fluoreszenz, der in [7] vorgestellt wurde. Diese Plattformen werden in einer Messkampagne ausführlich getestet, die die beiden zuvor diskutierten Kategorien energieautonomer WSN repräsentiert.

2 Chlorophyll Fluorometer

Chlorophyllfluoreszenz ist eines der Nebenprodukte des Photosynthese Prozesses. Da diese Fluoreszenz Rückschlüsse über den Zustand des Photosystems II erlaubt, kann ihre Messung viele Informationen über den Gesundheitszustand der Pflanze offenbaren [2,3]. Daher wird ein bereits entwickeltes Chlorophyllfluorometer, dass in [7] vorgestellt wird, als Implementierungsbasis verwendet, um die Leistung der Mikrocontroller-Plattformen im Verlauf dieser Arbeit zu testen und zu vergleichen.

Die Hauptkomponenten für das Chlorophyllfluoreszenz-messsystem werden wie in [7] beschrieben eingesetzt. Eine blaue LED, moduliert mit 1 kHz und mit verschiedenen Intensitätseinstellungen, löst die Photosynthese in einem Blatt aus. Die resultierende Fluoreszenz wird optisch gefiltert und von einer Photodiode mit einem angeschlossenen analogen Transimpedanzverstärker gemessen. Die Signalintensität wird durch den Mikrocontroller mithilfe des internen Analog-Digital-Wandler (ADC) bestimmt. Insgesamt werden 512 Datenpunkte mit einer Abtastrate von 20 kHz aufgezeichnet. Anschließend werden diese Datenpunkte verwendet, um die schnelle Fourier-Transformation (FFT) zur Bestimmung der Signalintensität bei der Stimulationsfrequenz (1 kHz) zu berechnen.

3 Mikrocontroller Auswahl

Der Mikrocontroller, der in einem solchen Chlorophyllfluorometer verwendet wird, sollte über einen integrierten ADC, einen Digital-Analog-Wandler (DAC), eine digitale Signalverarbeitungseinheit (DSP), nichtflüchtigen Speicher und vor allem über einen äußerst geringen Stromverbrauch verfügen.

Die überwiegende Mehrheit der Controller, die diese Anforderungen erfüllen basieren auf der ARM Cortex M0(+) oder ARM Cortex M4-Architektur. Cortex M0(+) basierte Controller verfügen über alle erforderlichen Peripheriemodule, besitzen jedoch keinen Hardwarebeschleuniger für die Berechnung der FFT. Die führt dazu, dass die komplexen Berechnungen eine energieintensive Operation darstellen. Cortex M4 basierte Mikrocontroller wiederum verfügen über alle geforderten Peripheriemodule inklusive der benötigten Hardwarebeschleuniger zum Berechnen der FFT. Zum Beispiel erreicht der Ambiq Apollo 3 einen äußerst niedrigen Stromverbrauch, indem er im aktiven Modus bei hoher Taktfrequenz einen sehr niedrigen Stromverbrauch besitzt, was einen hohen Datendurchsatz ermöglicht und gleichzeitig sehr energieeffizient ist [8]. Ein anderer Ansatz wird von Texas Instruments mit der MSP430-Architektur verfolgt. Diese Mikrocontroller erreichen einen äußerst niedrigen Stromverbrauch, indem sie im Tiefschlafmodus sehr wenig Strom verbrauchen. Einige Mikrocontroller der MSP430-Familie sind zusätzlich mit einem Low-Energy-Accelerator (LEA) ausgestattet, welcher erlaubt DSP-Operationen durchzuführen und damit die meisten Anforderungen zu erfüllen. Die Marktanalyse wird mit der Auswahl von zwei potenziellen Kandidaten für die Energiemessung abgeschlossen. Der erste Kandidat ist der MSP430FR5994 [9]. Er basiert auf einer 16-Bit-RISC-Architektur, verwendet 256 kB Ferroelektrischen Random-Access-Speicher (FRAM), erweiterte Low-Power-Modi, die Standby-Ströme bis zu 350 nA bei 1,8 V ermöglichen, und einen Stromverbrauch im aktiven Modus von bis zu 120 μ A/MHz, einen frei konfigurierbaren Haupttakt von bis zu 16 MHz und einen integrierten LEA. Der zweite Kandidat ist der Ambiq Apollo 3 basierend auf der ARM Cortex M4F-Architektur. Der Apollo 3 bietet 384 kB SRAM, einen Stromverbrauch von etwa 6 μ A/MHz im aktiven Modus, einen Stromverbrauch von etwa 2 μ A bei 1.8V im Tiefschlafmodus sowie einen Haupttakt von entweder 48 MHz oder 96 MHz und einen integrierten Hardwarebeschleuniger für DSP-Berechnungen.

4 Testdefinition

Um die beiden im Einleitungsteil erwähnten WSN-Kategorien darzustellen, wurde ein Test mit geringer und ein Test mit hoher Komplexität konzipiert. Für den Test mit geringer Komplexität wurde ein Messprotokoll für die Datenerfassung erstellt. Gemäß diesem Protokoll sollte der Mikrocontroller 512 Datenpunkte mit einer Abtastrate von 20 kHz erfassen und anschließend im nichtflüchtigen Speicher gespeichert werden. Für den Test mit hoher Komplexität wurde ein Messprotokoll für die komplexe

Datenverarbeitung entworfen. Hierbei sollte der Mikrocontroller die im Speicher gespeicherten Daten lesen, die FFT berechnen und die Werte bei 1 kHz extrahieren. Für die Tests wurde der MSP430FR5994 mit einer Taktfrequenz von 8 MHz konfiguriert, der Apollo 3 mit 48 MHz. Für die Durchführung der Messungen wurde der folgende Testaufbau entwickelt. Die Mikrocontroller-Plattform wird von einem HAMEG Industries HM8142-Netzteil mit Energie versorgt. Zur Energie- beziehungsweise Strommessung wurde ein Joulescope JS110 [10] verwendet, welches von einem Python-Skript gesteuert und durch den Mikrocontroller kontrolliert wurde. Die drahtlose Datenübertragung war nicht in die Systeme integriert.

5 Ergebnisse und Diskussion

5.1 Sampling

Der MSP430FR5994 (im Folgenden als MSP430 bezeichnet) integriert einen 12-Bit-ADC, während der Apollo3 einen 14-Bit-ADC (hier auf 12-Bit eingestellt) integriert, beide implementiert als sukzessive Approximation-Register (SAR). Beide Mikrocontroller erlauben verschiedene Betriebsmodi für den ADC. Der Apollo 3 kann den ADC in drei Energiesparmodi betreiben, nämlich LPMODE0, LPMODE1 und LPMODE2. Die Wahl dieser Energiesparmodi hängt von der Abtastfrequenz ab. Für die erforderliche Abtastfrequenz von 20 kHz wird der LPMODE0 verwendet. In diesem Modus bleibt der ADC kontinuierlich aktiv. Die Messungen wurden zur Sicherstellung der Konsistenz der Ergebnisse 100-mal wiederholt, und in Tabelle 1 dargestellt.

Mikrocontroller	Energie (µJ)	Standardabweichung (µJ)	mittlere Leistung (mW)	Zeitbedarf (ms)
Apollo 3	57,504	0,0216	2,169	26,511
MSP430	32,449	0,0149	1,237	26,218

Tabelle 1 Vergleich des Energie- und Leistungsverbrauchs zwischen Apollo 3 LPMODE0 und MSP430 bei einer Abtastfrequenz von 20 kHz

Es zeigt sich, dass der MSP430 energieeffizienter ist, da er nur etwa 56% der Energie verbraucht, die vom Apollo 3 benötigt wird. Der Apollo 3 benötigt trotz seines nominell niedrigeren aktiven Stromverbrauchs (µA/MHz) mehr Leistung aufgrund seiner hohen Taktfrequenz von 48 MHz im Vergleich zu 8 MHz. Gemäß den aktuellen Konfigurationseinstellungen ist die CPU beider Mikrocontroller während der Abtastung aktiv, daher verbraucht der Apollo 3 naturgemäß mehr Energie als der MSP430. Durch Einstellen des Apollo 3 auf LPMODE1, bei dem der ADC zwischen den Abtastungen größtenteils abgeschaltet ist, sollte die benötigte Leistung reduziert werden.

5.2 Datenverarbeitung

Das Datenverarbeitungsmessprotokoll besteht aus den folgenden Schritten. Zunächst werden die Daten aus dem FRAM im Falle des MSP430 und aus dem SRAM im Falle des Apollo 3 abgerufen. Dann wird die Welch-Fensterfunktion angewendet und die FFT-Parameter werden

festgelegt. Die FFT wird unter Verwendung der LEA im MSP430 und unter Verwendung des Hardwarebeschleunigers im Apollo 3 berechnet. Am Ende wird die resultierende absolute Signalamplitude bei einer Frequenz von 1 kHz extrahiert. Tabelle 3 fasst die Ergebnisse der von beiden Mikrocontrollern verbrauchten Energie und benötigten Leistung zusammen.

Mikrocontroller	Energie (µJ)	Standardabweichung (µJ)	mittlere Leistung (mW)	Zeitbedarf (ms)
Apollo 3	21,079	0,0127	1,871	11,268
MSP430	242,473	0,0319	1,659	146,096

Tabelle 2 Vergleich des Energie- und Leistungsverbrauchs zwischen Apollo 3 und MSP430 bei der Durchführung von FFT-Berechnungen.

Es ist ersichtlich, dass der Apollo 3 wesentlich energieeffizienter ist und die Aufgabe etwa 135 ms schneller als der MSP430 abschließt. Seine hohe Taktrate, der dedizierte Hardwarebeschleuniger in Kombination mit einer effizient geschriebenen Bibliothek tragen zusammen zu einer äußerst effizienten Berechnung bei. Im Vergleich zum MSP430 spart er beim Durchführen komplexer FFT-Berechnungen etwa 91 % Energie.

6 Zusammenfassung

In dieser Studie wurde ein Umwelt-WSN zur Messung der Chlorophyllfluoreszenz unter Verwendung von zwei Mikrocontrollern entwickelt: dem MSP430FR5994 von TI und dem Apollo 3 von Ambiq. Diese wurden aufgrund ihrer Rechenfähigkeiten, Architektur und ihrem äußerst niedrigen Stromverbrauch ausgewählt. Das Hauptziel war es, ihre Leistung und ihren Energieverbrauch zu bewerten, um den bestgeeigneten Mikrocontroller für Umwelt-WSNs zur Waldüberwachung zu bestimmen.

Die Experimente zeigten, dass der MSP430FR5994 für die Datenerfassung etwa 56 % weniger Energie verbrauchte als der Apollo 3. Die höhere Taktfrequenz des Apollo 3 trug nicht zur Reduzierung der Gesamtdauer bei, führte jedoch zu einem erhöhten Stromverbrauch im aktiven Betrieb. Bemerkenswert ist, dass der Apollo 3 während der FFT-Berechnungen eine signifikant höhere Energieeffizienz aufwies und dabei etwa 11,5-mal weniger Energie und 12,9-mal weniger Zeit als der MSP430FR5994 benötigte.

Zusammenfassend kann festgehalten werden, dass der Apollo 3 komplexe Algorithmen, wie sie beispielsweise zur Einschätzung von Auswirkungen des Klimawandels benötigt werden, mit höherer Effizienz berechnen kann als der zum Vergleich verwendeten MSP430FR5994. Für Aufgaben wie das Auslesen von Sensordaten ist jedoch der MSP430FR5994 vorzuziehen. Diese Studie bietet Umweltwissenschaftlern eine Referenz zur Auswahl der geeignetsten Plattform für langfristige Waldüberwachungs-WSNs.

7 Danksagung

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Design und Anwendung wartungsfreier, autarker Sensorknoten für Funktionsgebäude

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Kurzfassung

Der Beitrag diskutiert essenzielle technische Fragestellungen und Lösungen für die Entwicklung extrem energieeffizienter wartungsfreier, autarker und drahtloser Sensorknoten für die intelligente, energiesparende Steuerung von Energieverbrauchern in Gebäuden (Beleuchtungsquellen, Heizung, Lüftung, Klimatisierung, Verschattung). Kompakte Bauformen, der Einsatz von einfacher kostengünstiger Sensorik und der mitunter schwache Energieeintrag der Solarzellen bei stark schwankenden Beleuchtungsbedingungen stellen hohe Anforderungen an das Energiemanagementkonzept, das eine garantierte Wartungsfreiheit für 10 Jahre ermöglichen soll. Diskutiert wird eine im Projekt verwendete, kostengünstig zu realisierende Systemsimulation für das Energiemanagement der Sensorknoten auf Basis einer Discrete Event Simulation (DES), die neben der Abschätzung der Erreichbarkeit der Zielparameter den Vergleich verschiedener Designs und die Optimierung des System ermöglicht. Mit den im Projekt entwickelten Komponenten wird in der Versuchshalle eines Forschungsbaus die intelligente, energieeffiziente Lichtsteuerung erprobt.

Abstract

The article discusses essential technical issues and solutions for the development of extremely energy-efficient, maintenance-free, self-sufficient and wireless sensor nodes for the intelligent, energy-saving control of energy consumers in buildings (lighting sources, heating, ventilation, air conditioning, shading). Compact designs, the use of simple, low-cost sensor technology and the sometimes weak energy input of the solar cells under strongly fluctuating lighting conditions place high demands on the energy management concept, which should enable guaranteed maintenance-free operation for 10 years. A system simulation for the energy management of the sensor nodes based on a discrete event simulation (DES), which is used in the project and can be implemented cost-effectively, is being discussed. In addition to estimating the achievability of the target parameters, this simulation enables the comparison of different designs and the optimization of the system. The components developed in the project will be used to test intelligent, energy-efficient lighting control in the test hall of a research building.

1 Einführung

Wartungsfreie, autarke, drahtlose Sensorknoten mit passiver und aktiver Steuerfunktion bieten für die Realisierung einer intelligenten, energiesparenden Steuerung von Energieverbrauchern in Gebäuden (Beleuchtungsquellen, Heizung, Lüftung, Klimatisierung, Verschattung) essenzielle Vorteile. Neben der signifikanten Energieeinsparung durch smart geregelte Verbraucher liegt hier das Augenmerk auf einfacher und kostengünstiger Sensorik im Vergleich zu konventionellen Systemen. Konzeptionell soll über eine garantierte Wartungsfreiheit für 10 Jahre, in denen beispielsweise kein Austausch von Batterien oder Akkus erforderlich ist, eine deutliche Minimierung der Umweltbelastung sowie eine deutliche Steigerung der Wirtschaftlichkeit erreicht werden.

Die kompakten Bauformen der Sensor Devices stellen dabei oft eine besondere Herausforderungen dar. Beim Einsatz von photovoltaischen Wandlern ergibt sich durch die kleinere Fläche der Solarzelle und die stark schwankenden

Beleuchtungsbedingungen meist nur ein schwacher Energieertrag. Daraus ergeben sich hohe Anforderungen an das Energiemanagementkonzept. Die Konvertierung und Zwischenspeicherung der gewonnenen Energie muss möglichst verlustfrei erfolgen. Ein Backupspeicher zur Überbrückung längerer Dunkelphasen ist unverzichtbar und daher integraler Systembestandteil. Die Systembasis bilden hier sehr sparsame, optimal dimensionierte und perfekt aufeinander abgestimmte Module, Bauelemente, Operationsmodi (Sensorik, Funk, ..) und Wake-Up-Konzepte unter Verwendung eines eigens entwickelten Low-Power-Timer-ASICs (Application Specific Integrated Circuit).

2 Der passive Sensorknoten

Der passive Sensorknoten (**Bild 1**) hat die Aufgabe, in einstellbaren aber regelmäßigen Abständen Sensordaten der aktuellen Lichtstärke, Temperatur und Luftfeuchte kabellos (hier über ein Zigbee-Funkmodul) an ein zentrales Gateway zu kommunizieren, um z.B. entsprechend die Beleuchtungsquellen in der Werkhalle oder den Büroräumen nachregulieren zu können.

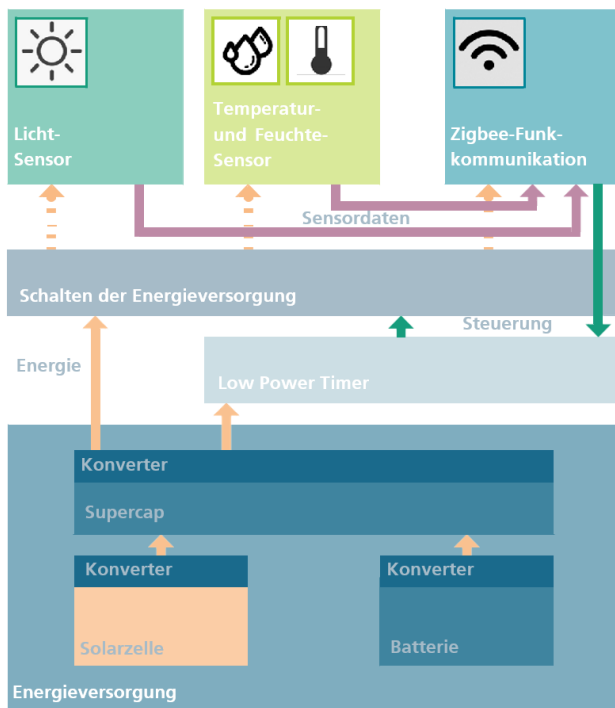


Bild 1: Architektur des passiven Sensorknotens.

Die Energieversorgung des Sensorknotens wird über einen Zwischenspeicher (Supercap) sichergestellt, der mittels DC-DC-Konverter entweder über kleine im Wandelement installierte Solarzellen oder einen Backupspeicher geladen wird. Das zyklische Aufwachen des Systems und somit die Energieversorgung der Sensoren und des Kommunikationsmoduls wird über einen energiesparenden Low-Power Timer ASIC gesteuert.

3 Energiemanagement im Sensorknoten

Die Realisierung kompakter Sensorknoten mit einer Wartungsfreiheit von mindestens 10 Jahren stellt sehr hohe Anforderungen an das Energiemanagementsystem, mit einer sehr effektiven Energiewandlung, möglichst verlustfreier Energiespeicherung und sehr sparsamen, intelligent gesteuerten Verbrauchern.

Das betrachtete System (Bild 1) muss in der Lage sein, mit natürlichem Licht und verschiedenen Kunstlichtquellen effektiv zu arbeiten.

Ein hoher Energieeintrag bei moderaten bis sehr schwachen Lichtverhältnissen bei kompakter Solarzellengröße ist eine Grundvoraussetzung, um den Zwischenspeicher (hier Supercap) ausreichend laden zu können und gleichzeitig die Versorgung des Systems gewährleisten zu können. Eine Auswahl an Solarzellen und Supercaps wurde umfangreichen Labormessungen unterzogen, da die Hersteller-Informationen (zum Beispiel Datenblätter) für diesen Anspruch bei weitem nicht aussagekräftig genug sind. Ein Backupspeicher (Batterie) zur Überbrückung längerer Dunkelphasen ist unverzichtbar und daher integraler Systembestandteil. Nur eine sorgfältige Abstimmung und

Konfiguration aller Komponenten der Energieversorgung, die auch alle DC-DC-Konverter einschließt, führt zu einem hinreichend geringem Verbrauch im Backupspeicher, der wiederum die Lebensdauer des Systems bestimmt.

Ein selbst entwickelter Low-Power-Timer ASIC mit äußerst geringer Verlustleistung realisiert ein sehr sparsames Wake-Up-Konzept, mit zyklischem, bedarfsgesteuertem Aktivieren der jeweilig aktiven Verbraucher in Form der Umweltsensoren, des Controllers und des Funkkommunikations-Moduls.

4 Systemsimulation für das Energiemanagement im Sensorknoten

4.1 Ansatz der Discrete Event Simulation (DES)

Für die Auslegung des Energiemanagements müssen unterschiedlichste Schaltungskonzepte und Bauelemente im Hinblick auf die Erreichbarkeit der Zielparameter (zum Beispiel die Lebensdauer des Energiezwischenspeichers) bewertet und ausgewählt werden. Eine vollständige und exakte Schaltungssimulation unter Einbeziehung des Zeitverhaltens aller Verbraucher inklusive Controller und Funkkommunikation wäre für den vorliegenden Fall sehr kostenintensiv und mangels ausreichender Information aus Datenblättern oder wegen nicht vorhandener beziehungsweise aufwändig zu erstellender Modelle in vielen Fällen nur schwer realisierbar.

Die im Projekt verwendete, vergleichsweise kostengünstig zu realisierende Systemsimulation für das Energiemanagement der Sensorknoten basiert deshalb auf einer Discrete Event Simulation (DES) [1,2]. Diese Art der Simulation modelliert den Betrieb eines Systems als eine (diskrete) Folge von Ereignissen in der Zeit. Jedes Ereignis tritt zu einem bestimmten Zeitpunkt ein und markiert eine Zustandsänderung im System. Dabei können bestimmte Ereignisse wiederum neue Ereignisse auslösen und ermöglicht so auch die Simulation komplexeren Verhaltens. Vorteil dieser Art der Simulation ist, dass nur die jeweiligen Ereignisse simuliert werden und nicht alle Zeitpunkte zwischen selbigen. Damit können sehr lange Zeiträume innerhalb kurzer Zeit und mit geringem Datenaufwand simuliert werden, wobei dennoch komplexe Zusammenhänge, Abläufe und Kalkulationen realisierbar sind. Wesentlich ist auch die vergleichsweise einfache zu realisierende Implementierung des sehr kompakten Simulator-Modell-Frameworks.

4.2 Discrete Event Simulation für den passiven Sensorknoten

Das Energiemanagementsystem des passiven Sensorknotens wurde auf Basis der Discrete Event Simulation implementiert. Der energetische Einfluss aller Verbraucher (Bild 1), also das Zeitverhalten der Sensoren, des Funkmoduls

und weiterer Komponenten muss dabei in die Simulation einbezogen werden. Kern der Simulation sind jedoch die Energieströme zwischen und Verluste in allen Komponenten des Powermanagements, insbesondere die Solarzelle, der Zwischenspeicher (Supercap), der Backup-Speicher (Batterie), aber auch Converter (zum Beispiel DC-DC-Wandler), der Low-Power-Timer und weitere Komponenten (**Bild 2**).

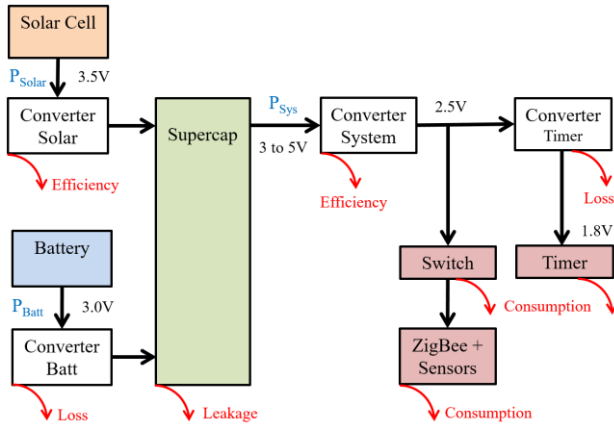


Bild 2: Struktur des Energiemanagements im passiven Sensorknoten.

Die optimale Definition der States und diskreten Events ist die Voraussetzung für eine zielführende und erfolgreiche DES (**Bild 3**).

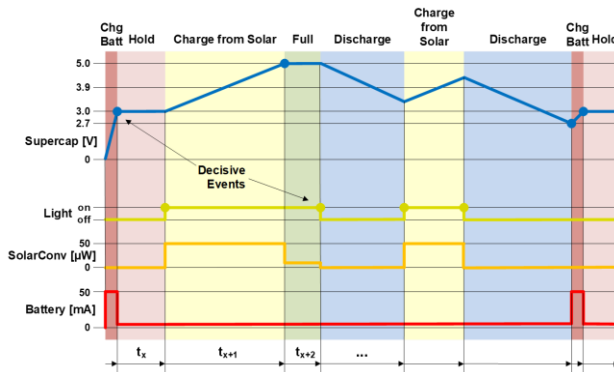


Bild 3: Discrete Event Simulation - Lade- und Entladevorgänge der Speicher des passiven Sensorknotens werden durch entsprechende States (vertikale Balken) repräsentiert, die zeitlich nächstfolgenden Ereignisse durch die Decisive Events (farbige Punkte).

Für jede Speicherkomponente (Zwischenspeicher, Backup-Speicher) muss für jeden definierten State und dessen Zeitdauer (Bild 3, Zeitachse) eine detaillierte Energiebilanzkalkulation bereitgestellt beziehungsweise erarbeitet werden. Eine dafür ausreichende Charakterisierung der wesentlichen Komponenten wie Solarzelle, Supercap, und der Buck- und Boost-Konverter konnte für diese Applikation nur durch detaillierte labortechnische Messungen entsprechend dem Stand der Technik [3, 4] erreicht werden. Für weniger relevante Komponenten kann eine Abschätzung anhand von Datenblättern oder einfachen Modellen ausreichend sein.

Die Implementierung der Discrete Event Simulation für das Energiemanagement des passiven Sensorknotens erfolgt in Python 3.12 [5] unter PyCharm (JetBrains s.r.o.) [6] als leicht zugängliches, flexibles Framework, mit umfassender Tool- und Bibliotheksunterstützung, mit dem sehr kompakter und leicht lesbarer Code realisiert werden kann.

Die erzielte Implementierung ermöglicht den automatisierten Vergleich verschiedener struktureller und methodischer Energiemanagementsystem-Ansätze und darüber hinaus eine genauere Analyse der konkreten Auswirkungen von Komponentenauswahl und -konfiguration in Hinblick auf die Zielparame-ter („10 Jahre Lebensdauer“), wie beispielhaft in **Bild 4** dargestellt.

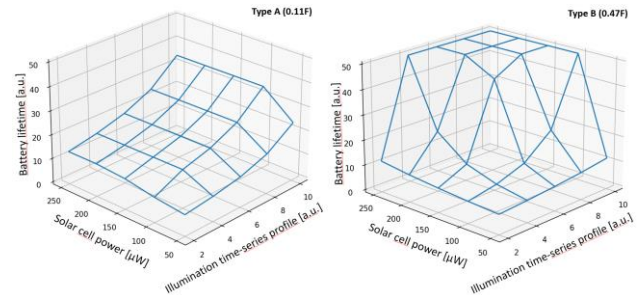


Bild 4: Battery Lifetime in Abhängigkeit von der Solarzellenleistung und den Beleuchtungszeitreihenprofilen - Vergleich Supercap Typ A mit Supercap Typ B.

Die in Bild 4 gezeigten Diagramme stellen als Simulationsergebnisse die jeweils zu erwartende Batterielebensdauer (Z-Achse) bei Einsatz von 2 verschiedenen Supercap Typen vergleichend gegenüber. Die Darstellung erfolgt jeweils in Abhängigkeit von der Solarzellenleistung (X-Achse) und den Beleuchtungszeitreihenprofilen (Y-Achse). Alle weiteren Parameter der Energiemanagementschaltung sind für beide Simulationen identisch. Die dargestellten Diagramme verdeutlichen, dass bei Einsatz des Supercaps Typ B (rechtes Diagramm) für den überwiegenden Teil des betrachteten Parameterraums eine wesentlich höhere Batterielebensdauer zu erwarten ist, als bei Einsatz des Supercaps Typ A.

Durch automatisiertes Iterieren von Konfigurationen und Parametern für die Hauptkomponenten konnte mit dieser Methode eine signifikante Optimierung des Systems erzielt werden. Automatisch generierte Zeitdiagramme können bei Bedarf für Detailanalysen und Verifikation herangezogen werden.

5 Ausblick

Als Testumgebung für die entwickelten Komponenten dient eine beleuchtete Versuchshalle (**Bild 5**) im Forschungsbau SCALE der Leibniz Universität Hannover [7].



Bild 5: Ausrüstung einer beleuchteten Versuchshalle im Forschungsbau SCALE an der Leibniz Universität Hannover als Testumgebung.

Zentral ist dabei, dass über die Erfassung der aktuellen nativen Helligkeit durch Tageslicht und durch Kunstlicht mit einer Anzahl einfach zu montierender, kompakter, autarker passiver Sensorknoten die individuell dimmbare LED-Beleuchtung in der großen Versuchshalle örtlich adaptiert werden kann. Ähnliches wird über eine Präsenzsteuerung im Wartungsgang erreicht. Aktive Sensorknoten in Form von Bedienelementen auf Basis von elektromagnetischem Energy Harvesting befinden sich in der Entwicklung. Die Methodik und das Systemkonzept beschränken sich dabei nicht generell auf Funktionsgebäude wie Lagerhallen, Produktionshallen, Verkaufsräume und Behördenräume. Auch Quartiere wie private oder kommerziell genutzte Wohnräume stehen im Fokus.

6 Danksagung

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Design of an Energy Harvesting-Based Vibration Sensor for Predictive Maintenance

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Abstract

This research involved the design of a passive vibration harvester utilized as a sensor for measuring the frequency of periodic vibrations. The oscillator design is aligned to a specific frequency and uses the eigenfrequencies of the material and geometry. Combined with a piezoelectric structure, energy conversion sufficient for signal generation occurs only at resonance. This creates an active sensor system that does not need an external energy supply for signal generation.

1 Introduction

The Industrial Internet of Things (IIoT) offers new opportunities to connect, monitor, and analyse industrial data for predictive maintenance [1]. Continuous monitoring sensors are required to prevent failures and anticipate maintenance procedures, resulting in reduced downtime. Vibration is often used for fault detection and condition monitoring because it correlates with machine operation. Variations indicate process changes and certain frequencies can indicate defects [2]. Many existing vibration sensors still require an external power source, which is a challenge for integration into the IIoT [1]. Energy harvesting offers a promising solution for creating autonomous sensors with independent energy supplies [3,4].

For maximum output, an energy harvester should operate in resonance with the ambient frequency of the environment. This is achieved by aligning the oscillator design to a specific frequency and utilizing the eigenfrequencies of the material and geometry. Combining the oscillator with a piezoelectric structure; energy conversion for signal generation occurs at resonance. Designing a harvester to target predefined damaging frequencies enables it to function as a cost-effective and autonomous sensor for predictive maintenance.

The adoption of additive manufacturing methods for their production is on the rise, as energy harvesting technologies continue to advance. Compared to traditional technologies, such as moulding, 3D printing offers benefits such as faster development, no requirement for moulds, and fewer additional process steps for fabricating complex geometries. Additionally, it has the potential to reduce waste, lead time, and costs [5,6].

Certain challenges persist, particularly regarding the limitations imposed by the electrical properties and complex fabrication of additive manufactured piezoelectric structures [7, 8].

Using standard piezoelectric structures and combining them in the additive manufacturing process is a promising solution to overcome these challenges. By utilizing established piezoelectric components, manufacturers can access new opportunities that are easier to implement and more cost-effective.

2 Design

The sensor design is based on a cantilever beam with a proof mass given in Figure 1. This enables a compact construction and adaptation to different frequencies.

COMSOL Multiphysics was used for the finite element method (FEM). The eigenfrequencies of the sensor structure were determined using simulation software. A parameter study was made to design a probe with a specific eigenfrequency of 204 Hz. The dimension of the sensor can be seen in Table 1.

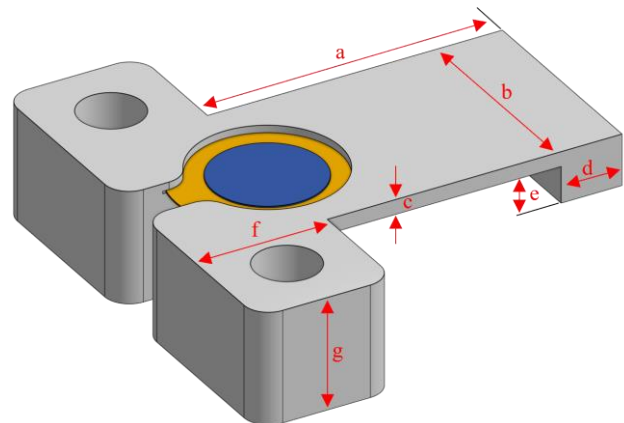


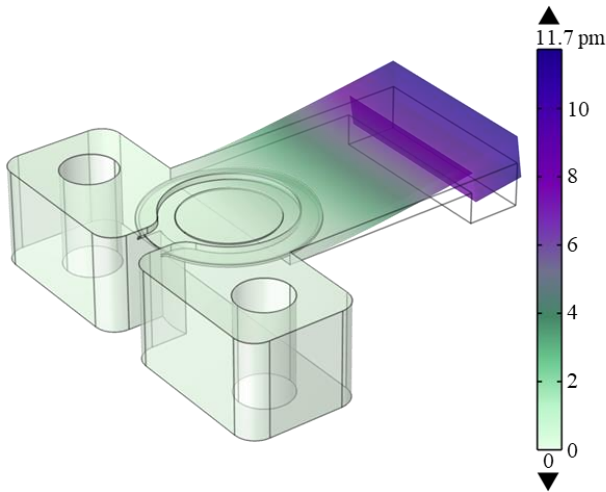
Figure 1 Sensor structure with polymer-part (grey), piezo-material (blue) and metal-part (yellow)

The sensor utilizes its first eigenmode, as seen in Figure 2, in conjunction with a piezoelectric ceramic mounted on a metal disc for efficient energy conversion, enabling defect detection at this frequency. Strategic placement of the piezo transducer at the clamping point optimizes sensitivity, capitalizing on the highest stress concentrations for enhanced output voltage.

There is a recess in the holder for the connection cable of the piezo transducer. Multiple sensors can be stacked to create a redundant system or to analyse different frequencies. The sensor is attached using through holes.

Table 1 Parameters of the 204 Hz eigenfrequency sensor

Parameter	Value in mm
a	24.2
b	17
c	1.2
d	5
e	3
f	11.2
g	9.2
∅ Piezo-material	9
∅ Metal	15
Thickness Piezo-material	0.12
Thickness Metal	0.1

**Figure 2** First eigenmode with the maximum displacement at 1 g acceleration

3 Material and Methods

3.1 Material and Machine

The developed sensor version was manufactured with the Neotech AMT 15X SA with a 0.2 mm layer height and 100% filling density. The material utilized for the 3D-printed part is polyethylene terephthalate glycol (Prusament PETG, Prusa Research). The piezoelement is the EPZ-15MS60W from Elektrotechnik Karl-Heinz Mauz GmbH. Copper wires are required to connect the sensor to the measuring device.

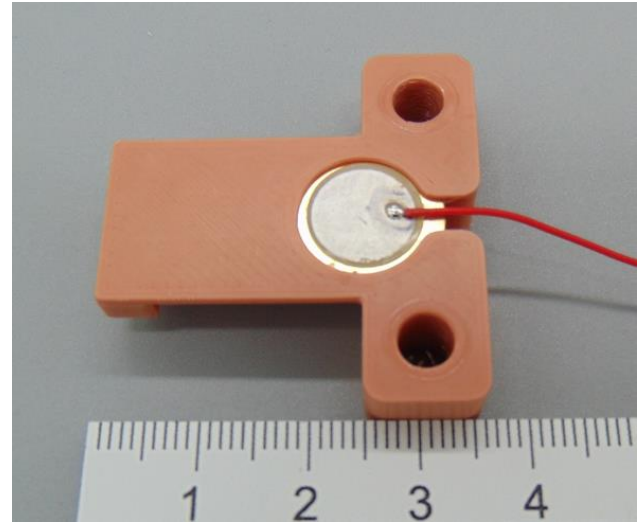
3.2 Working Principle

Mechanical energy in general can be harvested using electromagnetic, electrostatic or piezoelectric harvesting techniques [9]. Piezoelectric transduction is a common mechanical energy harvesting mechanism due to its high electromechanical coupling factor and piezoelectric coefficient compared to electrostatic, electromagnetic transduction [10].

The mechanical vibration-induced strain is converted into alternating current (AC) electricity power through the direct piezoelectric effect.

3.3 Fabrication

The process of hybrid manufacturing starts with additive manufacturing of the oscillator up to a certain layer. Then, a printing pause is implemented to allow for precise positioning of the piezo transducer within the printed component. Printing resumes and encapsulates the piezo transducer with a polymer layer to facilitate material bonding. The metal part of the transducer is prepared with adhesive spray to ensure good bonding of the extruded polymer to the metal surface. Furthermore, the transducer is seamlessly integrated into the polymer, ensuring long-term functionality and a form-fit integration within the oscillator. Figure 3 shows a fabricated sensor sample.

**Figure 3** Hybrid manufactured sensor sample with a simulated eigenfrequency of 204 Hz

3.4 Experimental Setup

To verify the results of the simulations two samples were fabricated and tested. The sensor design was evaluated in an experimental setup. The sensors were connected to an oscilloscope. The WaveAce 1001 (Teledyne LeCroy) was applied to measure the voltage of the transducer. The sensor was mounted on the mini “combo” shaker (Sentek Dynamics) which was connected to a WaveStation 2012 (Teledyne LeCroy) waveform generator. The data has been evaluated in MATLAB.

4 Results and Discussion

Two Harvesters were tested and their resonant frequencies with corresponding peak voltage outputs were captured at 206 Hz and 206.5 Hz, as displayed in Figure 4. Compared to the simulated eigenfrequency of 204 Hz does this equate to a deviation of 1.2%. This deviation may be due to deviating material parameters or geometric deviations due to manufacturing tolerances. In addition, the position of the transducer may deviate from the theoretical position due to the process.

The peak voltage also varies between the two samples. Sample 1 has a peak Voltage of 2.2 V and sample 2 has a peak Voltage of 1.4 V. This is a Deviation of 36% between

the two samples. The temperatures in the manufacturing process may have partly depolarised the piezo transducer. General manufacturing tolerances of the piezo transducer may also be responsible. It could also be due to a lack of adhesion between the piezo-Transducer and the polymer, as a result of which the deformation is not transferred.

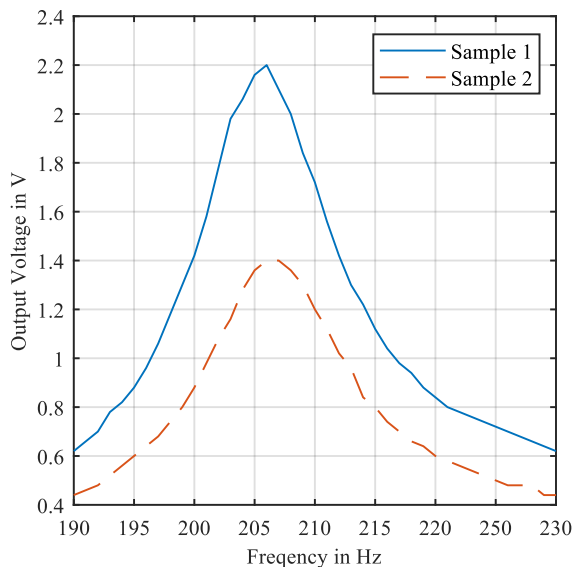


Figure 4 Measured voltage (peak to peak) of the samples at various frequencies

5 Conclusion

The successful manufacture of the sensor using 3D printing opens up new design possibilities and low-cost options. This allows for the creation of complex components with integrated vibration sensors or other sensor technologies in a simple manner. The sensors can be scaled and customized for new applications.

6 Future Work

The effects of other geometry's, other materials than PETG as well as printing parameters like layer height, infill pattern or nozzle diameter will be subject of future research.

7 Acknowledgement

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Push-Button Rotational Energy Harvester for Wireless Sensor Nodes

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Abstract

This paper presents the results of a newly developed switch-based energy harvester (EH) and compares them with the previous version. First, the functionality of the harvester is elucidated before the simulation-improved analysis for creation of a new version is explained. Finally, the two versions are compared with each other in terms of induced voltage and energy yield.

1 Introduction

Energy harvesters (EH) are becoming increasingly important in the context of digitalisation, the energy transition and the Internet of Things (IoT). The growing integration of low-power wireless sensors, the increase in longevity and the reduction of maintenance costs for such systems are reasons for the implementation of EH. [1]

Energy harvesting refers to the generation of electrical energy by converting another form of energy, such as thermal, mechanical or photonic energy. Therefore, EH are individually adapted to its ecological environment and the required parameters such as voltage, energy or available space. [2]

Various commercial energy harvesters are already available on the market [3,4]. However, there is currently no compact, switch-based EH that provides the energy of more than 0.6 mJ at a minimum voltage of 1.8 V required for some IoT, smart home and embedded systems applications [5].

In this article, a compact electromagnetic EH (called EH II) with a reduced construction volume and a higher energy yield is presented and compared with its predecessor model (EH I).

The EH I has already been set up and analysed in [6]. It was found that the generated induced peak-voltage of $V_p = 300$ mV is still far from the desired target values of at least $V_p = 1.8$ V. Moreover, the harvested energy has to be increased from 0.6 mJ to at least 4 mJ, which is necessary for activating an integrateable transmitter module. Therefore, simulation-based analyses were carried out for increasing the harvested voltage and energy. Additionally, a suitable switch-sized miniaturisation of the EH has been investigated.

2 Operation Principle

The design of the EH (**Figure 1**) enables the energy storage in a spring (spring constant of $c = 0.523$ N/mm²) by manually pressing a button. As soon as the button is released, the spring relaxes and transfers energy to the gear, which is firmly connected to the shaft. This causes the eight 1 mm permanent magnet segments above the coil system to rotate. The segments have a remanence of $B_R = 1.4$ T.

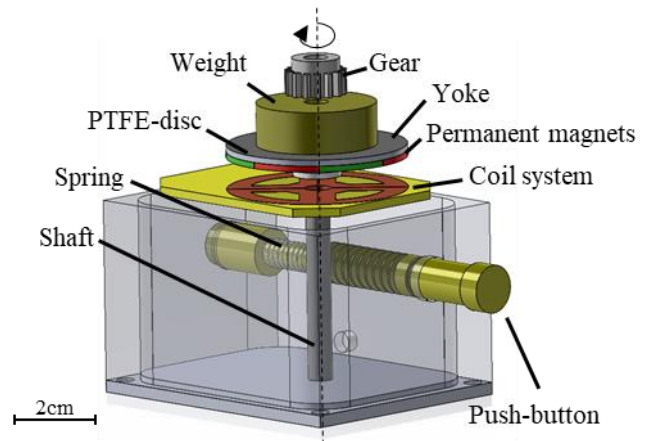


Figure 1: Explosion view of the EH I

They are arranged alternately in north and south direction and are connected concentrically to a permalloy yoke.

The coil system consists of four coils, each consisting of 10 layers with 10 windings resulting in 100 windings in total. Their overall height is 1.3 mm. In order to increase the induced voltage while keeping the resistance low, two coils are connected in series and these groups are then connected in parallel.

To reduce friction between the coil system and the permanent magnets, a PTFE-disc is installed, which also creates a defined air-gap. As a result, of the rotation, a voltage is induced in the fixed coil system by the alternating magnetic field.

3 Simulation

In order to increase the induced voltage and the converted energy of EH I, a simulation-based analysis of the system was carried out.

As a result, a non-optimal flux guide was identified, as shown for EH I in **Figure 2**, top. The red and green segments in the figure illustrate the alternating alignment of the magnets. The letters N and S within a segment describe the north- and south-pole.

The greater the distance between the coil system and the permanent magnet, the less field lines are passing through the coils.

If a second row of permanent magnet segments is attached underneath the coil system (**Figure 2**, bottom), the magnetic field lines are more concentrated through the coil system resulting in a denser magnetic field and a higher magnetic field strength.

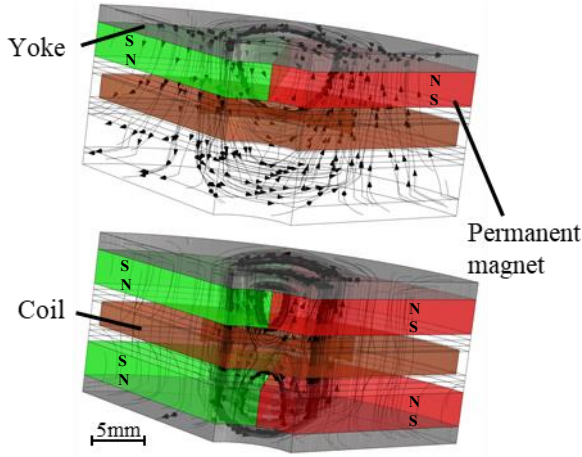


Figure 2: Simulation comparison of the course of the field lines in EH I (top) & EH II (bottom)

A closer look at the magnetic field strength H within the coil confirms that in EH I the magnetic field strength is higher on the surface of a coil close to the permanent magnets, which then gradually decreases with increasing distance to them. As a result, at the lower layers of a coil, the induction is weaker than on the top layers. (**Figure 3**, left).

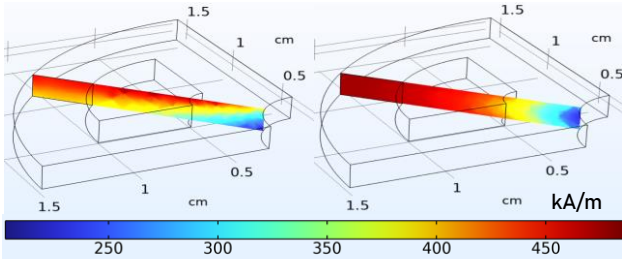


Figure 3: Cross section simulation of the magnetic field strength through a coil. On the left side with permanent magnets over the coil, on the right side on both sides of the coil.

The chosen solution for optimised magnetic flux routing consists of implementing an identical additional row of permanent magnet segments with a remanence of $B_R = 1.4T$ below the coil system. In addition, the thickness of the permanent magnets has been increased from 1 mm to 2 mm on both sides for the EH II. As a result, the magnetic field strength is stronger and more homogeneous through the coil system, as can be seen in the simulation in **Figure 3**, right.

After the design modification in the simulation program COMSOL Multiphysics®, an analysis of the induced voltage has been carried out in order to validate the design of the EH II. For the simulations of both EHs, the rotation speed has been set to 1,000 rpm, the outer radius of the coil system equals 15.5 mm and the inner radius 3 mm.

As a result, an increase in the induced open-circuit peak-voltage V_P from 150 mV per coil to 380 mV per coil for the new design has been simulated (**Figure 4**).

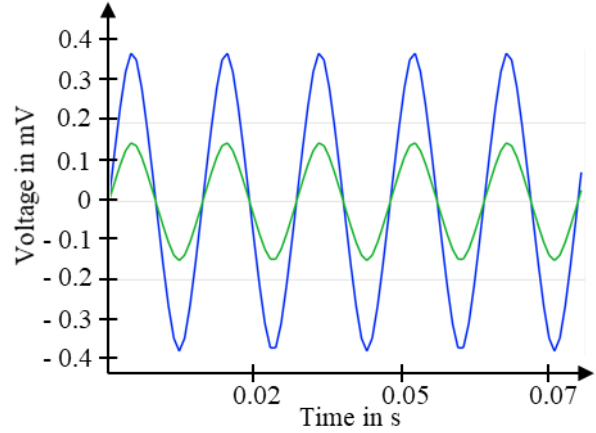


Figure 4: Simulation based comparison of the induced voltage of the EH I (green) and EH II (blue)

4 Experimental Results

Due to the integration of the second layer of permanent magnet segments under the coil system, the mechanical design of the EH was revised as shown in **Figure 5**. Both ferromagnetic yokes are firmly attached to the shaft enabling a stable air-gap without the required PTFE-disc. In addition, an identical second coil system including four coils was integrated in the EH to further increase the induced voltage.

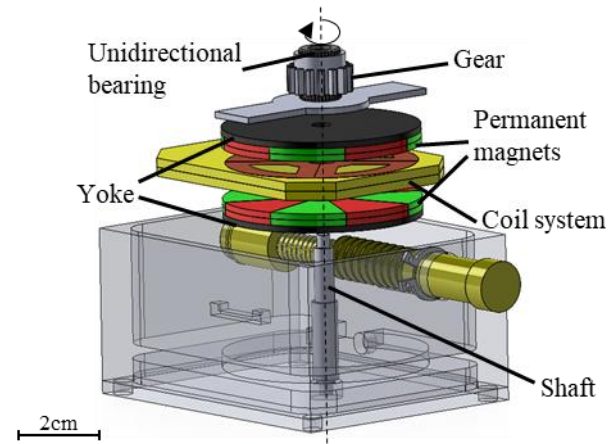


Figure 5: Structure of the EH II

Furthermore, the unidirectional bearing was mounted directly in the gear, removing the space-consuming weight from the EH I, that was included for pressing the yoke downward against the PTFE-disc and guarantee a constant air-gap to the coil system.

As a result of all the mechanical modifications, the construction space has been reduced by 35 %. Regarding the induced open-circuit voltage of both EHs, upon pressing the button, a peak-voltage of $V_P = 300$ mV was achieved with the EH I. This has been increased by factor 5 to

$V_P = 1.5$ V for EH II by restructuring and optimising the magnetic flux path (**Figure 6**).

The rotation time of 1.6 seconds and the rotation speed of 1,000 rpm were unchanged.

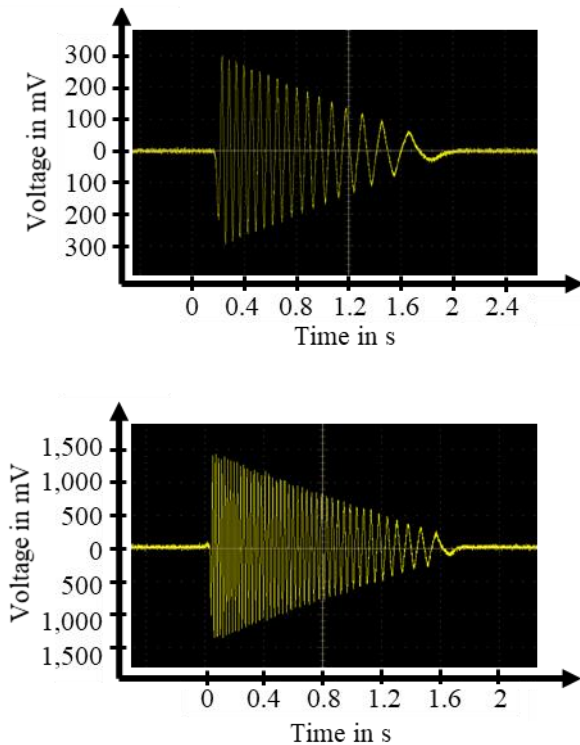


Figure 6: Comparison of the generated open-circuit voltage of the two energy harvesters EH I (top) & EH II (bottom)

In order to maximise the energy yield of the EH, the electrical load has to be analysed. For this purpose, various electrical resistors have been connected to the EH in order to measure the induced voltage and energy output with different electrical loads. The results have been compared with the previous EH I (**Figure 7**).

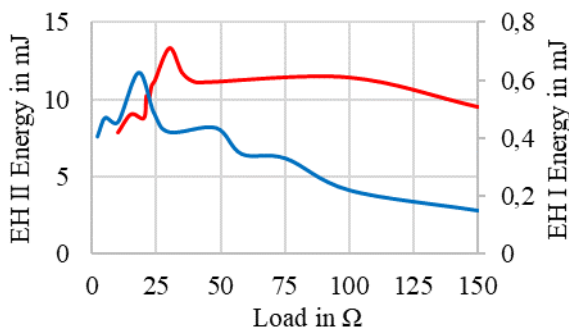


Figure 7: Comparison of the harvested energy in relation to the electrical load of the EH I (blue) and EH II (red)

With EH I, a converted electrical energy of up to 620 μ J was achieved with an electrical load of 20 Ω . EH II achieved a converted energy of up to 13.3 mJ with an applied electrical load of 30 Ω . The energy yield was thus improved approximately by the factor of 21. This high energy

yield enables additional functions to be powered by the EH such as an LED for confirming transmitted signals.

5 Conclusion and Outlook

In this paper, an energy harvester type one (EH I) consisting of a coil system and rotating permanent magnets has been analysed and improved to fulfill the requirements of a higher achievable voltage of at least 1.8 V and greater harvested energy amount of at least 4 mJ. After a simulation-based validation of EH I, an improved EH II has been realised.

Simulation results showed the requirements to increase the magnetic field strength and homogeneity of the magnetic field flux in the coil system for EH II. This was realised by a symmetric construction with a second disc of permanent magnets and an increase of the thickness of the permanent magnets from 1 mm to 2 mm. Due to the mechanical conversion and the integration of a second identical coil system, the induced voltage and the converted energy were further increased from 0.3 V to 1.5 V and 0.6 mJ to 13.3 mJ. The peak-voltage of $V_P = 1.5$ V has to be further increased by e.g. using a paramagnetic material for the yoke or by redesigning the coil system. Further future developments will focus on a compact and surface-mountable version of the system.

6 Acknowledgements

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Neuartiger Wärmestromsensor auf Siliziumbasis

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Kurzfassung

Die hier vorgestellte Entwicklung zielt auf die Realisierung möglichst kleiner, kostengünstiger Sensorelemente ab, die in der Lage sind, die physikalische Größe *Temperatur* nicht nur als präzisen Absolutwert, sondern auch hochdynamisch als vektorielle Größe zu erfassen. Zudem gestattet die Integration innovativer hochauflösender Temperatursensoren mit einem mehrdimensionalen Kennlinienfeld die Bereitstellung umfassender Funktionen zur industriell zunehmend relevant werdenden Selbstdiagnose. Fast ausschließlich alle Wärmestrom-Sensoren, die auf dem Markt verfügbar sind, arbeiten nach dem Seebeck-Effekt. Im vorliegenden Fall wird ein Sensor entwickelt, der als funktionale Einheit über in Reihe geschaltete Temperaturdioden verfügt. Dieser Sensor hat gleich mehrere Vorteile: er hat einen größeren Signalhub, man kann auch absolute Temperaturen messen und er ist erheblich preisgünstiger.

Abstract

The presented development aims to realize the smallest possible, cost-effective sensor elements that are able to record the physical quantity of temperature not only as a precise absolute value, but also highly dynamically as a vector quantity. In addition, the integration of innovative high-resolution temperature sensors with a multi-dimensional characteristic field allows the provision of comprehensive functions for self-diagnosis, which is becoming increasingly relevant in industry. Almost all heat flow sensors available on the market work according to the Seebeck effect. In the present case, a sensor is being developed that has temperature diodes connected in series as a functional unit. This sensor has several advantages: it has a larger signal size, you can also measure absolute temperatures and it is significantly cheaper.

1 Ziel der Entwicklung

Die CiS Forschungsinstitut für Mikrosensorik GmbH in Erfurt hat sich innerhalb der letzten Jahrzehnte zu einem etablierten Entwickler und Zulieferer von hochpräzisen siliziumbasierten Sensoren für international agierende Unternehmen nicht nur im Bereich der industriellen Prozessmesstechnik entwickelt. Dabei lag und liegt der Fokus insbesondere auf der Realisierung neuer innovativer Sensor-konzepte.

Vor diesem Hintergrund schafft das Projekt „**Si-HFS**“ neben den wissenschaftlichen, technologischen sowie metrologischen Voraussetzungen für die Entwicklung neuartiger Wärmestromsensoren eine solide Ausgangsbasis, die insbesondere bei der Entwicklung kundenspezifischer Lösungen im Bereich der stetig wachsenden industriellen Oberflächentemperatur- sowie Wärmestrommesstechnik Anwendung finden wird.

Dabei zielt das „**Si-HFS**“-Vorhaben auf die Realisierung möglichst kleiner, kostengünstiger Sensorelemente ab, die in der Lage sind, die physikalische Größe *Temperatur* nicht nur als präzisen Absolutwert, sondern auch hochdynamisch als vektorielle Größe zu erfassen. Zudem gestattet die Integration innovativer hochauflösender Temperatursensoren mit einem mehrdimensionalen Kennlinienfeld die

Bereitstellung umfassender Funktionen zur industriell zunehmend relevant werdenden Selbstdiagnose.

Entsprechende neuartige Wärmestromsensoren können nicht nur herkömmliche Primärwandler zur Ermittlung von Wärmeenergiemengen ergänzen oder ersetzen, wie diese beispielsweise in herkömmlichen Heizkostenverteilern Anwendung finden, sondern bieten sich insbesondere hinsichtlich der präzisen Messung von Oberflächentemperaturen an.

Bei der Bestimmung der Oberflächentemperatur eines Körpers ermöglichen sie parallel zur eigentlichen Temperaturmessung die Ermittlung der systematisch bedingten Wärmeableitung durch den aufgebrachten Oberflächentemperatursensor, was erstmals eine adaptive Korrektur resultierender Messabweichungen gestattet. Dies ist beispielsweise bei der Temperaturmessung an Rohrleitungen der Fall, wo durch den Einsatz von Oberflächentemperatursensoren zunehmend versucht wird auf kostenintensive, invasive Messstellen zu verzichten.

Aber auch z.B. in der dimensionellen Messtechnik, wie der Koordinatenmesstechnik, eröffnet die nichtinvasive, hochauflösende, reproduzierbare und insbesondere messabweichungsarme Bestimmung der Prüflingstemperaturen anhand ihrer Oberflächentemperatur weitere Einsatzfelder. Ungenau bekannte Prüflingstemperaturen verursachen hier

infolge der thermischen Ausdehnung der Messobjekte einen Großteil der real auftretenden Messunsicherheiten. Vergleichbare Anwendungen sind ebenfalls im Bereich der Medizintechnik denkbar, um z.B. auf Basis der Hauttemperatur auf die tatsächliche Körpertemperatur zu schließen. Darüber hinaus ermöglicht die direkte, hochdynamische Messung kleinster Temperaturgradienten nicht nur Einsätze in sicherheitsrelevanten Bereichen. Ein diesbezüglicher Anwendungsfall liegt beispielsweise im Bereich der Energiespeichertechnik u.a. für Elektrofahrzeuge. Hier ist es nicht nur im Fehlerfall essentiell, den Anstieg der Temperatur einer einzelnen Akkumulatorzelle in kompakten Anordnungen gegenüber benachbarten Zellen schnellstmöglich zu detektieren.

In allen beschriebenen Fällen erweitert die Möglichkeit zur Selbstdiagnose der neuartigen Wärmestromsensoren den Nutzwert für den Anwender erheblich. So kann nicht nur wie bei anderen Sensorkonzepten ein Totalausfall detektiert werden, sondern es können ebenfalls Dekalibrierungseffekte sowie thermische und elektrische Überlastungen eindeutig sowie physikalisch plausibel identifiziert werden.

2 Technologie

2.1.1 Der Siliziumchip

Da für die angestrebte Applikation aufgrund der zu erwartenden nicht allzu großen Differenzen bezüglich der Temperatur zwischen der Vorderseite und der Rückseite des Sensors insgesamt ein größerer Signalhub und eine größere Steilheit wünschenswert ist, werden in diesem Falle mehrere Dioden hintereinandergeschaltet (Bild 1). Da die Dioden gegeneinander elektrisch isoliert werden müssen, wird in diesem Fall SOI – Material verwendet. Somit hat man die Möglichkeit durch einen Ätzzvorgang die Device-schicht, die eine Stärke von $2\text{ }\mu\text{m}$ hat, bis auf die Diodengebiete zu entfernen. In einem letzten Arbeitsgang werden die Dioden durch eine Metallisierung miteinander verbunden. Diese Technologie wurde bereits erprobt, und zwar mit jeweils drei, fünf, sieben und zehn Dioden in Reihe.

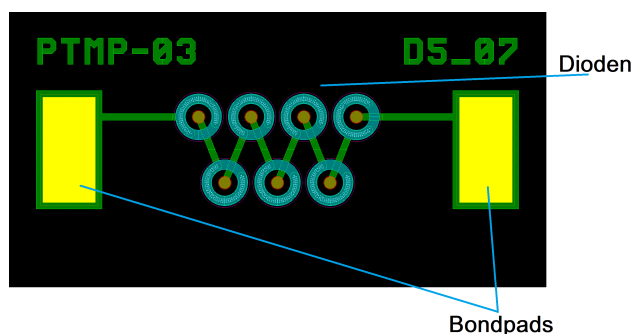


Bild 1: Layout von sieben in Reihe geschalteten Temperaturdioden

In Bild 2 sind drei Kennlinien solch eines Chips im Temperaturbereich von -40°C bis 120°C dargestellt bei drei verschiedenen Strömen ($100\text{ }\mu\text{A}$, $300\text{ }\mu\text{A}$ und $500\text{ }\mu\text{A}$).

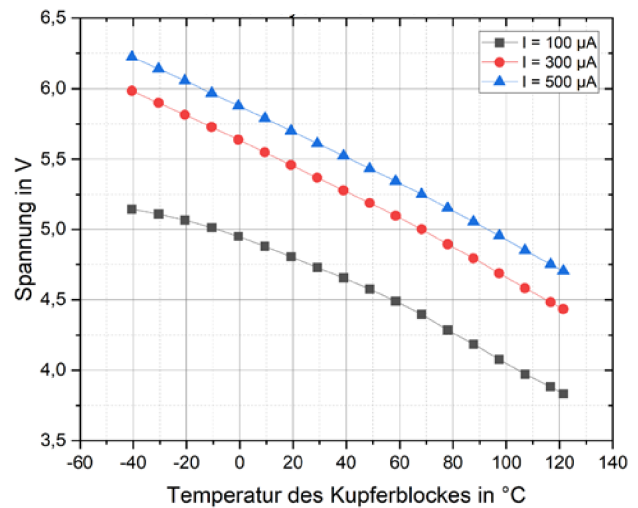


Bild 2: Temperatur-Spannungs-Kennlinien von in Reihe geschalteten Temperaturdioden [1]

2.1.2 Der Gesamtaufbau

In Bild 3 ist der Gesamtaufbau des Sensors wiedergegeben. Er besteht aus zwei Siliziumchips, auf denen sich jeweils zwei Gebiete mit in Reihe geschalteten Temperaturdioden befinden. Dazwischen befindet sich der thermische Isolator (entweder aus Quarz-Glas oder aus Fused-Silica-Glas). Von den thermischen Eigenschaften sind diese beiden Glassorten sehr ähnlich; welche verwendet wird entscheidet sich durch die Qualität der Bondverbindungen [2] [3].

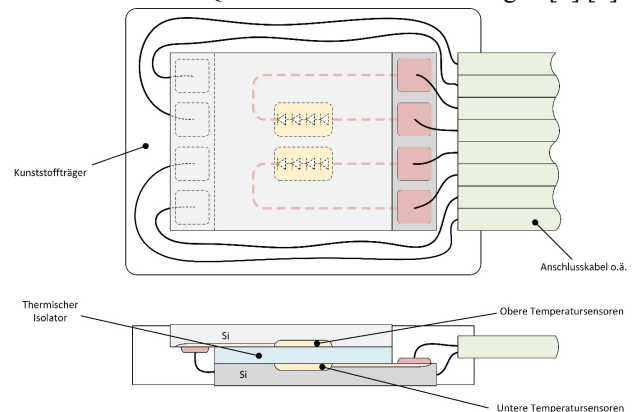


Bild 3: Schema des Sensoraufbaus, bestehend aus den oberen und unteren Temperatursensoren und der dazwischenliegenden Isolatorschicht

Im Längsschnitt sieht man den Stapelaufbau. Zwei weitere Wafer können noch als Schutzschicht gebondet werden. Diese bestehen wahlweise aus Silizium oder aus Keramik.

Des Weiteren müssen die vier Sensorelemente auch noch verschaltet und angeschlossen werden. Insgesamt sind auf dem Sensor vier Elemente vorgesehen, damit man sie zu einer besseren Signalerfassung zu einer Vollbrücke wie in Bild 4 dargestellt, verschalten kann.

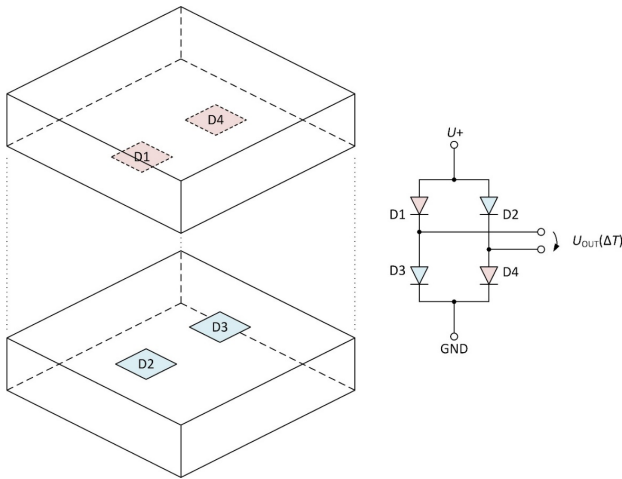


Bild 4: Mögliche Auslegung des Sensors mit einer Brückenschaltung

Unsere Kalkulationen im Vergleich zu einem herkömmlichen Wärmestromsensor gehen von folgenden Voraussetzungen aus:

- Sensorelement von $4 \times 4 \text{ mm}^2$
- Messung der Temperaturdifferenz anhand einer Vollbrücke mit je 7 in Reihe geschalteten Dioden (2x 7 auf Oberseite, 2x 7 auf Unterseite)
- Temperatur der Umgebung: $20 \text{ }^\circ\text{C}$
- Thermischer Kontakt der Oberseite des Sensors zur Umgebung: ruhende Luft (Wärmeübergangskoeffizient $9,1 \text{ W}/(\text{m}^2\text{K})$)
- Temperatur des Messobjektes: $80 \text{ }^\circ\text{C}$
- Kontakt zwischen Sensor und Messobjekt: Wärmeleitpaste ($25 \text{ }\mu\text{m}$ Schicht mit Wärmeleitfähigkeit von $10 \text{ W}/(\text{m}^2\text{K})$).

Mit den obigen Bedingungen gilt für einen Wärmestromsensor in der hier beschriebenen Art:

- Wärmeleitfähigkeit des Sensors (eigentlich irrelevant – nur für Vergleichszwecke): $1,7 \text{ W}/(\text{m}^2\text{K})$
- „gemessene“ Wärmestromdichte: $179,5 \text{ W}/\text{m}^2$
- Elektrische Empfindlichkeit: $25,3 \mu\text{V}/(\text{W}/\text{m}^2)$ (das ist die metrologisch eigentlich interessante Größe)
- Oberer interner Temperatursensor: $79,837 \text{ }^\circ\text{C}$
- Unterer interne Temperatursensor: $79,999 \text{ }^\circ\text{C}$
- Temperaturdifferenz zwischen beiden internen Sensoren: 162 mK
- Spannungssignal am Sensorausgang: $4,5 \text{ mV}$

Mit einer besseren thermischen Ankopplung würde man auch größere Temperaturgradienten erzeugen und somit größere Signale erhalten.

Ein vergleichbarer Wärmestromsensor der herkömmlichen Bauart hätte hier die folgenden Eigenschaften:

- Sensorfläche: $4,4 \times 4,4 \text{ mm}^2$
- Wärmeleitfähigkeit des Sensors: ca. $1,1 \text{ W}/(\text{m}^2\text{K})$
- „angenommene“ Wärmestromdichte: $179,5 \text{ W}/\text{m}^2$
- Elektrische Empfindlichkeit: $1,5 \mu\text{V}/(\text{W}/\text{m}^2)$

- Oberer und unterer interner Temperatursensor: keine Messung der Absoluttemperatur mit diesem Sensor möglich
- Temperaturdifferenz zwischen beiden internen Sensoren: innerer Aufbau unklar da keine Berechnung möglich
- Spannungssignal am Sensorausgang: $0,3 \text{ mV}$

3 Danksagung

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Implementierung eines Algorithmus zur Erkennung epileptischer Anfälle auf Ultra-Low-Power-Mikrocontroller mit KI-Beschleuniger

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Kurzfassung

Neueste Entwicklungen im Bereich stromsparender Hardware- und Software-Frameworks haben den Bereich TinyML entstehen lassen, der sich mit maschinellem Lernen (ML) im Sub-mW-Bereich auf Edge-Hardware beschäftigt. Dies öffnet die Tür zu neuen Anwendungen für ML im Gesundheitswesen, in der Umweltsensorik, der intelligenten Landwirtschaft und der Erkennung von Anomalien. TinyML erfordert eine Synergie zwischen dem Modell und der Hardwareplattform, um eine niedrige Inferenzenergie und Latenzzeit zu erreichen und gleichzeitig die Genauigkeitsanforderungen für eine bestimmte Anwendung zu erfüllen. Dies wird durch eine hardwarenahe Suche nach neuronalen Architekturen erreicht, die ein Modell für die Ausführung auf einem bestimmten Hardware-Ziel optimieren. Um den Optimierungsprozess zu beschleunigen, ist es wünschenswert, Energiemessungen auf der Hardware durch Energieabschätzungsverfahren zu ersetzen. Klassische Energieschätzverfahren verwenden einen bekannten Parameter als Stellvertreter für die Energie, z. B. die Anzahl der CPU-Zyklen oder die Anzahl der Multiplikations-Akkumulationszyklen pro Schlussfolgerung. Neuartige Verfahren zur Energieschätzung verwenden maschinelle Lerntechniken wie Decision-Tree-Ensembles, um die Energie zu schätzen. In diesem Beitrag konzentrieren wir uns auf einen Algorithmus zur Erkennung epileptischer Anfälle, ein Convolutional Neural Network. Dieser Algorithmus ist auf dem Silicon Labs EFR32MG24 Mikrocontroller implementiert, der über einen KI-Beschleuniger verfügt. Die Messungen der Inferenzenergie werden mit Schätzungen verglichen, die von klassischen und auf maschinellem Lernen basierenden Methoden stammen. Die Kompromisse zwischen Inferenzgenauigkeit und Energie werden untersucht.

1 Einleitung

Schätzungsweise 65 Millionen Menschen weltweit leiden an Epilepsie [1]. Da 30 bis 40 % der Epilepsiepatienten auf antiepileptische Medikamente nicht ansprechen [2], sind neue Behandlungsmethoden für Epilepsie erforderlich. Neurostimulation wie das EASEE-System (Precisis AG, Heidelberg, Deutschland) ist eine vielversprechende Behandlung, bei der das Gehirn des Patienten unabhängig von der epileptischen Aktivität durch regelmäßige Stromimpulse stimuliert wird [3].

Das Projekt Brain-MEP zielt darauf ab, die bestehenden Systeme durch die Entwicklung eines Neurostimulationsgeräts mit geschlossenem Regelkreis zu erneuern, bei dem Stromimpulse als Reaktion auf die erkannte Aktivität epileptischer Anfälle erzeugt werden. Zu den neuartigen Methoden zur Erkennung epileptischer Anfälle mit Hilfe von EEG-Signalen gehören Convolutional Neural Networks (CNN) [4], die dank Software-Frameworks wie Tensorflow Lite for Mikrocontroller und einer zunehmenden Vielfalt von Hardware-Plattformen mit speziellen KI-Fähigkeiten [5] nun in Edge-Geräte integriert werden können. Im vorliegenden Fall müssen sowohl das Modell als auch die Hardware-Plattform sorgfältig ausgewählt werden, um den Gesamtenergieverbrauch zu minimieren und gleichzeitig die Genauigkeitsanforderungen zu erfüllen. Hardware-bewusstes Design kann mithilfe der Neural Architecture Search (NAS) durchgeführt werden, bei der die Architektur eines neuronalen Netzes optimiert werden

kann, um ein oder mehrere Ziele zu erreichen [6], [7]. In dieser Arbeit wollen wir NAS an einem CNN-Modell durchführen, um den besten Kompromiss zwischen Inferenzenergie und Genauigkeit zu ermitteln. Da die wiederholte Messung der Inferenzenergie für verschiedene Architekturen zeitaufwendig ist, ist es wünschenswert, die Genauigkeit der Energieschätzungsmethoden zu bewerten. Die Beiträge dieser Arbeit sind wie folgt:

- 1) Identifizierung der Pareto-Front in Bezug auf Modellgenauigkeit und Energie aus einem NAS-Prozess.
- 2) Vergleich von CNN-Inferenz-Energieschätzungsmethoden und Validierung anhand von Messungen.

Die in dieser Arbeit verwendeten Methoden werden in **Abschnitt 2** vorgestellt. Die Ergebnisse werden in **Abschnitt 3** vorgestellt und diskutiert. Schließlich werden in **Abschnitt 4** die Beiträge dieser Arbeit zusammengefasst.

2 Methoden

2.1 Datensatz und Vorverarbeitung

Die CHB-MIT Scalp EEG Database [8] ist eine Sammlung von EEG-Aufzeichnungen von 22 pädiatrischen Probanden mit epileptischen Anfällen, gruppiert in 24 Fällen. Das EEG wird mit 256 Hz und einer Auflösung von 16 Bit abgetastet. Aus den 664 Aufzeichnungen wählen wir die 129 Dateien aus, die mindestens einen Anfall enthalten. Wir beschränken die Anzahl der verwendeten EEG-Kanäle auf die vier temporalen Kanäle (F7-T7, T7-P7, F8-T8 und T8-

P8). Der Beginn und das Ende von Anfallsereignissen werden annotiert. Die Vorverarbeitung des Datensatzes erfolgt wie in [9], [10] beschrieben.

2.2 Convolutional Neural Network

Wir modellieren die Anfallserkennung als eine binäre Klassifizierungsaufgabe mit einer einzigen Ausgangsvariablen, wobei 0 für das Nichtvorhandensein eines Anfalls und 1 für das Vorhandensein eines Anfalls steht. Wir implementieren EpiDeNet, ein leichtes CNN zur Anfallserkennung, das von Ingolfsson et al.[9] vorgestellt wurde. Das Netzwerk besteht aus 5 Blöcken, die jeweils eine Convolution-Schicht, gefolgt von einer Pooling-Schicht und einer abschließenden Fully-Connected-Schicht enthalten. Die Architektur des EpiDeNet ist in **Tabelle 1** dargestellt.

Tabelle 1 Convolutional Neural Network Architektur.

	Schichttyp	#Kernels	Size	Output
0	Input			1024, 4, 1
1	Conv2D	4	1, 4	1024, 4, 4
	MaxPool2D		1, 8	128, 4, 4
2	Conv2D	16	1, 16	128, 4, 16
	MaxPool2D		1, 4	32, 4, 16
3	Conv2D	16	1, 8	32, 4, 16
	MaxPool2D		1, 4	8, 4, 16
4	Conv2D	16	16, 1	8, 4, 16
	MaxPool2D		4, 1	8, 1, 16
5	Conv2D	16	8, 1	8, 1, 16
	MaxPool2D		8, 1	1, 1, 16
6	Dense			1

2.3 Hardware-Plattform

Das CNN ist auf dem Mikrocontroller EFR32MG24 von Silicon Labs (Texas, USA) implementiert. Der EFR32MG24 hat einen 32-Bit ARM Cortex-M33 Prozessor mit 1536 kB Flash-Speicher, 256 kB RAM-Speicher und einer maximalen Betriebsfrequenz von 78 MHz. Er ist ein interessantes Bauteil für eine Implantatanwendung, da er über ein Funk-Transceivermodul mit Bluetooth-Unterstützung, einen sehr niedrigen Stromverbrauch im Ruhezustand und einen Matrix-Vektor-Prozessor (MVP) zur KI-Beschleunigung verfügt.

Silicon Labs unterstützt offiziell den Einsatz von KI-Algorithmen mit dem TensorFlow Lite for Microcontrollers Framework. Das Modell wird zunächst mit Keras entwickelt, auf dem Computer trainiert und dann auf 8-Bit-Integer quantisiert. Anschließend wird es in ein Format konvertiert, das von der TF Lite for Microcontrollers-Runtime auf dem Mikrocontroller interpretiert werden kann.

2.4 Neural Architecture Search

NAS wird verwendet, um die Modelle zu ermitteln, die die Vorhersagegenauigkeit maximieren und den Energieverbrauch minimieren können. Da diese beiden Ziele im Allgemeinen im Widerspruch zueinanderstehen, erhält man eine Pareto-Front, d. h. die Grenze, an der die Optimierung eines Ziels zu einem Leistungsverlust bei einem anderen

Ziel führt. Dieses multikriterielle NAS-Verfahren ist in Python mit Optuna 3.5.0 implementiert und besteht aus drei Komponenten: einem Suchraum, einer Suchstrategie und einer Strategie zur Leistungsbewertung [6].

Der Suchraum besteht aus 10 freien Parametern: die Anzahl des Kernels und die Kernelgrößen für die 5 Convolutional-Schichten (siehe **Tabelle 1**). Die Anzahl des Kernels kann zwischen 4 und 32 in 4er-Schritten (8 Möglichkeiten) und die Kernelgröße zwischen 2 und 32 in 2er-Schritten (16 Möglichkeiten) liegen, so dass insgesamt $8^5 + 16^5$ Kombinationen möglich sind.

Als Suchstrategie wird der Multiobjective Tree-Structured Parzen Estimator (MOTPE) verwendet, ein Bayes'scher Optimierungsalgorithmus, der lernt, welche Parameterwerte zur besten Leistung führen.

Schließlich muss eine Strategie zur Leistungsbewertung verwendet werden, da es nicht möglich ist, jedes Modell vollständig zu trainieren und zu bewerten. Das Modell wird einmal trainiert, wobei die Anfälle der Patienten 2-24 das Trainingssatz und die Anfälle von Patient 1 den Testsatz bilden. Das Training wird durch Early-Stopping mit einer Patience von 5 abgekürzt. Andere Trainingsparameter werden wie in [9], [10] beschrieben eingestellt.

Die beiden Optimierungsziele sind die an dem Testsatz gemessene Sensitivität und die gemessene Inferenzenergie. Da dieser Schritt zeitaufwändig ist, wird die Energie auch parallel geschätzt. Die NAS-Studie wird mit 250 Versuchen durchgeführt.

2.5 Energiemessung

Die Energiemessungen sind mit einem Joulescope JS220 durchgeführt. Die Versorgungsspannung beträgt 1,8 V und die Hardware arbeitet mit 78 MHz.

2.6 Energieschätzung

2.6.1 Proxy-Metrik: FLOPs

In den meisten Fällen wird die Energie indirekt durch die Verwendung einer Proxy-Metrik geschätzt, von der erwartet wird, dass sie sich proportional zur Energie verhält [7]. Eine solche Metrik ist die Anzahl der Gleitkommaoperationen (floating-point operations, FLOP), die auf dem Computer mit dem TensorFlow-Profiler geschätzt werden kann. Diese Metrik ist auch dann relevant, wenn das Modell quantisiert ist, da die Anzahl der Gleitkommaoperationen gleich der Anzahl der Ganzzahloperationen ist.

2.6.2 Energie pro Befehl

Manzouri et al. [4] führten eine auf den Betrieb von Mikrocontrollern zugeschnittene Methode ein. Zunächst wird die Anzahl der Rechen-, Speicherlese- und Speicheroperationen für jede Schicht berechnet. Dann wird die Energie auf der Grundlage der Energie pro Befehl für den gegebenen Prozessorbefehlssatz geschätzt. Die erhaltenen Energiewerte müssen dann skaliert werden, um den Verarbeitungs-Overhead und die spezifische Mikrocontroller-Implementierung zu berücksichtigen.

2.6.3 Silicon Labs Model Profiler

Silicon Labs bietet einen Model Profiler für den EFR32MG24 als Teil ihres Machine Learning Toolkit (MLTK) an. Dieses Tool schätzt die Energie pro Schicht in zwei Schritten. Zunächst wird die Anzahl der CPU- und Beschleunigungszyklen aus der Ausführung des Modells mit einer simulierten Laufzeit ermittelt. Zweitens werden diese Zykluszahlen zusammen mit den Schichtparametern in einen Decision Tree Ensemble-Schätzer eingegeben, um einen Energiewert zu erhalten.

3 Ergebnisse und Diskussion

3.1 Pareto-Front

Die Leistung aller NAS-Versuche in Bezug auf Sensitivität und Inferenzenergie ist in **Bild 1** dargestellt. Der Kompromiss zwischen Sensitivität und gemessener Inferenzenergie E_{gemessen} ist deutlich zu erkennen: Eine Steigerung der Sensitivität von 87% auf 93% erfordert eine Vervielfachung der Inferenzenergie von 112 μJ auf 480 μJ . Die Leistung des in [9] vorgestellten nicht optimierten Modells (Basismodell) liegt hinter der Pareto-Front, was zeigt, dass die Verwendung von NAS zu einer optimaleren Lösung in Bezug auf Sensitivität und Inferenzenergie führt.

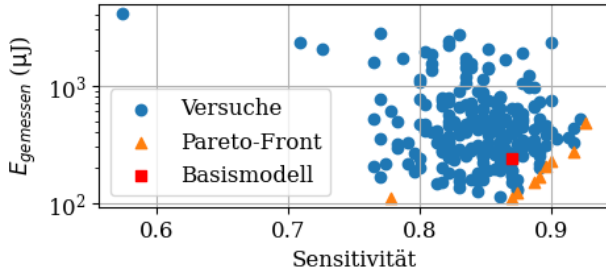
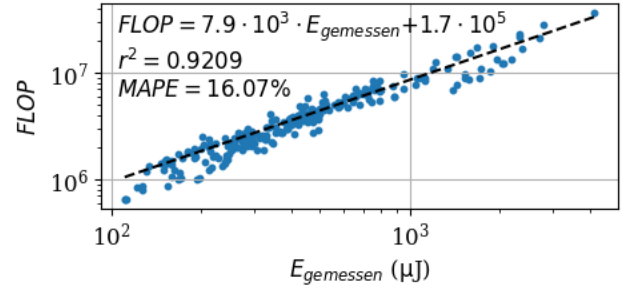


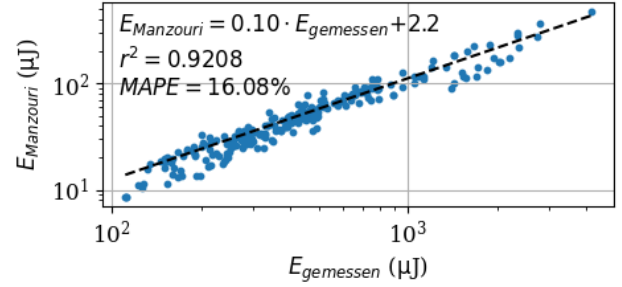
Bild 1 Abwägung zwischen der Sensitivität und der gemessenen Inferenzenergie E_{gemessen} .

3.2 Methoden zur Energieschätzung

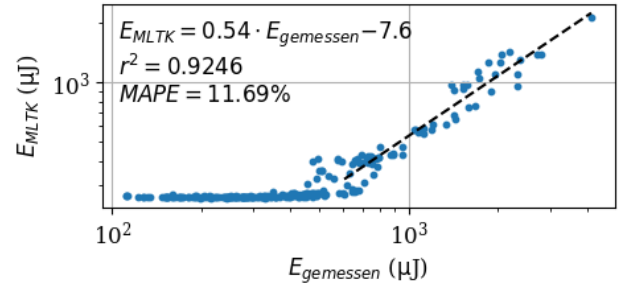
In **Bild 2** werden die Schätzungsmetriken mit den tatsächlich gemessenen Energiewerten verglichen. Die Schätzung mit der Proxy-Metrik FLOP ist linear proportional zu E_{gemessen} mit einem mittleren prozentualen Fehler (mean average percent error, MAPE) von 16,07 %. Die nach der Methode von Manzouri et al. [4] geschätzte Energie E_{Manzouri} unterschätzt E_{gemessen} um den Faktor 10. Das Bestimmtheitsmaß (r^2) und der MAPE entsprechen denen der FLOP-Proxy-Metrik, was darauf hindeutet, dass die Berücksichtigung der Energie und des Auftretens einzelner Operationen möglicherweise nicht mehr Informationen liefert als die Verwendung der gesamten FLOP-Zahl. Die mit dem MLTK-Modell-Profiler geschätzte Energie E_{MLTK} zeigt zwei unterschiedliche Betriebsbereiche. Für $E_{\text{gemessen}} < 700 \mu\text{J}$ tendiert E_{MLTK} zu einem konstanten Wert von 270 μJ . Für $E_{\text{gemessen}} > 700 \mu\text{J}$ ist E_{MLTK} linear proportional zu E_{gemessen} und unterschätzt es um den Faktor 2. In diesem linearen Bereich haben die Schätzungen von E_{MLTK} einen MAPE=11,69%, was besser ist als FLOP und E_{Manzouri} .



(a) Anzahl der Gleitkommaoperationen (FLOP).



(b) In [4] vorgestellten Methode geschätzte Energie.



(c) Silicon Labs Model Profiler geschätzte Energie.

Bild 2 Vergleich von drei Energieschätzungsmethoden mit der gemessenen Inferenzenergie E_{gemessen} .

4 Zusammenfassung

In diesem Beitrag haben wir gezeigt, dass es bei der Erkennung epileptischer Anfälle mit einem CNN einen Kompromiss zwischen Inferenzenergie und Empfindlichkeit gibt: Um die Empfindlichkeit von 87 % auf 93 % zu erhöhen, muss die Inferenzenergie von 112 μJ auf 480 μJ vervielfacht werden. Dieser Kompromiss wird mit Hilfe von NAS charakterisiert. Um diesen Prozess zu beschleunigen, ist es wünschenswert, die Inferenzenergie zu schätzen, anstatt sie direkt zu messen. Sowohl die Proxy-Metrik FLOPs als auch die durch die Methode von Manzouri et al. [4] geschätzte Energie sind linear proportional zu realen Energiemessungen. Die mit dem Silicon Labs Model Profiler geschätzte Energie ist nur bei Energiewerten über 700 μJ linear proportional zu realen Messungen.

5 Danksagung

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Modelling and Optimization of the Energy Consumption of a Wireless Sensor Network for Industrial Applications

Modellierung und Optimierung des Energiebedarfs eines drahtlosen Sensornetzwerkes für industrielle Anwendungen

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Abstract

Wireless sensors do not need a wired connection for energy supply and data transmission and therefore enable new sensing applications in various industrial fields, which cannot be solved efficiently using classic wired sensors. For the design of a wireless sensor network modelling and optimization of energy consumption is crucial to maximize battery lifetime. In this work, we have built an ultra-low-power wireless sensor network using vibration measurement for condition monitoring. The energy consumption for the wireless transmission and data processing has been determined separately to find an optimal data processing approach for the trade-off between battery life time and amount of data provided to the user.

1 Introduction

In industrial automation, several trends have been observed in recent years that require or favor the use of wireless sensor networks: Data-driven production processes, software defined manufacturing, the IIoT (industrial internet of things), condition monitoring of machines and systems, the use of sensors at the end-effectors of robots and hygienic environments, where cables are undesired.

Condition monitoring of existing machine parks generates a demand of wireless retro fitting solutions, which provide health state data to IT-networks for remaining useful life prediction and predictive maintenance. Wireless sensor networks can therefore help to make shopfloor data accessible to the IT-world without interfering in real-time OT-networks (operation technology) such as industrial field buses. Wireless mesh networks which transmit data from node to node can cover extended areas in industrial plants without high energy consumption for large individual radio ranges.

For the energy supply of wireless sensors for sensing, data processing and transmission of data, primary or secondary cells, that need to be replaced or charged, as well as energy harvesting can be considered [1][2]. In the case of wireless and battery-powered sensors, the question of load distribution of signal processing tasks between the sensor and wired devices such as gateways or cloud computers must be reassessed with regard to energy consumption. The goal is to extend battery life to 10 years and beyond. This is all more important as sensors become increasingly intelligent and take on additional features and functions, such as comparing measured values with threshold values, counting tasks,

providing cumulative sensor data for observing trends, sensor fusion, signal processing for statistical values and evaluations using machine learning.

Several wireless technologies and standards are available on the market which focus on high data rates such as 5G, real time capability such as IO-Link wireless or ultra-low-power such as Bluetooth Low Energy and MiraOS [3].

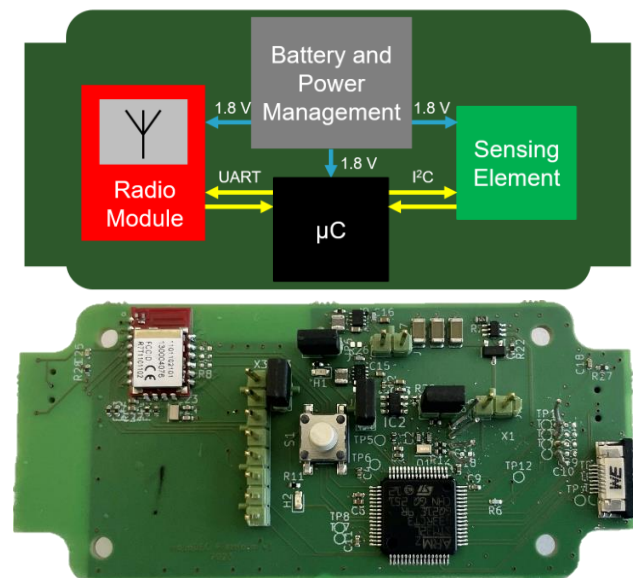


Figure 1 Modular hardware platform (upper part: schematic, lower part: photo) with the components radio module, power management, microcontroller (μC) and sensing element. Two lithium batteries on the back of the circuit board are not visible.

2 Wireless Sensor Network and Energy Measurements

2.1 Modular Hardware Platform

To model and optimize the energy consumption of a wireless sensor network, a modular hardware platform was developed and built (Figure 1), which includes the following components [4]:

- Microcontroller STM32L433 to read out the measuring data of the sensing elements and to process the signals as well as forwarding it to the radio module
- Sensing elements to be connected separately (listed below)
- Microcontroller nRF52840 with an antenna integration combined in the Thyone-I module of Würth Elektronik to forward packets between the STM32L433 and the wireless mesh network
- Power management with two batteries, each 2600 mAh and 3.6 V

The following components are provided as sensing elements:

- Optical time-of-flight sensor for filling level detection in intralogistics applications
- MEMS module LIS2DS12 for vibration measurement on machine parts

2.2 Acquisition of a Vibration Data Set

In order to compare the data processing approaches in an equivalent way, a reference data set of raw acceleration values was collected and used for the following evaluation. The energy consumption of the sensing elements was therefore not included into the power measurement. The motor fault testbench “VibDemo” was used to simulate different scenarios in a rotating machinery environment (Figure 2) [5]:

- Ordinary operation without a belt
- Ordinary operation with a belt between the shafts
- Broken belt between the shafts
- Broken bearing on the 2nd shaft
- Static imbalance on the 1st shaft
- Dynamic imbalance on the 1st shaft



Figure 2 “VibDemo” testbench for collection of data set

For capturing the resulting vibration signals, the MEMS mounted on a bearing of the 1st shaft of the “VibDemo”. It provides acceleration values in a 12 bit resolution with a sampling frequency of 3.2 kHz for each of the three axes. The acquired data set is then stored in two bytes objects per measuring value on the microcontrollers memory to access them directly for upcoming evaluation.

2.3 Wireless Mesh Network

Lumenradio’s MiraOS is a proprietary embedded operating system comprising the MiraMesh protocol, which builds up an ultra-low energy wireless mesh network. There are three different modes available to set up a node. A root node collects the information of the different devices and is configured as the destination for all other nodes to send their information to. A mesh node sends its information to the root node and forwards packets of other nodes in addition. A leaf node can only send its own data to the root or to a forwarding mesh node.

As a gateway, a MiraUSB stick is used, which is configured as a root node. An executable starts the gateway, which builds up the wireless mesh network. The gateway acts with the highest performance available, to collect the data of its related nodes in the fastest way possible. It forwards the incoming UDP packets to the host computer. MiraOS runs on the nRF52840, which is part of the Thyone-I module. It is configured as a mesh node and has a medium net rate. According to the maximum payload size of 800 Bytes per transmission, the implemented stack splits larger packets into multiple packets. Mira splits those packets internally again for wireless transmission according to the protocol [3].

In the following measurements there were no additional nodes running in the wireless mesh network.

2.4 Setup for Energy Measurements

The source measurement unit STLINK-V3PWR serves both as a 1.8 V power supply and as an amperemeter for precise measurements of the energy consumption (Figure 3). Either only the STM32L433 microcontroller is powered for measuring the calculation energy or the STM32L433 and the radio module are both powered for measuring the calculation and the transmission energy.



Figure 3 Source measurement unit STLINK-V3PWR

The STLINK-V3PWR is connected to a computer and driven by the software STM32CubeMonitorPower. It does not only allow capturing and visualization of the current measurement, but also calculates the energy consumption during a selected time frame by integrating the current waveform. Figure 4 shows an exemplary screenshot of a transmission energy measurement:

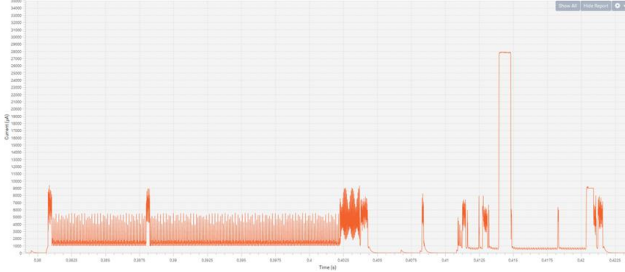


Figure 4 Exemplary current measurement during transmission of RMS values

The evaluation includes different amounts of raw values (128 or 256) and different approaches, namely the transmission of the complete raw data or the calculated RMS value only. For each scenario, multiple energy measurements are performed in order to achieve a valid average value.

3 Results

Table 1 shows the energy consumption for two data processing approaches. Due to our acquisition scheme of the vibration data of 3 axis with a resolution of 12 bit, the amount of transmitted data results in 1152 and 576 bytes of transmitted data respectively after a bit packing method is run on the microcontroller during the evaluation.

	Raw Data	RMS	Raw Data	RMS
Amount of measured data points	256		128	
Amount of transmitted data [bytes]	1152	12	576	12
Data transmission energy [μ J]	3600	161	1600	161
Calculation energy [μ J]	0	10,5	0	5,7
Total energy [μJ]	3600	172	1600	167

Table 1: Comparison of energy consumption for two approaches and two amounts of measured data points

The energy for data transmission strongly depends on the amount of transmitted data. MiraMesh allows a payload of approximately 150 bytes per packet resulting in 6 to 8 packets which each correspond to a discrete amount of energy.

The RMS calculation includes squaring the measured values, adding the squared values and dividing by the number of data points. The result is transmitted without calculating the root square to save energy. The energy consumption for

this operation also depends on the amount of data points, but the absolute values are much smaller compared to the data transmission.

4 Conclusion and Outlook

Our work clearly shows that the energy for wireless transmission is one or two orders higher than for processing the data. Calculations and transmission of the RMS values reduces the total energy by 90 to 95 % compared to the transmission of the complete raw data. This depends on the amount of data points. Therefore data processing is a successful method for the optimization of the total energy consumption. To provide the complete raw vibration data instead of the RMS values to a user for a more detailed condition monitoring analysis, lossless or slightly lossy compression [6] of the vibration data can be a promising method for energy saving. Alternatively, spectral analysis methods such as FFT of the vibration data followed by a transmission of a reduced set of the dominant frequency contributions should be tested.

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Artificial intelligence for the calibration of mobile spectral analyzers

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Abstract

Mobile spectral analysis has gathered a lot of interest throughout the last years. It enables the determination of object composition, material properties or other application relevant information directly on-site. This could be very interesting in agriculture, food business, environmental monitoring, medical or other fields. Autonomous operated systems could be handheld or mounted to robots as well as unmanned aerial vehicles (UAVs). The components have become compact and affordable so far. The evaluation of spectral data, for example in the near infrared range, requires stable calibration to extract the relevant information to extract concentration or composition information. Complex chemometric models and broad data bases are necessary. These are valid for selected devices only, transfer to other equipment is difficult. Furthermore, changes like aging of the light source must be calibrated from time to time. In close future artificial intelligence (AI) will help to change this situation by providing automated calibration and compensation routines.

1 Introduction

Optical spectroscopy is a strong tool in physics and chemistry. Since its invention, spectral analysis has been used in many fields, starting from the sun spectrum [1] to complex analysis in optical microscopy [2]. As an example, absorption measurements in the near infrared spectral region (NIR) enable material testing and on-site composition analysis. Mobile spectroscopy has gathered huge interest throughout the last years. This could serve numerous tasks such as agriculture, environmental monitoring, food, pharmaceuticals, medical to chemical industry or logistics. Spectrometers have been designed which feature small size (**figure 1**), low power consumption and sufficient robustness for mobile and autonomous use [3].

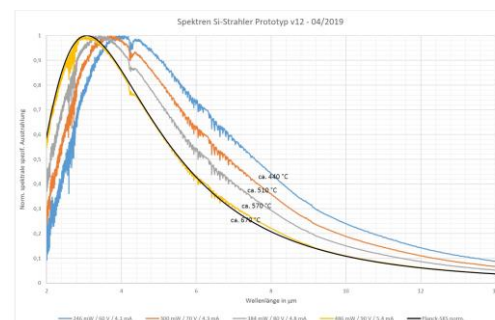
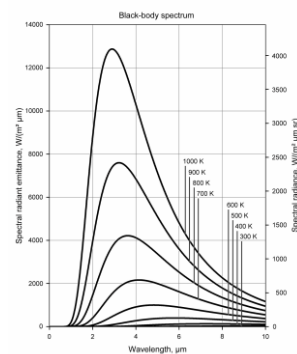


Figure 1 Ultra compact NIR spectrometer.

A limiting factor for reliable on-site operation turns out to be the calibration of the spectrometer system in combination with the optics, light source and surrounding conditions. A simple dark and white light compensation is insufficient for precise and long-term stable measurements, especially under rough conditions. The effort for on-site calibration must be kept low. Ideally the routines shall run automatically without manual interaction with the user. Here

the methods of the so-called artificial intelligence can be used today.

Besides the spectrometer itself, further influences have to be considered carefully. Applying emission spectroscopy, the source of radiation is analyzed. Examples are hot surfaces (“thermal emitters”) or plasma gas discharges as used in semiconductor production equipment. Material analysis is performed in transmission or reflectance, here the light from a source illuminates the sample. In any case, the intensities undergo further changes when passing through the optical path, absorption in air, lenses or optical fibers. Inside the spectrometer a grating with a wavelength specific efficiency and a detector having a wavelength dependent sensitivity contribute to further changes. Even worse, temperature influence and long-term changes have to be considered for reliable and stable evaluation results (**figure 2**).



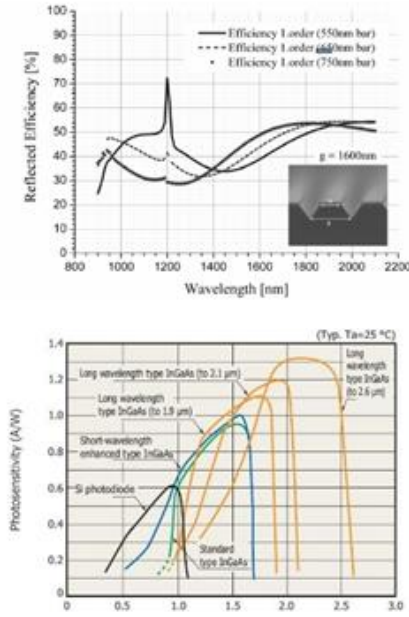


Figure 2 From top to down: Planck radiation distribution [4], IR spectrum with absorption bands from CO₂ and H₂O, grating efficiencies [5] and detector sensitivities.

2 AI approach

The initial spectrum $I_{\text{initial}}(\lambda)$ undergoes multiple changes along the optical path. Each step can be described as a mathematical operation, which could be depended on the surrounding condition and time, respectively aging. In the end the measured intensity distribution $I_{\text{meas}}(\lambda)$ is generated by the folded mathematical operators $F_i(t, T, \dots)$:

$$I_{\text{meas}}(\lambda) = F_1(\dots) \times F_2(\dots) \times F_3(\dots) \times \dots \times F_n(\dots) \times I_{\text{initial}}(\lambda)$$

To recompute the initial spectral intensity distribution, which is relevant for the information desired, the inverse function would be required:

$$F = F_1(\dots) \times F_2(\dots) \times F_3(\dots) \times \dots \times F_n(\dots); \quad F^{-1} = ?$$

Unfortunately, it is very complex or just impossible to estimate the inverse function F^{-1} as the contribution functions F_i are unknown or not accessible. Here methods using so called artificial intelligence (AI) may offer new options for the estimation of the inverse function F^{-1} :

A precisely known spectrum is fed into the system, for example from a calibrated black body source which emits a Planck distribution for a given temperature. The resulting spectrum is acquired and the transfer function computed. Then the inverse operation is estimated. Based on this an AI based algorithm for automated calibration is implemented. Numerous, up to now not finally clear how many, repeated teaching runs will be required until the AI model is stable. The AI concept has been proven on other sensor based applications with very promising results

3 Experimental

To evaluate the options for the implementation of an inverse mathematical operation for a compensation of measurement errors, initial experiments have been conducted. The known spectrum of a light source passes through an optical path consisting of a collimator, optical fiber, grating monochromator and detector. The influence of the optical path has been analyzed for an NIR wavelength range from 1000 nm to 2200 nm. The spectra gathered by the spectrometer change when an optical fiber or an additional collimator lens is added (**figure 3**).

Comparison of emitted and acquired spectrum gives access to the changes and thus to a correction function. Different conditions have to be evaluated to ensure a stable model. The next step will be the first implementation of a self-learning (AI) compensation algorithm.

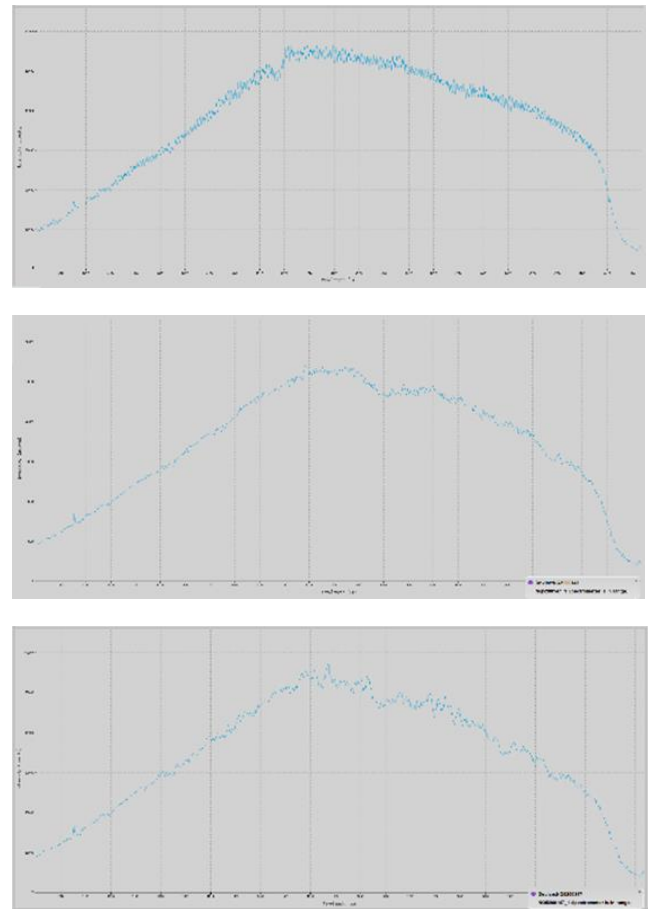


Figure 3 NIR spectra measured on identical equipment and source; up: source only, middle: source and fiber length 2m, lower: source and fiber with collimator lens.

4 Conclusions

An algorithm to compensate the influence of the optical path, monochromator efficiency and detector sensitivity on the shape of the spectrum can serve both, emission and absorption spectroscopy. A concept was developed and first measurements have been performed.

Now the first implementation of the algorithm is intended. Based on this the stability of the model will be evaluated and the stability and accuracy of the algorithm will be improved step by step

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Smart Infrastructure – Autonomous Energy Supply of a Sensor Node (Intelligente Infrastruktur – Autonome Energieversorgung eines Sensorknotens)

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Abstract

In the project ALFRIED (Automatisiertes und vernetztes Fahren in der Logistik am Testfeld Friedrichshafen <http://www.alfried.net>) the development of a complex and comprehensive mobility system at the testing area in Friedrichshafen was publicly sponsored with the specific focus on inner city transportation of goods. The mobility system is comprised of smart infrastructure, smart vehicles, a digital platform, and a smart city control and data center. Therein Hahn-Schickard developed the energy supply and energy management for a sensor node (roadside delineator) as part of the smart infrastructure with the goal of energy autonomy, harnessing multi-modal energy sources. Possible energy sources were identified and characterized regarding their energy input and harvesting complexity, specifically, light, wind, vibrations and temperature gradients at the delineator post. The sensor nodes itself were fitted with ultra wide band sensors, which are able to detect passing vehicle type, speed, and road conditions, like ice, mist or rain. The smart energy management is based on a maximum power point tracking, which combines multiple energy sources, like solar and wind energy. In order to keep the design of a regular delineator post, it was fitted with white solar panels. This allows for roadside energy extraction of up to 10 W. Aiming to maintain functionality over 20 days without harvested energy input, the design was enhanced with a specifically designed battery pack. Furthermore commercially available wind generators were tested for energy harvesting potential and maximum input power. Lastly, an algorithm for future energy availability was developed, which predicts the harvested energy amount on basis of local environmental situation and weather forecast data.

1 Introduction

In addition to a vehicle equipped with sensors, automated and connected driving also requires an intelligent infrastructure for recording, processing and forwarding relevant information (environmental data, traffic data, position data, object data). In addition to larger objects such as intersections, the intelligent infrastructure also includes delineators equipped with sensors and wireless communication. These intelligent delineators will primarily be installed on free-ways and dual carriageways at a distance of 50 m from each other at the roadside. There are also plans to install additional mobile delineators in roadworks areas. As a rule, there is no wired infrastructure to supply the delineators with power either at the roadside or in the roadworks area. In terms of cost-effectiveness, maintenance costs (e.g. changing a battery) must be kept to a minimum. However, this requires new, autonomous energy supply concepts, which include both suitable energy storage and energy harvesting technologies [2, 4].

2 Main Concept

The aim of the "Smart Energy" sub-project is to develop and integrate an intelligent, independent and low-maintenance energy supply for the operation of electronic components in intelligent delineators.

The realization of an autonomous and low-maintenance energy supply in the road network requires the effective use of available energy sources from the immediate vicinity of the delineators with the help of innovative technologies and

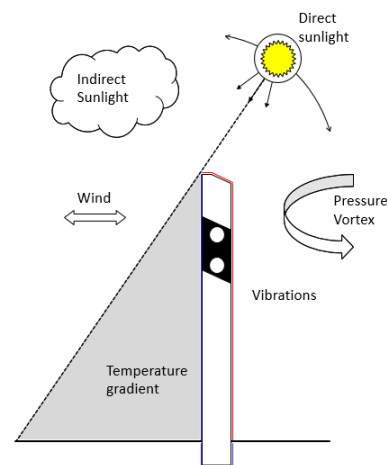


Figure 1: Possible energy sources at a roadside delineator post.

concepts. In the sub-project, a multimodal energy harvesting system (Figure 1) in conjunction with a high-performance energy storage system is to be developed, implemented as a prototype and validated. The innovative core of the development is a smart energy management system with "energy awareness", which enables optimized energy extraction, monitors incoming and outgoing energy flows, records the status of the energy storage system and supplies the consumers with electrical energy, taking into account the specific input parameters.

In addition, an energy forecast based on deterministic conditions and current forecast data (e.g. weather data) is to be created and made available with the help of a predictive embedded model. This energy forecast can be used to plan

and prioritize tasks (task scheduling) for the sensors in the control post and thus avoid an energy bottleneck (task energy starving: the inability to complete a task).

2.1 Smart Energy Management

Figure 2 outlines the overall structure of the energy management system. Depending on availability, the system is supplied via a variable constellation of sources that are connected via the SEE1...SEE5 interfaces. For the energy harvesting devices ("harvesters"), load adjustment for optimized power extraction is required in addition to voltage conversion. All sources feed an internal energy bus, which supplies both the internal electronics of the energy supply and the other components of the system. Via the SIE1 interface, the control unit can issue commands to the energy supply and switch the energy outputs SEA1...SEAn "on" and "off". The energy flow in the system is monitored at relevant points. The purpose of this is to monitor the function of the sinks. On the source side, the determination of the currently available power from a respective harvester is used to train the energy prediction algorithms.

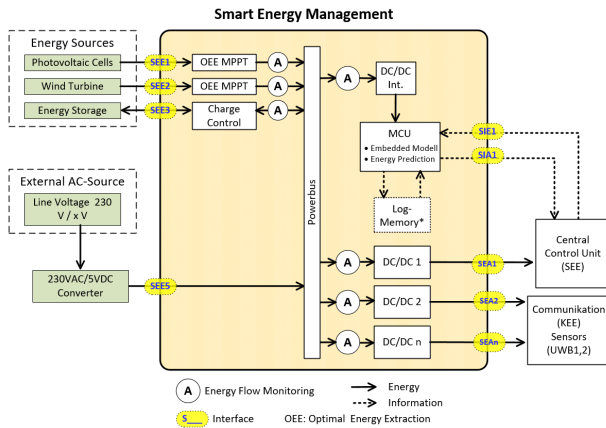


Figure 2: Smart energy management block diagram.

2.2 Hardware

The electrical sub-circuits defined by the system design shown in figure 2 were constructed, characterized and optimized accordingly. The following sub-circuits were designed for the energy supply unit of the intelligent control station (**Figure 3, left**):

- Maximum power extraction (MPPT) for a large voltage and current range
- Input power measurement for intelligent control of maximum power extraction
- Charge management for controlled charging of the battery with a defined current
- Power switch for controlling the supply to the other components in the intelligent control post
- Regulator for the supply voltages required by the other components in the delineator post, like sensors and communication devices.

A battery pack was developed to buffer the harvested energy. The capacity was determined using the tools developed in such a way that the fluctuations in energy input to be expected for a delineator post can be buffered over a

period of 20 days. This means that a constant operating profile corresponding to the average energy input will always be possible over this period despite fluctuating ambient energy. The battery pack has been designed to fit



Figure 3: Left: Smart energy management with MPPT and power converters on a single PCB. Right: Delineator post with white solar power panels.



Figure 4: 20 Ah battery-pack with fuel gauge and control systems.

into the delineator with the lowest possible height. LiFePO cells are used because they offer increased safety compared to conventional lithium-ion batteries and are more tolerant of low temperatures (**Figure 4**). Research results [3] suggest that operation with a correspondingly reduced charging rate will still be possible well below 0°C.

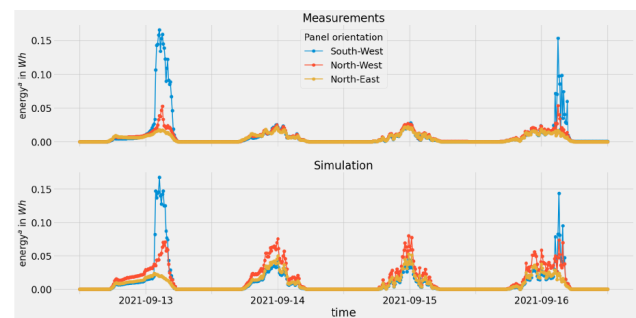


Figure 5: Simulated and actual energy input of 100 cm² solar panels.

Regarding harvested solar energy a tool for measuring and expected energy return was designed and compared to actual energy intake (**Figure 5**). The panels on the delineator posts are 2000 cm² in size and produce up to 10 Wh on a sunny day (**Figure 3, right**).

2.3 Power Availability Prediction

Various power forecasting algorithms were investigated and further developed as part of this project [1, 5]. In particular, the extension of location profiling algorithms, such as ProEnergy, was developed in conjunction with the weather data from the German Weather Service. As can be seen in **Figure 6**, the improved Forecast Pool Pro Energy (default & extended) FPPE algorithms stand out from the previously available algorithms in terms of lower root mean squared error.

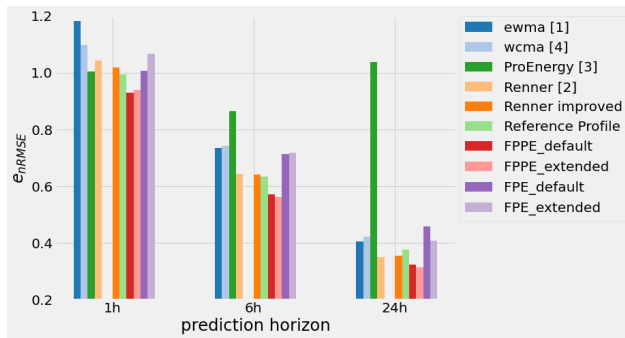


Figure 6: Forecast errors of the analyzed and developed algorithms as a function of the forecast time horizon.

2.4 Wind Power Roadside Generation

Field tests were also carried out with various small wind generators. A special Maximum Power Point Tracking (MPPT) design was developed for this purpose, which withstands the power ranges of the selected (commercially available wind generators (1 mW to 100 W specified). The experiments carried out show that under optimum conditions (several trucks in a convoy drive past the generator at 80 km/h (22 m/s), the generator is 50 cm away from the roadside) the energy input at the wind generator is less than 1 W, as the wind speed at the generator is only approx. 3 m/s (**Figure 7**). The integration of wind generators is therefore not pursued further, as the cost/benefit factor is low.

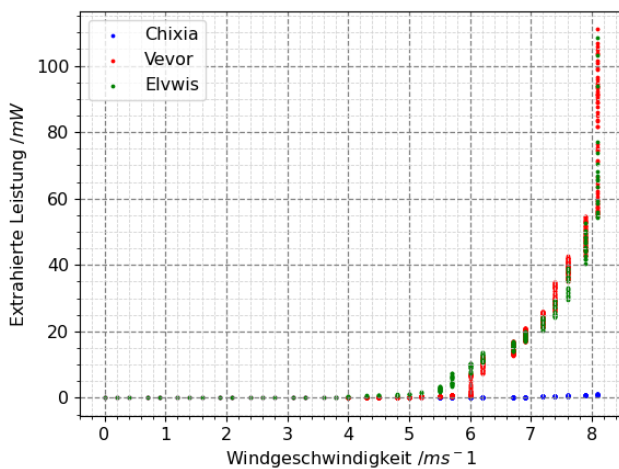


Figure 7: Extracted power at the tested commercially available wind generators in the power range of 1 mW-100 W as a function of the wind speed at the wind generator.

3 Conclusion

The smart energy management system developed as part of the project enables energy autonomy of a sensor node far away from the energy infrastructure, energy supply of a sensor node with multimodal energy harvesting (solar and wind), voltage conversion to supply the various sensors, bridging a low-energy environment with an individual battery pack solution, and maximum sensor utilization through smart power forecasting. Field tests are ongoing.

4 Acknowledgement

We gratefully thank the German Federal Ministry for Digital and Transport for funding this project.

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Energy demand of typical IIoT sensors and their supply via energy harvesting

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Abstract

The digitalisation megatrend Industry 4.0, and the IIoT (Industrial Internet of Things) in particular, require even more powerful and smaller devices such as sensors and actuators. In order to be accepted by the industry, these devices need to be easily integrated into existing systems. This requires devices that can communicate over the air and be powered cordlessly. Only in this way can these devices be integrated cost-effectively and without long interruptions to production. Currently, batteries or rechargeable batteries are the most common source of energy for this type of IIoT device, because they are standardised on the market and replacements are easy to obtain.

Uptime is primarily determined by the operating mode of the IIoT device. This means that the data acquisition rate and, in particular, the transmission rate have a significant impact on uptime and, therefore, maintenance costs. The cost of a simple battery change can be as much as \$50 or more per IIoT device, depending on where it is located [1]. Therefore, it is important to adapt the operating mode and acquisition rate to the application. This avoids oversampling and reduces the energy demand.

The typical data acquisition of IIoT devices can be broken down into 3 key stages. *Sleep*, *Modem Sleep* (CPU and ADC on) and *Active* (CPU and RF-modem on). For a typical chipset with a WiFi modem, such as the ESP32, the power consumption is as follows: 30 μ W for *Sleep*, 30 mW for *Modem Sleep* and 594 mW for transmitting.

Wireless IIoT devices are therefore indispensable for the digital transformation, but they consume a lot of energy to achieve the appropriate broadcasting range and data transmission rates. However, wireless IIoT devices only make sense if they are continuously supplied with energy. Energy harvesting therefore has great potential in this area.

But it is not always clear which energy harvesting principle can generate enough energy under the given conditions to power such an application.

The aim of this paper is to analyse which energy harvesting principles can provide this amount of energy in the field of Industry 4.0. Based on commercially available solutions, the paper will also show the cost and installation volume of such an energy harvester.

1 IIoT-Device

IIoT devices will form the basis of Industry 4.0. IIoT devices are hardware such as sensors, actuators, appliances or machines programmed for specific applications that can transmit data over the internet or other networks [2]. These devices continuously collect data to monitor and control complex processes. The application determines which measurements to transmit at which intervals. Measurement intervals can range from hours, e.g. silo levels, to milliseconds, e.g. highly dynamic process data.

It is important that the sampling rate is matched to the cycle of the process. If the sampling rate is too low, fast changes cannot be detected, see figure 1. Consequently, Shannon's sampling theorem must be satisfied. In contrast, too high a sampling rate leads to oversampling, which only increases power consumption and does not provide any additional information. The most important step in the determination of the sampling rate for wireless IIoT sensors is therefore the accurate analysis of the behaviour of the measured value to be examined. Therefore, the signal should be observed over a longer period of time and for different operating states. If safety critical states are detected with this IIoT device, the sampling interval must be set in such a way that the critical state is detected between two sampling points and that this state does not escalate within this interval.

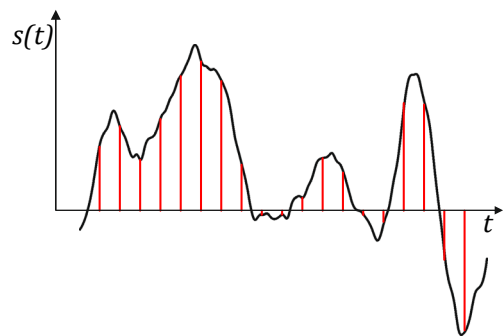


Figure 1: Sampling rate of process signal $s(t)$

The typical process of an IIoT sensor consists of 3 phases. *Sleep*, operation of μ Controller without modem and data transmitting. In the simplest case, the RTC (real-time clock) wakes up the μ Controller from sleeping at a fixed interval in order to acquire the measurement signal. The disadvantage of this is that the system is completely deactivated during the sleep phase. This means that critical values are not detected. For safety-critical applications, the sampling rate would have to be increased. But this would also increase the energy consumption, or a Wake-up trigger device would have to be implemented. Wake-up triggers are very low-power or passive devices that wake up the μ Controller by an external impact. These are often produced using MEMS technology [3], e.g. for vibration and

acceleration events. However, there are no general solutions for every type of critical value.

In the active phase, the μ Controller is woken up and data acquisition begins. For analogue input data, an ADC is used for the digitalisation. The question is whether to send the data immediately or to collect them. As sending consumes the most energy, it is important to evaluate what data the application needs. Direct data transmission is usually essential for dynamic applications, like control and automation applications in the product line. For non-critical applications, such as room temperature control, it can be considered whether data should only be transmitted when the measured value has changed by a relevant amount.

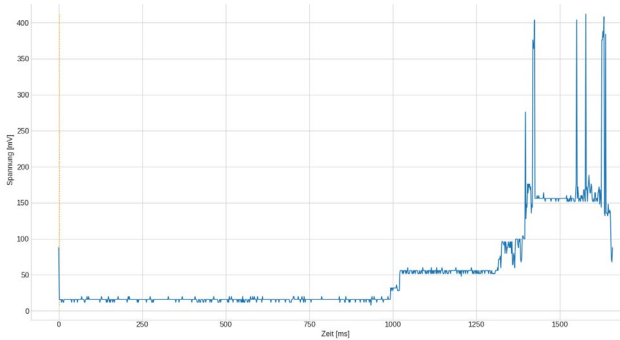


Figure 2: Typical operation cycle: sleep, data acquisition and WiFi transmitting (voltage drop on 1Ω shunt for a ESP32)

The highest energy consumption occurs during transmission and receiving, as this is when the transceiver or modem is activated, see the right side of the diagram in figure 2. This illustrates the current consumption in the different phases Sleep, Active and Transmit based on the voltage drop across a 1Ω shunt resistor. This characteristic was measured using an ESP32 WiFi module as an example, which is a module that is widely used in IIoT applications. Figure 3 shows an ESP32 on a development board. The high peak of approx. 400 mA for transmitting (TX) is clearly visible, as receiving (RX) only requires approx. 150mA. The current intensity depends not only on the radio protocol used but also on the selected transmission power and thus the achieved transmission range. The maximum transmission power of the ESP32 is 20.5 dBm [4]. Connecting to WiFi can take from 250 ms to more than a second to complete. This is heavily dependent on the number of users and the amount of data being transmitted [5]. Figure 4 demonstrates the occupancy of the popular 2.4 GHz ISM band with WiFi and Bluetooth devices.



Figure 3: ESP32 Modul

However, the transmitting (TX) portion of broadcasting is quite small, see figure 2. In this case, the transmission time

is approximately 370 ms, with an energy consumption of 178 mWs.

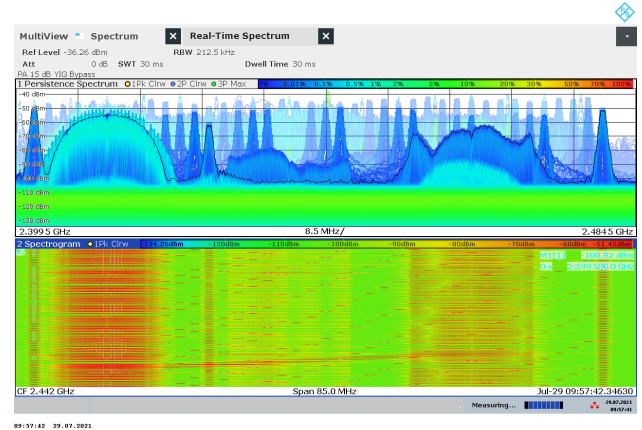


Figure 4: Occupancy of the 2.4 GHz ISM band with WiFi and Bluetooth devices, measured by FhG IEM

2 Energy consumption at different sampling rates

As outlined in the previous section, the RF modem that is used to send and receive data is the largest consumer of energy in an IIoT device. For this reason, the cycle time at which data is measured and transmitted has a major impact on the operating lifetime of a battery-powered device, like an ESP32. In the following, the predicted operating lifetime is based on a CR123A battery with a capacity of 1.6 Ah. In order to assess the different acquisition profiles, a standardised cycle is used, which is divided into the following steps.

Deep-Sleep:

The device is initially in deep-sleep mode. So, only the RTC memory and RTC peripherals are powered up. WiFi and Bluetooth connection data are stored in the RTC memory. The current demand is approx. 10 μ A, which corresponds to an energy consumption of 33 μ Ws.

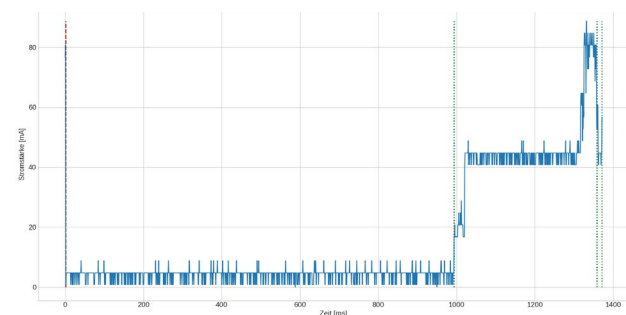


Figure 5: ESP32 transition from sleep to active mode

Changing Powermode (Wake-up):

The CPU is starting. The RTC memory and RTC peripherals, as well as the ULP coprocessor are running. Wake-up time is approx. 360 ms with a current draw of 41 mA and an energy consumption of 54 mWs. Changing power mode is the transition from sleep mode to modem-sleep modem see figure 5.

Modem-Sleep (Active):

The CPU is operational and the clock is configurable. The WiFi/Bluetooth baseband and radio are disabled. When activated, the analogue sensor voltage at one of GPIO-pin is immediately acquired and digitised, see figure 5 starting from 1360 ms. This step only takes about 10 to 13 ms. The current draw is approx. 47 mA and the energy consumption is approx. 2 mWs.

WiFi Transmitting:

Once the data has been collected, the ESP32 initiates a WiFi connection and the data is transferred. As described in the previous section, the connection time depends heavily on the occupancy of the channel. For a busy channel, the average of several transmissions gives a duration of about 750 ms. Transmissions of 250 ms and less are also possible. However, 750 ms is more realistic in an industrial environment. This results in an average current draw of 180 mA and an energy consumption of 345 mWs.

2.1 Use Case

Depending on the application, different sampling rates are required. For this reason, the following sampling rates are defined for the energy demand.

- every second,
- every minute,
- every hour and
- every day

These different configurations result in different energy demands per day. With a standard CR123A battery, these would result in different operating times for the IIoT device. Table 1 summarises these results.

Sampling rate	Energy consumption per day	Operation time with CR123A (1.6Ah)
1 s	30 kJ	15 h
1 m	502 J	38 d
1 h	11 J	4,7 y
1 d	133 mJ	16.5 y

Table 1: Energy consumption and runtime at different sampling rates

As this simple application example shows, instantaneous measured value, as required in many control and regulation technology tasks, can hardly be realised economically with such wireless IIoT devices. Even with a minute-by-minute acquisition rate, this would only give 38 days of use. Therefore, only an hourly acquisition will provide a long enough operating life of approximately 5 years, so that the cost of maintaining the battery can be neglected.

In future, as wireless IIoT gathers more and more data from the process every second, energy harvesters will be needed to generate the required amount of energy. In the following, the energy harvesters that are able to provide the required energy of 30 kJ will be analysed.

3 Energy Harvester for industrial IIoT applications

In order to assess which energy harvesting concept is suitable for the generation of 30 kJ, the following assumptions are made:

- The required energy is buffered in a lossless storage unit.
- Conversion losses are neglected.
- The harvester requires an average output power of approx. 350 mW.

A comprehensive overview of the different energy harvesting principles and their performance is described in [6]. On the basis of this research, the following principles will be assessed.

3.1 Photovoltaic

A solar panel should have a continuous output of about 1 watt to generate enough energy during the day for the night. Such a module would be about 80x80x1.5 mm in size and have a weight of about 18 g. The price is just a few euros. The typical energy density is approx. 100 mW/cm².

RF-Energy

The RF energy harvesting system converts electromagnetic waves in the frequency band of 3 kHz-300 GHz. In [7], several tests were carried out with a RF harvester at a distance of 6.5 km from a TV broadcasting station. The power output was in the region of 70 μ W. The typical energy density is approx. 0.1 μ W/cm² [9].

3.2 Triboelectric

In [8], a triboelectric harvester with an output of 36 mW was presented. The harvester has a diameter of 200 mm and was driven at 300 rpm. However, commercial systems are rarely available on the market as this technology is still at an early stage of development.

3.3 Piezoelectric

The piezoelectric effect makes it possible to convert mechanical energy into an electrical voltage. Piezoelectric harvesters are often used to convert vibrations. In [10] a piezoelectric harvester is presented that can generate 100 mW at 157 Hz. Piezoelectric harvesters are currently commercially available with an output of around 57 mW. For example, the S452-J1FR-1808XB from Mide has dimensions of 71 x 25.4 x 1.32 mm and delivers an output voltage of 16.7 V. But the cost of around 300 € is quite high. The typical energy density of piezo harvester is approx. 1 mW/cm² [9].

3.4 Thermoelectric

The Seebeck effect is the basic principle of the thermoelectric generator, i.e. the temperature gradient in the thermoelectric material creates a potential difference across the material. A module with an output power of about 1.3 W is 18 x 18 x 2.8 mm in size and costs around 20 €, like the

MGM250-49-10-12HS. The power it generates when the hot side is 250°C and the cold side is 30°C. In the case of 100°C/30°C the power decreases down to 170 mW. The typical energy density is approx. 10 mW/cm² [9].

3.5 Electromagnetic

Electromagnetic generators operate according to Faraday's law of induction. The simplest principle is the DC motor, which can also be used as a generator. Due to the large number of motors available on the market, there is a wide range of choices and the costs are very low < 1 €. The typical energy density is > 20 mW/cm³ [9].

3.6 Magnetostrictive

The magnetostrictive energy harvester is based on the Joule and Villary effects and realises the transformation between the strain energy and the magnetic energy of the magnetostrictive materials. Such a harvester is presented in [11], but it has a power of only 705 µW. The typical energy density is approx. 15 mW/cm³ [9].

3.7 Electrostatic

The structure of the electrostatic energy harvester based on the electrostatic effect is similar to that of a variable capacitor. The power that can be achieved is a few hundred µW [9], [12].

4 Conclusion

Wireless IIoT devices are a key building block in the implementation of Industry 4.0. The energy demands of these systems increase dramatically when high sampling rates are required for these IIoT applications, such as 1 sample per second. Then up to 30 kJ of energy per day is consumed by a typical component such as the ESP32. In order to operate autonomously, energy harvesters need to harvest this energy demand throughout the day.

The simplest and most cost-effective supply is possible with photovoltaics. If this is not possible, electromagnetic harvesters offer the best yield with the highest energy density and the lowest cost of manufacturing. Thermoelectric harvesters can also provide the required energy, but the necessary high temperature difference is not always available. Other harvesting principles are either too expensive or not yet commercialised.

As energy requirements increase due to ever higher sampling rates and IIoT systems require ever more compact designs, it makes sense to make greater use of the electromagnetic principle. New capabilities in additive manufacturing and micro-machining make it possible to harvest kinetic energy more efficiently and easily.

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A self-powered sensor with wireless data transmission for use on rotating parts

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Summary

Rotating parts such as shafts, gear wheels, ball bearings or rollers are subject to wear that limits their lifetime. Damage causes production downtime and consequential damage to the entire production plant. This system design makes it possible to record and wirelessly transmit measured values on rotating parts without an additional voltage source. The prototype is presented using the example of an application on a support roller and the economic efficiency of the system is analysed.

1 Motivation

Rollers (Fig. 1) are an essential component of belt conveyor systems as passive support and guide elements for the conveyor belt. The conveyor belt circulating endlessly between a head and tail pulley must be supported. This support of the (top) loaded upper run and the (bottom) returned lower run of a belt conveyor system is provided by rollers, which create rolling contact between the support frame and the conveyor belt. In mining, for example, belt conveyor systems can have a length of several kilometres and a width of several metres. The belt speed is up to 10 m/s.



Fig.1: Cut-away model of a roller $d = 159$ mm
 (Source: own photo, BTU)

Rollers usually consist of a fixed axle and a rotating shell which is connected to the axle via bearings. Sealing systems prevent the ingress of dirt and moisture into the bearings (Fig. 1).

The load on the roller is essentially determined by the following factors:

- vertically to the axis by the mass of the conveyor belt and the conveyed goods
- the speed of the roller, which is determined by the belt speed
- horizontal to the axis by the tensile forces which are determined by the mass of the conveyor belt, the mass of the conveyed goods and the mass of the other rollers belonging to the roller garland
- Weather conditions (precipitation, temperature, humidity)
- Operation mode (continuous, constant or variable speed)
- the operation time
- Level of soiling (e.g. clogging) of the rollers and the conveyor belt

If no action is taken beforehand, failure of the roller becomes apparent in two borderline cases:

- Wear of the roller cover to the point of destruction and thus destruction of the conveyor belt
- Wear of the roller bearings, which can lead to heating and increased rolling resistance and even ignition of the conveyor belt

The cost of a single roller used in open-cast mining is approx. 100 €. However, their damage can cause consequential damage amounting to several million euros plus production downtime costs.

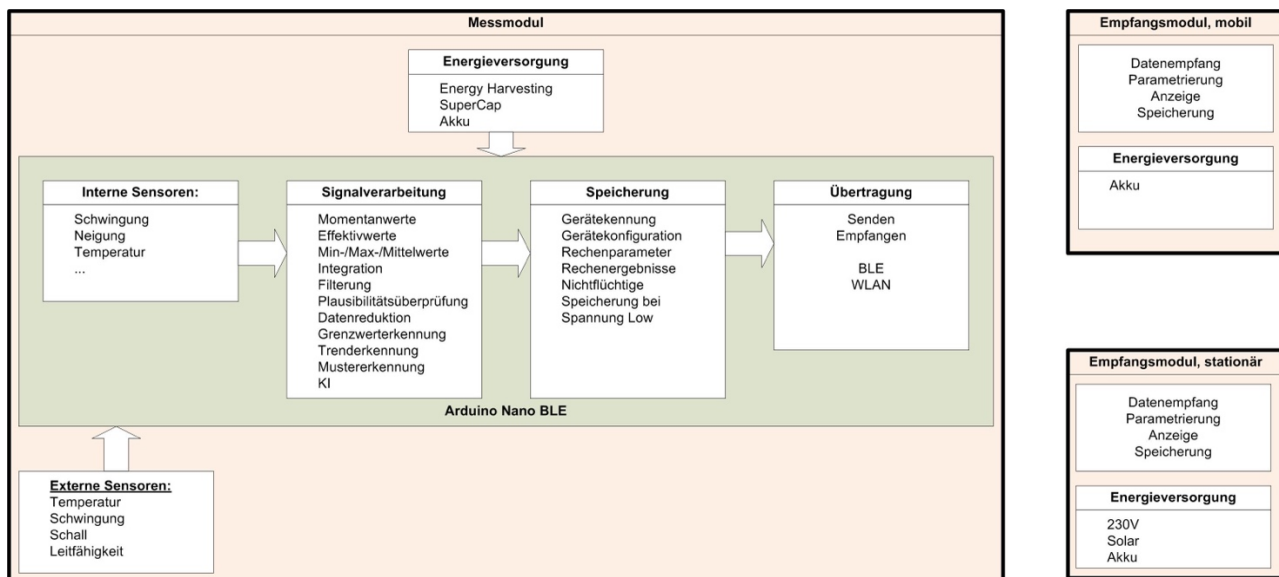


Fig.2: Main components and functional modules of the designed system

A system was designed and realised as a prototype that uses a self-sufficient energy supply and is as maintenance-free as possible to record and pre-process the key measured values of a roller and transmit them wirelessly to a receiver module.

2 Concept for a prototype

The system presented here should in principle be suitable for outdoor use in the industrial sector. The technical requirements were adapted for the prototype:

- Operating temperature range 0°C - 30°C
- Measurement of vibration accelerations up to +/- 4 g
- Transmission range of at least 200 mm
- No real-time capability
- Measured values are not provided with a time stamp, the measured value displayed is always the last measured value received
- Measured values are transmitted approximately every 2 minutes if energy is available.
- No archiving of the measured values received
- Not protected against dust and moisture

The system was constructed using components freely available on the market.

It consists of two main components (Fig. 2):
Measuring module with the functions

- Measurement
- Signal processing
- Power supply
- Data transmission

Receiver module with the main functions

- Data transmission and display
- Power supply

The measured variables ambient temperature and vibration acceleration are recorded and scaled in the prototype's measurement module.

For the purpose of data reduction, the vibration acceleration is measured over a time interval of a few seconds before each transmission cycle. The frequency spectrum is calculated from this and the dominant amplitudes and associated frequencies of the spectrum are transmitted.

The measuring module and receiver module communicate using the Bluetooth Low Energy (BLE) transmission standard, which is widely used in the consumer sector for fitness watches, for example. This ensures energy-saving communication and, in principle, communication is possible with any modern notebook or smartphone.

A key feature of the measuring module is that it is maintenance-free for as long as possible. This also includes a reliable and maintenance-free power supply, i.e. no batteries or accumulators.

The sensor presented here is to be installed in a roller. The shaft of a roller is fixed in place while the sheath rotates around the shaft. This means that there is always sufficient kinetic energy available during the operating time of the belt conveyor, which can be converted into electrical energy via an inductive system.

The energy harvesting system realised with the LTC3588 IC stores the induced energy in a SuperCap with a capacitance of $C = 0.1 \text{ F}$.

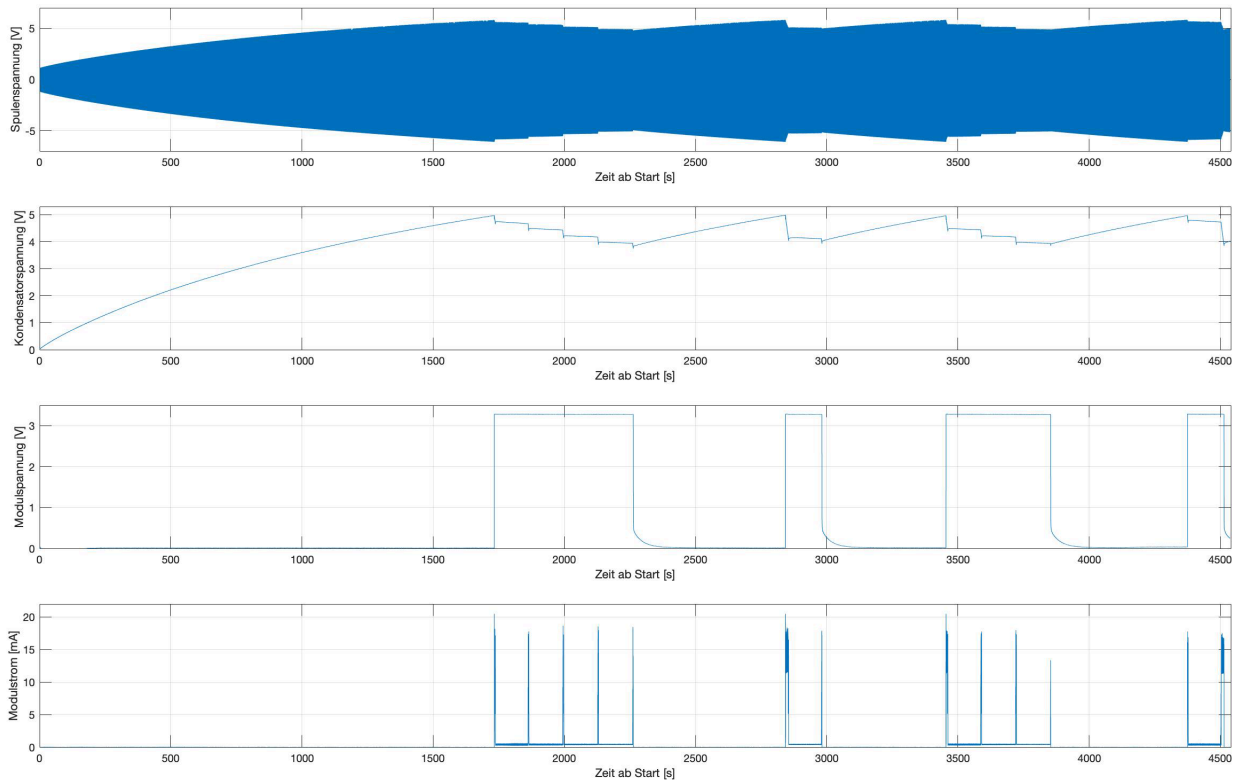


Fig.3 Course of electrical variables of the measuring module

Once the capacitor is sufficiently charged, the operating voltage for the measuring module is enabled, the measured values are recorded, pre-processed and transmitted via BLE to the receiver module, for example.

This means that operating cycles (measurement and transmission) are possible approximately every 140 s in the realised prototype.

Fig. 3 shows the curves of the induced voltage, the capacitor voltage, the operating voltage and the operating current of the measuring module.

In the realised sensor, the receiver module only has a receive and display function.

The receiver module is powered by conventional batteries. It is also possible to use a modern notebook or smartphone with a corresponding app.

3 Economic considerations

The basic prerequisite for the practical use of such a system is cost-effectiveness. Estimates have shown that the total costs of an equipped roller increase by 50 % without a longer service life.

The practical application of the system designed here therefore appears uneconomical, but is well suited for measuring and monitoring tasks in test and trial systems.

4 Summary and perspective

The system was realised and tested as a prototype. This demonstrated the suitability and functionality of the system. The use in rollers does not appear to be profitable.

Further investigations and further developments are planned with regard to, among other things.

- The thermal influences caused by the self-heating of the electronics and the heat development of the bearing
- Vibration resistance of the electronics
- Integration of further methods for analysing measured values in the measurement module and thus data reduction
- Optimisation of the energy harvesting system
- Functional enhancements to the receiver module
- Integration into higher-level IT-structures

Smart connected sensors platform for multi-nodal sensor fusion, gesture recognition, and full-body motion tracking

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Abstract

While many consumer electronics devices formerly could only rely on inertial sensing using only a single IMU (inertial measurement unit), more and more use cases emerge that require the fusion of data sampled by several sensor nodes simultaneously. Examples of such applications include joint angle monitoring for rehabilitation, complex gesture recognition for sports exercises and gaming, and full-body motion tracking.

As many applications require the sensors to be mounted to different locations on the human body, wireless connectivity must be established between all sensor nodes. With this connectivity, it is possible to exchange and fuse data of multiple sensor nodes without needing a physical connection between nodes. Since most of the end-user devices for such applications are battery-powered, there is a clear requirement for low power consumption of each sensor node.

This work describes a ready-to-use smart connected sensor system platform for collecting, synchronizing, and fusing sensor data of up to 8 sensor nodes, with each node containing a smart sensor with an integrated IMU, a Bluetooth Low Energy (BLE) microcontroller as well as other sensors relevant for full body motion analysis, such as magnetometers and pressure sensors. As the aforementioned use cases vary in requirements on the number of nodes, sensor output types, and sampling rates, a flexible platform concept for rapid use-case adaption is a core feature of the described concept.

Key challenges of designing solutions for connected sensor applications are highlighted and discussed using an example system. Furthermore, the benefits of pushing sensor data fusion and machine learning algorithms to the edge are elaborated.

Finally, a wearable reference hardware design, as well as a software platform for rapid use-case implementation, will be presented.

1 Introduction

1.1 Motivation and trends

Many available wearable consumer devices are battery-powered and provide wireless connectivity features, such as BLE, for exchanging data between devices. Examples of such systems are True Wireless Stereo (TWS) based hearables, smart watches, smart rings, and fitness bands/watches.

As all of these devices are usually battery-powered, the power consumption of each system component must be minimized to provide services for appropriate time spans. Often, applications for these devices depend on fusing sensor data of multiple connected systems, for example, fusion of inertial sensor data between left and right ear TWS hearable devices or body area network applications [1].

In these multi-nodal sensor systems, it can be more power efficient to process sensor data on the devices as much as possible before transmitting data using wireless protocols, as the power consumption of radio transmission tends to be high compared to embedded microcontrollers running algorithms on sensor data. When the sensor data is processed, typically, the amount of data that must be transmitted over radio can be reduced drastically.

Another benefit of processing sensor data close to the sensor itself is that timing information of the actual point of time at which a data point was sampled can be retained more accurately because transferring data over radio systems generally introduces several uncertainties for timing. For example, the exact point in time when a sample was

transmitted and when a sample was handed over from the physical layer of the wireless connectivity stack to the application layer of a microcontroller can be unknown.

Having precise timing information is crucial for some algorithms that rely on the timing relationships between different sensors to be known.

1.2 Smart Sensors

Smart sensors combine computational processing capabilities with sensing elements in one physical package. The concept described in this work is based on Bosch Sensortec's smart sensor BHI380 [2], which combines a six-axis IMU with a 32-bit microcontroller in one package.

Figure 1 shows the main components of this chip.

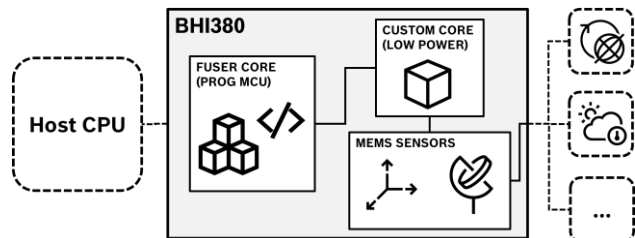


Figure 1 BHI380 component overview

The central concept of having processing capabilities close to the sensor instead of running all algorithms on a host microcontroller is that the smart sensor can run algorithms and provide intermediate results while the host microcontroller sleeps or performs other computational tasks. This change leads to more combined processing power or lower overall power consumption, as transferring sensor data to

the host microcontroller and processing it on this bigger system usually exceeds the power needs of the smaller smart sensor.

1.3 Connectivity in wearables/hearables

One of the main challenges of adding wireless connectivity to consumer electronic devices is power consumption, as transmitting data via an antenna usually consumes more power than operating a small microcontroller or transmitting data over wired serial interfaces.

BLE, one of the most popular technologies, aims to reduce power consumption overall. Challenges coming with wireless technologies for multi-nodal sensor applications include interference scenarios due to other radio traffic (e.g., WiFi) and obtaining exact timing information of all sensor nodes included in a BLE network [3].

2 Platform concept

The concept introduced in this work combines the smart sensor BHI380 for sampling and processing sensor data with a BLE microcontroller for transmitting and receiving sensor data, as well as events and algorithm outputs, over

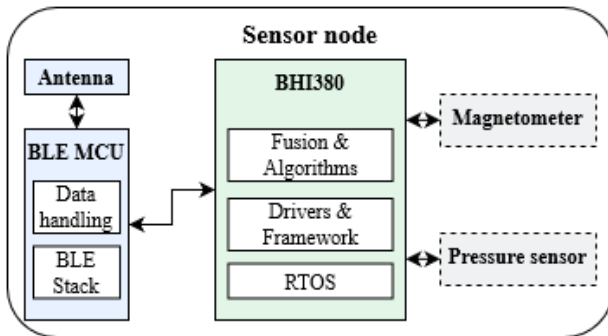


Figure 2 Sensor node concept: BHI380 with optional magnetometer and pressure sensor, connected to a BLE MCU with antenna

radio. This processing capability and connectivity combination will be referred to as a sensor node (see **Figure 2**). For handling applications based on spatially distributed sensors, up to eight sensor nodes can be connected to form a sensor network (see **Figure 3**).

The network concept is based on a star topology, meaning that a host device, such as a smartphone, connects to a central node, which then connects to up to seven leaf nodes, forming a smart sensor network of up to eight nodes. The star topology is used such that the sensor network can collect and process data independently of the host system, which can, in turn, either sleep or handle other computational tasks.

The sensor network, as described, can be used as a platform for various use cases, as the number of nodes, type of algorithm, and type of sensor are generic and can be configured to fit the needs of a specific use case. On top of that, already existing device classes, such as hearables and wearables, can be added to the sensor network without additional engineering efforts.

2.1 Connectivity

Even though, in principle, any connectivity standard could be used, this work focuses on BLE as the primary communication method. BLE is widely used and available in many consumer electronic end-user devices, which rely on short-range communication. Furthermore, BLE offers several

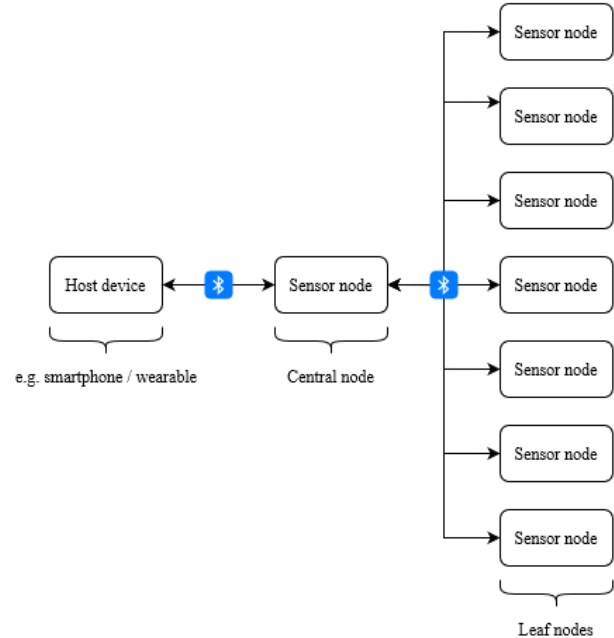


Figure 3 Sensor network concept with one central node and seven leaf nodes, connected to a host device via BLE

advantages over other standards, including lower power consumption and robustness against interference due to the adaptive frequency hopping principle [4].

2.1.1 Time synchronization

It's critical to have accurate information about how the local time domains of each sensor node relate to each other to fuse data from multiple wirelessly connected sensor nodes.

This information about how the different clock domains relate to each other contains many unknown delays and uncertainties related to timing, such as local clock speeds drifting away from each other, delays due to re-transmission of BLE packets, and stack delays.

A method for synchronizing all local clocks to the central sensor node's clock was developed to handle these differences in time domains, achieving a maximum absolute deviation of 1 ms between all local leaf node clocks and the central node clock, measured over 24 hours.

This method is especially needed since the BLE core specification often doesn't enforce the timing information of the physical layers to be shared with the application layer.

2.2 Sensor fusion and algorithms

As the core component of the proposed system is an IMU-based smart sensor, the main physical quantities measured are acceleration and angular velocity, which can already be

fused within the smart sensor, e.g., to output a game rotation vector [5] on each sensor node to create a 3D avatar application on a host device.

On top of accelerometers and gyroscopes, any sensor can be added to the platform. For example, magnetometers can be used to obtain a device's absolute orientation (rotation), while pressure sensor information can be helpful to refine certain algorithms and obtain vertical position information of each sensor node relative to each other.

Since the proposed platform concept enables applications including up to eight sensor nodes, more sophisticated algorithms have been developed to implement multi-nodal gesture recognition based on IMU data, including a quality score. Each sensor node either analyses its own sensor data to recognize a gesture connected to its body position or sends its raw data to the central sensor node. Based on all leaf node data, the central sensor node then counts repetitions of gestures observed by the full sensor network and assigns a score of how closely the gesture matches the trained pattern to each body part's performance.

2.3 Wearable hardware design

The wearable hardware design provides a way to implement use-cases rapidly on a physical device, without having to develop custom hardware or algorithms first. This hardware design, together with a battery and a housing, can represent one sensor node in the sensor network as depicted in **Figure 2**.

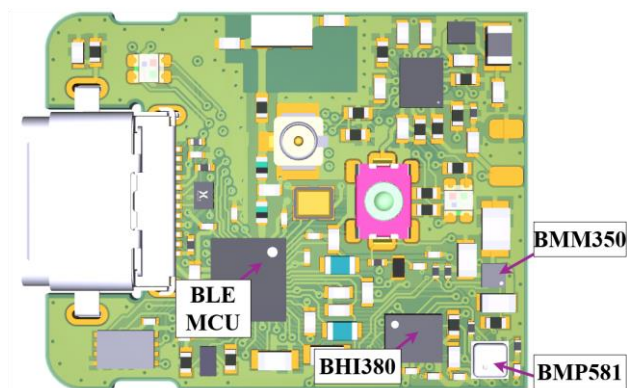


Figure 4 Wearable hardware PCB for sensor nodes, including a BLE microcontroller, BHI380 (smart sensor), BMP581 (pressure sensor) and BMM350 (magnetometer)

Figure 4 shows the wearable hardware PCB with the functional components highlighted. The main component is the smart sensor BHI380, which processes all algorithm and fusion-related tasks. The BMM350 magnetometer and BMP581 pressure sensor are connected to the BHI380 on a secondary interface, introducing additional degrees of freedom. A power management IC shuts down unused voltage domains to minimize power consumption further. Finally, a BLE microcontroller is included, which communicates to the BHI380 and transmits and receives data wirelessly.

A Lithium Polymer battery can also be attached to the PCB, and all components can be assembled in a housing,

which can be worn as a wearable sensor node on any body position.

3 Applications

The smart connected sensors platform enables various applications in the field of full body motion analysis:

One such field of applications is rehabilitation, such as joint-angle estimation or full-body motion analysis. For example, the knee joint angle of a patient after surgery can be measured and monitored based on inertial sensor data.

Furthermore, the multi-nodal gesture recognition algorithms can be used to track sports exercises and provide concrete feedback to the end user, such that the execution of an exercise can be optimized over time and the progress can be tracked.

3D-avatar applications for motion capturing or gaming applications can be realized using full-body rotation vectors, which can be used as an alternative method to conventionally used optical methods.

4 Conclusion

Overall, the concept presented in this work enables developers to quickly implement applications for novel use cases using wireless sensor networks, without having to implement multi-device sensor fusion algorithms. This means that in-depth domain knowledge is not mandatory anymore for implementing complex sensing applications.

Since the platform enables pre-processing of sensor data locally on each sensor node, the amount of data transmitted via BLE can be reduced. Therefore, overall power consumption of a target system can be reduced compared to approaches where raw sensor data of multiple sensor nodes is transmitted to a central processing device, which then handles and processes the data.

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Thermoelectric Energy harvesting with dual Phase Change Materials as thermal buffers

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Abstract

The contribution presents the study of using two Phase Change Materials (PCMs) of different melting temperatures as thermal buffers on either side of a thermoelectric generator (TEGs). The high latent heat of PCMs enables them to undergo an isothermal phase change while absorbing or releasing large amounts of heat. This feature of PCMs can be used to scavenge energy from the thermal fluctuations around the environment and to provide a temperature gradient along the TEG twice per thermal cycle. To demonstrate this, two commercially available PCMs, PCM 42 and PCM 24 with melting temperatures of 42° C and 24° C respectively, were used on either side of a TEG module and temperatures of these sides were monitored over time. The experimental results show a proof-of-concept of the dual PCM-TEG system by obtaining a reliable temperature gradient twice per thermal cycle.

1 Introduction

During the last few decades, a lot of research is based on energy alternatives that are sustainable and environment friendly. The non-renewable energy source depletion and increasing energy prices are leading to the exploration of “clean energy” and as an omnipresent form of energy ‘heat energy’ is gaining a lot of attention. The technology of scavenging/harvesting heat energy is regularly done via thermoelectricity. This is based on the Seebeck effect for converting heat into electricity as well as the Peltier effect for which current can be passed through the module, allowing it to act as an active cooling device.

Thermoelectric generators (TEGs), show distinctive advantages over other existing technologies like, direct power generation, vibration free operation, a lack of moving parts, low maintenance and a high environmentally friendliness. Thus, they have potential applications in different areas like, wireless sensors, bio-medical devices, space technology, automotive engines and electronic devices. [1] However, in most TEG applications attaining stable temperature boundary conditions is challenging. As the output power of a TEG is directly proportional to the temperature gradient ΔT , a transient temperature might affect the efficiency and cause variation in power generation. In order to address the challenges caused by thermal fluctuation several numerical as well as experimental studies have been conducted. Most of them report Phase Change Materials (PCMs) based thermal buffers to be used for the thermal management.

PCMs are latent heat storage systems that undergoes a phase transition at constant temperature. Among different PCMs, solid-liquid PCMs are abundantly deployed in thermal storage and management applications. [2] Owing to their high latent heat, they are able to store/release thermal energy during their melting/solidification (Figure 1) and

thus can be used to address the fluctuating temperature issue. Organic paraffin based PCMs with high latent heat, thermal stability and non-corrosivity are thus used along with electronic devices or TEG modules for this application.

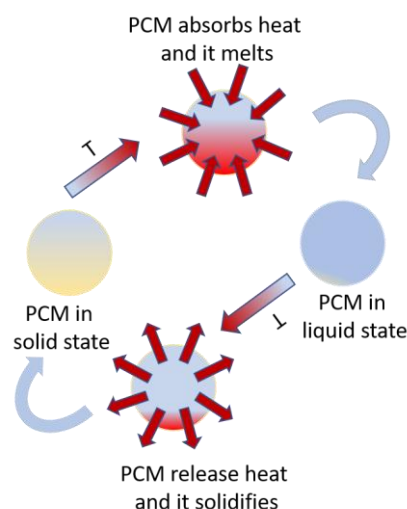


Figure 1: Phase change material - Thermal cycle

1.1 State-of-the-art

In an experimental investigation conducted by Jaworski et al. [3], PCMs were used for passive cooling of the cold side of TEGs for solar applications. The results showed improved performance during the PCM melting. Atouei et al. [4] reported the effects of using PCMs on either cold or hot sides or both of a TEG. Their results concluded that for PCMs on the hot side, the output power fluctuation was reduced and system could generate power even when the heat source was cut off. Selvam et al. [5] carried out a computational study on the thermal management of TEGs using

phase change materials. The results suggest that using the PCMs on the cold side could increase the temperature gradient and thus an increase in the efficiency by 30 – 36.7%. PCMs can also act as a heat source, providing a temperature gradient to the TEG from ambient temperature variations. Tuoi et al. [6] investigated a similar system with PCM as heat source and in their system the TEG without a PCM failed to generate output confirming the effectiveness of the PCM. Recently Borhani et al. [7] presented a numerical investigation in using PCMs on both sides of the TEG. Their study shows a positive effect by reducing the thermal fluctuation with increased working time. However, they report the downside as the output voltage drop and propose the idea of using thermally conductive porous medium to increase heat transfer inside the PCMs.

Almost all of the previous reports suggest that the PCM integration into TEGs has some positive effects. The PCM integrated on the hot side could reduce the voltage fluctuation and also produce continuous voltage for limited time even when the source is cut off. On the other hand, PCM on the cold side acts as a passive system for temperature control and maintains the thermal gradient.

In the present study, PCMs of different melting temperatures are simultaneously integrated on both sides of a commercially available thermoelectric generator. This study aims to utilize the dissimilar phase transition region of two PCMs providing a stable temperature gradient from the ambient temperature fluctuation.

2 Designs and Methods

2.1 Selection of PCMs and TEG

We chose the TEG and the PCMs for their commercial availability. A TEG module (QC-31-1.4-8.5M, Quick-Ohm Küpper & Co. GmbH) with dimensions 20 x 20 x 3.4 mm and an internal resistance of 0.37Ω was used. Organic, bio-based paraffin PCMs with different melting temperatures like 24°C and 42°C were obtained from the Companies CrodaTherm and Rubitherm respectively. Table 1 shows the physical properties of the PCMs as given in the datasheets.

Table 1: Physical properties of paraffin PCMs used to evaluate the performance.

Physical Properties	PCM 42	PCM 24
$T_m (^\circ\text{C})$	41	24
$C_p (\text{kJ/kgK})$	2	3.7
$\Delta H (\text{kJ/kg})$	165	184
$\kappa (\text{W/mK})$	0.2	0.2
$\rho (\text{kg/l})$	0.8	0.9

The PCMs were filled inside a cylindrical container of 30 mm inner diameter and 2.5 mm wall thickness (Figure 2 and Figure 3 inset picture) with 16 ml of internal volume, fabricated via 3D printing (Formlabs Form 3; Rigid 4K resin). The container is designed with open ends and custom copper plates with 35 mm diameter were used to seal

the PCM inside the container. The copper plate has a thickness of 6 mm and a 4 mm step with 30 mm outer diameter protrudes outwards from the container, ensuring the thermal contact with the sides of the TEG module.

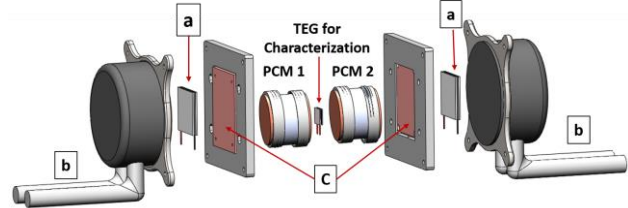


Figure 2: Sketch of the dual PCM-TEG along with a temperature adjustment and control setup (TACS) for measurement.

2.2 Experimental setup

Figure 2 shows the schematic of the experimental set-up for the dual PCM – TEG system and involves the following components: a) TACS Peltier modules for accurate temperature control (see below) b) Liquid-cooled heat exchangers c) Copper thermal plates and the actual TEG module sandwiched between the two PCM containers. The temperature control of the system during measurements was enabled by using a custom-built temperature adjustment control setup (TACS) [8]. Figure 3 shows the photograph of the complete setup with dual PCM-TEG sandwiched in TACS for the measurement.

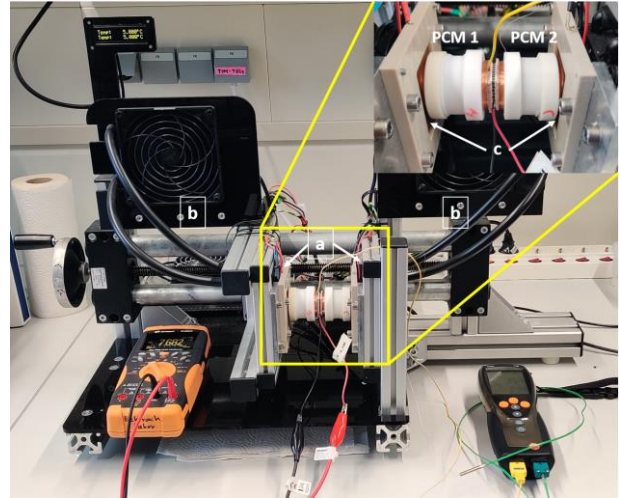


Figure 3: Picture of the TACS measurement setup with the dual PCM-TEG, with the inset picture showing the TEG sandwiched between two PCM containers with dissimilar PCMs.

3 Results and Discussion

For the experiment, PCM 42 and PCM 24 filled in 3D printed containers were placed on either side of a TEG module. The dual PCM-TEG system was provided with same temperature (50°C) on both sides by the TACS system. For better thermal transfer along the PCMs, copper wool was added as a thermal conductivity enhancer matrix inside the PCM container (see [8] for details). Apart from the copper plates of the PCM container touching the copper

thermal plates of TACS, the other surfaces were all exposed to ambient air. The measured temperature of either side of the TEG and the corresponding temperature difference ΔT is plotted in the graph shown in Figure 4.

Starting from room temperature (or a below for PCM 24) a heat source of 50 °C was applied to both PCM containers using the TACS and three distinctive regions with significant ΔT were observed. The first region at the beginning of heating, lasting approximately 16 min coincided with the melting temperature of PCM 24. During this time, the PCM 24 with lower melting point will start to absorb heat and melt, thereby reducing the rate of temperature increase, while PCM 42 in its solid state just heats up. This difference creates the first temperature gradient across the TEG.

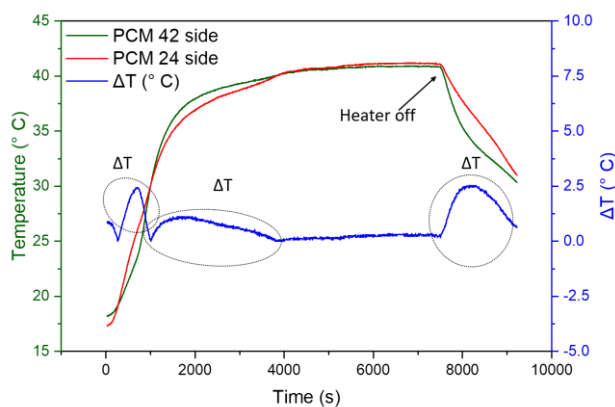


Figure 4: Variation of temperature on either side of the TEG along with corresponding ΔT during the measurement.

Subsequently, maintaining a similar temperature for a short period of time, a second region was observed, characterized by a smaller temperature gradient and closer to the onset melting temperature of PCM 42. However, this region lasted for about 45 min and mostly because of the phase change effects. At this stage PCM 24 is completely melted while PCM 42 remains mostly solid but stays on the onset of melting. Since the provided temperature of 50° C was not sufficient to raise the temperature of the PCMs further, both sides reached a saturation at around 40° C and a plateau region with negligible temperature gradient was observed.

For the third region, during cooling phase, the heater was actively cooled to room-temperature. The temperature on either side started to decline sharply. But due to the combined effect of latent heat release and thermal transport across the PCMs, a third significant ΔT was observed for around 25 min.

Based on this experimental observation and prior research in the field, it seems reasonable to speculate that the observed temperature profile is due to the combined effect of phase change and enhanced thermal transfer facilitated by the copper wool within the PCM. Addition of copper wools helped in uniform heat dissipation and likely thermal conductivity enhancement, contributing to the observed temperature profile. Further studies could include detailed modelling and simulation to study the underlying mechanism and experimental studies with modified system addressing the thermal loss to further validate our results.

Nevertheless, the study shows the potential of using dissimilar PCMs on both sides of a TEG module, contributing to a temperature gradient extended over a considerable period of time during heating and cooling phases.

4 Acknowledgement

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Indoor Light Harvesting with Organic Photovoltaics

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Abstract

Photovoltaics (PV) have drawn much attention for powering the expanding market of Internet-of-Things (IoT) devices, including sensors, actuators, and wearables. By utilizing solar cells and rechargeable batteries, it is possible to eliminate the cost and environmental impact of replacing disposable batteries. Notably, IoT devices are frequently used indoors under artificial light, which, unlike outdoor sunlight, has a narrower spectrum, limited to the visible range with an intensity being typically 500-1,000 times lower. Consequently, the optimal band gap of the absorber shifts to about 1.9 eV (~ 650 nm) where theoretical efficiencies of about 50 % are achievable. Organic photovoltaics (OPV) can meet these requirements, while being lightweight, flexible and processible with energy and cost-efficient techniques such as roll-to-roll (R2R). Secondly, due to the lower irradiance indoors also the power output is only in the $\mu\text{W}/\text{cm}^2$ range, though with efficient and intelligent area usage of the device housing a considerable amount of energy can be harvested. Under 500 lux LED light, between 20 % and 30 % efficiency have been already shown on lab-scale, while on a full 8 cm² module with a serial connection of eight cells more than 17 % (~200 μW) have been achieved. Such devices are operable even at illumination levels as low as 50 lx. Long-term aging studies under continuous LED illumination or elevated temperature showed almost no degradation under light for more than 15,000 h (1.7 years) at 50,000 lux, and for more than 2,500 h under 85°C more than 80 % of the initial performance have been maintained. Under typical indoor conditions which are rather mild (100-1,000 lux, 20-40 °C) the lifetimes may already be in a practical range of several years, assuming that there are no slow real-time degradation effects occurring independent of acceleration by light intensity and temperature.

1 Introduction

In recent years, new types of photovoltaics (PV), specifically organic PV (OPV) and perovskite PV (PPV), have achieved impressive power conversion efficiencies (PCEs). Certified records show 15.8 % and 25.2 % PCEs for OPV and PPV, respectively, with confirmed PCEs reaching 19.2 % and 26.1 %.^[1,2] These thin-film technologies are not only intriguing for outdoor applications but also for indoor light harvesting where up to now most light harvesters are based on amorphous silicon (a-Si). The bandgap of these emerging semiconductors can be adjusted to efficiently convert artificial indoor light into electricity. Despite minor differences among various lamp types (such as LED, compact fluorescent lamp (CFL), etc.) and their respective emission spectra, the optimal bandgap is calculated to be between 1.8 eV and 2.0 eV for typical indoor illuminations in the range of 200-1000 lx (0.3-3 W/m²). For instance, OPV achieved 30.2 % under 1000 lx LED light with PB2:FTCC-Br as absorber.^[3] Resulting in usable electrical power densities of about 30-50 $\mu\text{W}/\text{cm}^2$, thus they could harvest enough energy for low-power devices and protocols, respectively such as, LoRaWAN, ZigBee, Bluetooth or WiFi. Combinations with rechargeable batteries or super capacitors as energy storage widen the flexibility of energy usage, serve peak demand during transmission or bridge time spans without light. Also, fully monolithically integrated solar batteries are a promising solution.^[4] Although comparing efficiencies under indoor light conditions remains a challenge, several best practice proposals have recently been adopted.^[5-7] Further advantages

of OPV are their short energy payback time due to non-vacuum processing techniques, lightweight and mechanical flexibility or visual transparency.^[8] A hardly noticed feature is the application of monolithically integrated modules for low-power direct current (DC) high voltage (HV) use-cases of more than 1500 V, e.g. for dielectric elastomer actuators.^[9]

1.1 Indoor Photovoltaics

Energy-efficient modern lighting types like CFLs and LEDs, which emit light within the human vision range, influence solar cell design. Indoor light, being about 700 times less intense and having a narrower spectrum than outdoor light, leads to fewer photons and charge carriers, lower current density, reduced open-circuit voltage, and thus smaller power output, compare **Fig. 1**. Applying the Shockley-Queisser (SQ) limit^[10], which assumes perfect absorption and charge carrier generation above the band gap, to the LED spectrum, a maximum efficiency as a function of the band gap is derived. This efficiency is depicted in the inset of Fig. 1 alongside the well-known SQ limit curve for AM1.5G for comparison. The power density (P_{in}) of the LED spectrum is 1.42 W/m², at 500 lx. The lower irradiance also results in lower device temperature and slower degradation speed. The narrower spectrum (no UV or IR) can lead to higher efficiency due to reduced thermalization and non-absorption losses, both mediated by the bandgap. However, photons with energies smaller than the bandgap are not absorbed and are lost, either transmitting the absorber or potentially heating up the device through parasitic absorption.

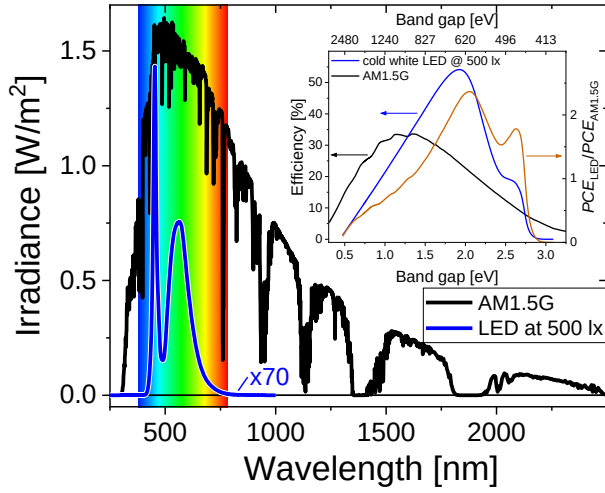


Figure 1: Spectral irradiances for AM1.5G and a 500 lx cold white LED; inset: calculated theoretical maximum efficiency for the two spectra as a function of the band gap.^[11]

1.1.1 Radiometry and Photometry

The performance evaluation of solar cells uses radiometric power density, denoted as P_{in} , measured in W/m^2 . Indoor settings often use photometric quantities, measured in lux, due to the design of artificial indoor lighting for human eye sensitivity.

Conversion between radiometric irradiance $P(\lambda)$ and photometric illuminance $L(\lambda)$ follows: $L(\lambda) = K_m P(\lambda) V(\lambda)$, where λ , $K_m = 683 \text{ lm/W}$, and $V(\lambda)$ represent the wavelength, luminous efficacy, and the photopic luminous efficiency function, respectively. The total illuminance of a light spectrum is calculated by integrating $L(\lambda)$. $P(\lambda)$, $V(\lambda)$, $L(\lambda)$ and $\int L(\lambda) d\lambda$ for a cold white (cw) LED at 500 lx is shown in Fig. 2.

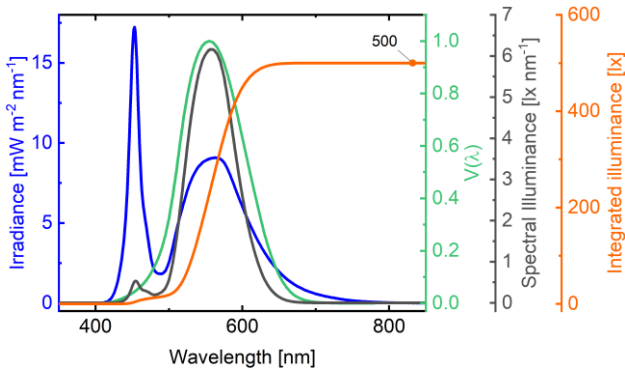


Figure 2: Radiometric and photometric spectra of the LED from Fig. 1.^[11]

2 Results and Discussion

2.1 Device Performance

Numerous OPV absorber materials in various solar cell stacks were investigated and the performance of the champion devices is summarized in **Tab. 1**. With PV-X plus, a material processable from non-halogenated solvents in an

indium tin oxide (ITO)-free cell architecture and a band gap of 1.43 eV PCEs of 19.9 %, 18.5 % and 18.2 %, respectively have been achieved under 500 lx cold white LED light on active areas between 0.1 cm^2 and 8.1 cm^2 .^[12]

Table 1: Figures of merit measured under 500 lx cold white LED for various OPV devices, including cells and modules. Note: (*) measured under 1000 lx warm white LED (3.79 W/m^2) ITO architecture.^[6,9,13]

Absorber/Device	J_{sc} [$\mu A/cm^2$]	V_{oc} [V]	FF [%]	PCE [%]	Area [cm^2]	Power [μW]
PV-X plus						
Cell, small	54.1	0.672	77.6	19.9	0.1	2.83
Cell, flexible	48.9	0.685	75.0	18.5	1.1	28.9
Module	7.03	5.137	71.6	18.2	8.1	209.3
HV Module*	0.071	1071.7	77.2	18.7	12.1	857.6
PM6:GS-ISO						
Cell, small*	83.3	1.074	70.0	20.5	0.0024	0.2
HV Module*	0.02	1523.4	60.0	5.7	12.1	261.4

A loss smaller than 5 % upon an area increase by a factor of about 90. Although the band gap is off the theoretical maximum it is still an excellent material since it compensates the drawback (low V_{oc}) by superior J_{sc} . Notable is also the comparable performance on a flexible substrate, which enables more versatile integration possibilities into IoT device housings. The module layout, number of cells connected in series or in parallel can be adjusted to the needs of the application, i.e. current and voltage are tuneable. In the underlying case we aimed for an operational

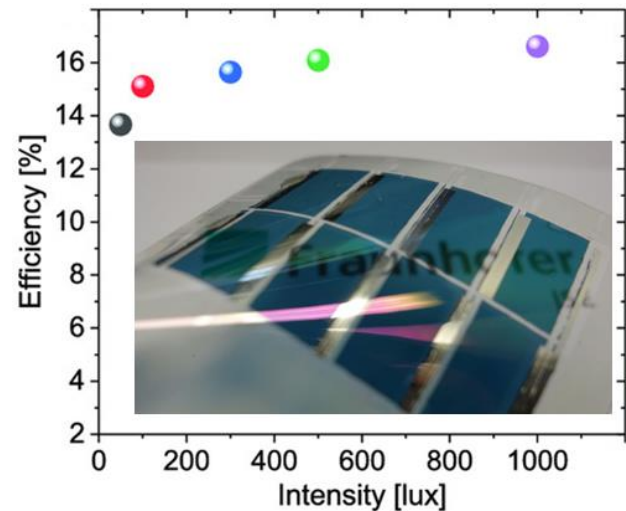


Figure 3: Performance of an 8.1 cm^2 ITO-free solar module with PV-X plus absorber measured under various intensities of a cold white LED.^[12]

voltage of about 4.5 V and achieved a power output of $209.3 \mu W$ ($25.8 \mu W/cm^2$) on the 8.1 cm^2 module with eight serially interconnected cells. With PM6:GS-ISO

PCEs and 25.3 % were achieved under 500 lx cw and 1000 lx warm white (ww) LED on small areas. The band gap of about 1.9 eV enables a high V_{OC} of above 1 V, however absorption and current extraction is not as optimized as for PV-X plus. With both, the higher and lower band gap absorbers, laser structured modules with more than 1600 interconnected cells on 12.1 cm² for high voltage application were successfully built. V_{OC} s of 1071 V and 1523 V could be demonstrated for PV-X plus and PM6:GS-ISO, respectively. The 8.1 cm² modules were also characterized under various light intensities between 50 lx and 1000 lx (see Fig. 3) and due to a high parallel resistance on the whole area, the high performance could be maintained even at ultra dim light conditions, e.g. 13.9 % (16 μ W), note that the P_{in} is only 14.2 μ W/cm² for 50 lx.

2.2 Long-Term Stability

As important if not even much more relevant as PCE is the durability of a device, hence the devices were aged under continuous illumination or elevated temperature and the performance of the devices is recorded on a regular basis. Fig 4 shows the evolution of the PCE for encapsulated

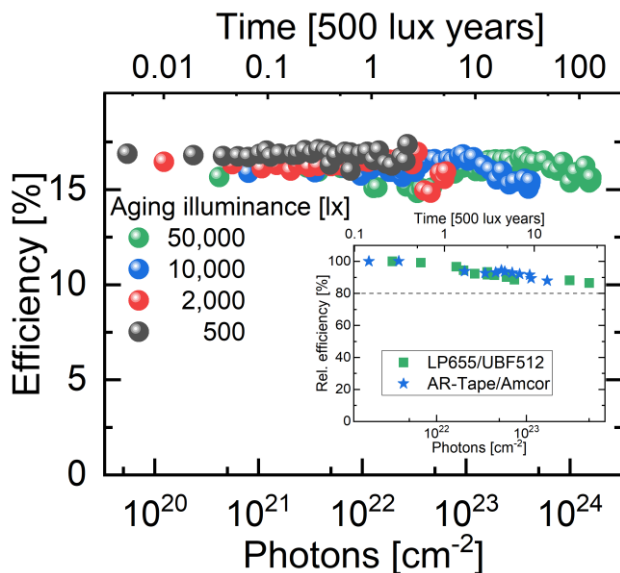


Figure 4: PCE evolution for PV-X plus solar cells aged under 500 lx, 2,000 lx, 10,000 lx and 50,000 lx, respectively as a function of the received photons. Top abscissa denotes the corresponding elapsed time with respect to a 500 lx illumination.^[13]

ITO-free PV-X plus solar cells under LED light between 500 lx and 50,000 lx. Over 90 % of the initial PCE could be maintained for more than 16 months independent of the intensity of the illumination. For flexible 8.1 cm² modules with flexible encapsulation after more than 6,100 h still more than 80 % of the initial PCE could be maintained, see the inset of Fig 4. In thermal stress tests at 85 °C in the dark PV-X plus solar cells maintained 80 % of the initial PCE for more than 2,500 h, see Fig. 5.

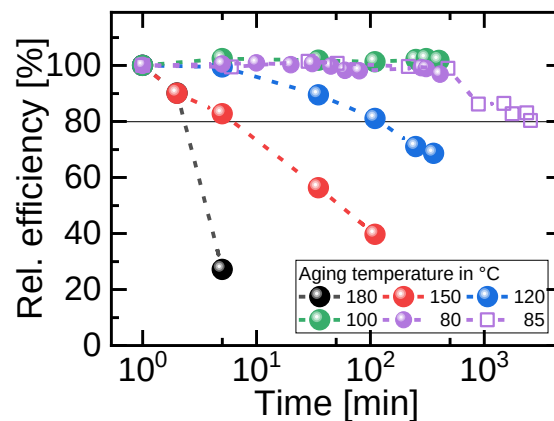


Figure 5: PCE evolution for PV-X plus solar cells aged under various temperatures.^[13]

3 Conclusion and Outlook

In summary the enormous potential of OPV and its current state-of-the-art with respect to power output and stability was demonstrated. PCEs as high as 18.2 % corresponding to a total power of 209 μ W for an area of 8.1 cm² under 500 lx LED light have been shown. Flexible or special high voltage devices with comparable performance were presented. Long-term investigations revealed significant stability, i.e. more than 16 months under a factor of 100 higher light intensity as common indoors as well as about 2,500 h under high temperatures. Overall, the readiness for industrial application of light energy harvesting with OPV were highlighted.

4 Acknowledgement

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Novel MEMS in-plane energy harvesting concept

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Conventional silicon-based cantilever harvesters with piezoelectric energy conversion [1] provide small energy conversion bandwidth and might show mechanical failure due to mechanical shocks. To overcome those limitations, a new in-plane concept is proposed. A seismic mass is supported by springs on either side, which allow for in-plane displacement and out-of-plane rotational motion. Multiple cantilever connect the mass to the surrounding frame. In-plane shocks or vibrations cause a torsion of the mass and deformation in the cantilever, which generate a voltage in the piezoelectric layer deposited on top of it. Introducing nonlinear behaviour makes the concept ideal for low power consumer applications that operate in the low acceleration range. Simultaneously, the concept provides resilience against accidental drops or potential damages during shipping.

Cantilever harvesters are supposed to operate in the linear regime of the employed materials. Furthermore, modelling techniques most often assume small displacements and thus benefit from linear device behaviour. To ensure stability of the harvester with respect to excessive excitation amplitudes, one commonly introduces displacement limitations which compromise the power output. This can be overcome by suspending both the mass and the opposite end of the cantilever by torsional springs. This drastically increases the device's stiffness in the out-of-plane direction and improves overload stability. The asymmetric mass distribution now renders the device sensitive to energy harvesting from in-plane excitation. The induced tilt of the mass causes the cantilever to bend, which introduces stress in the piezoelectric material. The double-clamped suspension is optimized to create a homogeneous stress distribution to achieve maximum output voltage.

1 Introduction

EH (energy harvesters), have widely been researched over the past decades. Depending on the required power output and field of application the type and size of harvester vary widely. Most EH are based on thermoelectric, piezoelectric, electromagnetic or electrostatic principles. For MEMS applications electrostatic and piezoelectric devices dominate the field. Electromagnetic and thermoelectric approaches have shown not to be compatible with MEMS fabrication technologies, due to the challenge of implementing magnets and the small achievable energy densities in thermoelectric devices [2].

For energy harvesting vibrations from the environment, piezoelectric harvesters are ideal. They have a comparably high power density and a simple structure. Most commonly a piezoelectric material stack is deposited on the cantilever beam. It consists of a bottom electrode, a piezoelectric material and a top electrode. At the tip of the cantilever a seismic mass is placed to increase the sensitivity and power output of the device.

2 Limitations of cantilever harvester

Cantilever harvesters are designed and operated such that they exhibit linear behaviour. Depending on the application, the design is adapted to maximize either their power output or the mechanical stability. A more sensitive device usually shows reduced mechanical stability. It is desirable that the device's mechanical properties change depending on the mode of operating mode, i.e. be stiffer at higher accelerations. To illustrate this, a cantilever is simulated in COMSOL Multiphysics with a constant force F applied to the tip.

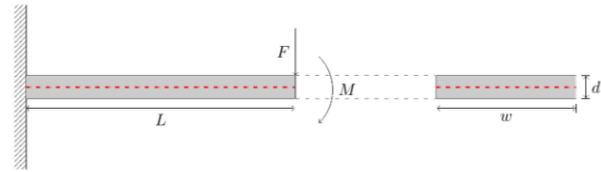


Figure 1 Test cantilever structure, left: side-view, right: cross-sectional view

As a test geometry a cantilever with the following dimensions is defined: $L = 2000 \mu\text{m}$, $d = 29 \mu\text{m}$ and $w = 500 \mu\text{m}$. The force is iteratively increased up to 50 mN and the deflection of the tip and the peak stress are recorded. Beam theory can be used to estimate the behaviour of the simple beam structure for small deflections.

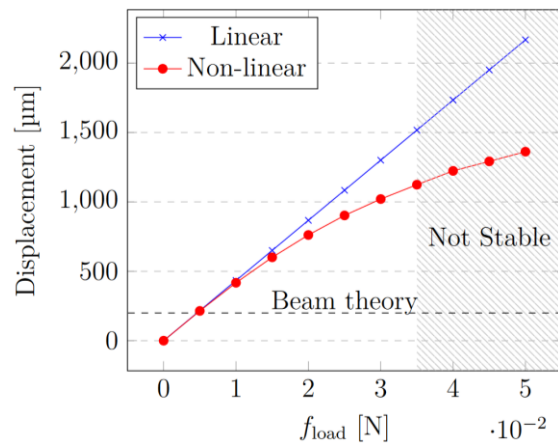


Figure 2 Comparison of linear and nonlinear models for the described cantilever beam

For the present cantilever nonlinear effects become significant at deflections bigger than 1000 μm , which are not

reached during normal operation. The mechanical integrity of the device can be ensured by limiting the deflections through top and bottom cap wafers. Thus, cantilever-based energy harvesters can be considered as predominantly linear devices.

3 In-plane harvesting concept

To introduce stronger nonlinear behaviour, two springs are added to the side of the seismic mass. Larger displacements from the resting position cause a larger restoring force from the springs on the mass, making the nonlinear effects more dominant. The springs cause the design to be stiff in the out-of-plane direction and only allow for movement in the in-plane direction. An in-plane shock will exert a compressive force on the plate, which causes it to bend.

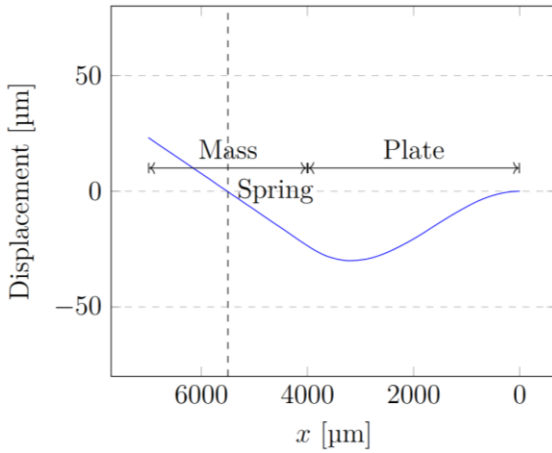


Figure 3 Bending shape along the cross section. The mass segment is tilted and the plate bends.

While this bending shape creates significant stresses in the piezoelectric layer, both tensile and compressive stress exist. This leads to opposite charges being generated on the electrodes. With a single electrode these charges cancel out, reducing the overall voltage generated. To illustrate this, the second Piola-Kirchhoff stress is analysed along the plate length.

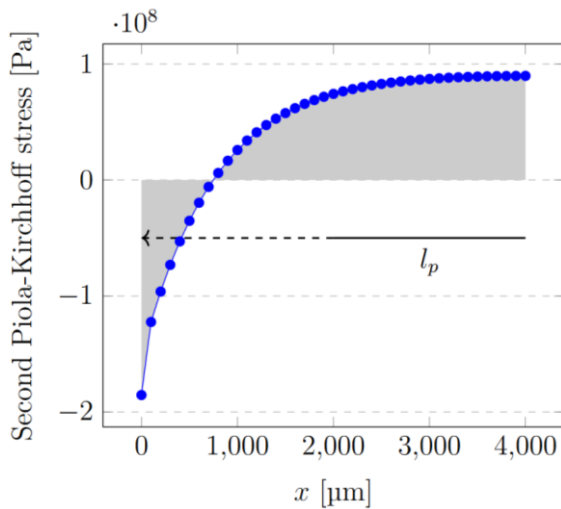


Figure 4 Stress distribution along piezoelectric layer

Around 750 μm from the left edge, the sign of the stress changes. If the whole surface of the cantilever or plate is covered, the open circuit voltage and overall power output are reduced. The open circuit voltage can be calculated with formula (1).

$$V_0 = -\frac{d \cdot S}{\epsilon} t \quad (1)$$

With S being the average stress in the piezoelectric layer. As seen in figure 4, the average stress along the piezoelectric layer decreases if more surface area of the plate is covered. This can be overcome by separating the electrode into two segments. The separation shall be introduced at the location of the zero-crossing. Such an approach introduces additional electrical and fabrication complexity. Each electrode requires electrically isolated conductor traces and contacts, as well as its own rectifying circuit. Furthermore, the ideal positions for the electrodes has to be determined. While it is trivial to define the electrode geometry for a single acceleration or load, the optimal electrode dimensions vary with the acceleration. Optimal harvesting efficiency is thus not achievable with a separated electrode approach.

To overcome this issue, we propose to optimize the bending shape instead. As stated above the generation of opposite charges stems from the S-bending shape, which in turn is caused by the fixed constraint of the plate. For optimal charge generation the plate would have to bend in a circular shape. This can be achieved by enabling the plate to rotate at the fixed edge. Therefore, the fixed constrained is replaced by two additional torsional springs, similar to the suspension of the proof mass.

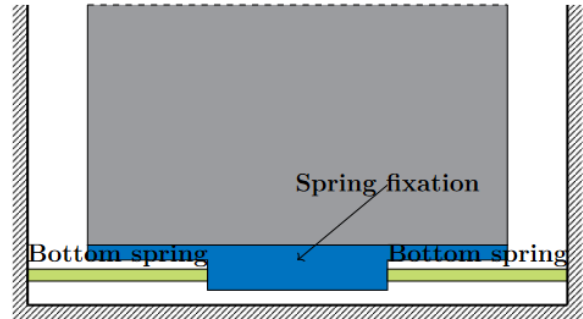


Figure 5 Bottom spring fixation. The suspension allows for rotation of the flexible plate.

To efficiently allow for rotation of the springs upon an in-plane excitation, a silicon truss is added to the edge of the device. The use of the suspension as combined lateral and torsional springs greatly improved stress homogeneity in the plate. A full overview of the spring-spring harvester is given in figure 6.

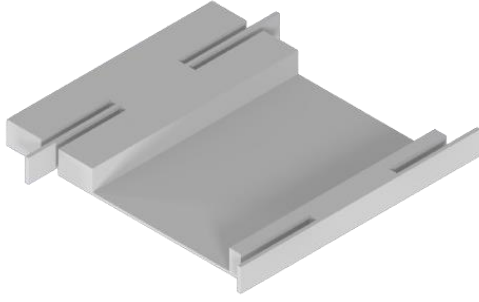


Figure 6 Overview of the spring-spring concept

To further improve the device performance, the seismic mass is fabricated utilizing the Powder MEMS technology [3], in which silicon cavities are filled with micron sized powder. This process allows for integration of materials with exceptionally high density, e.g. tungsten, increasing the overall inertia and sensitivity. Powder MEMS technology allows for filling rates of around 55 %. When filling the cavity with tungsten powder (19.3 g cm^{-3}), the seismic mass segment can reach an average density of 9.6 g cm^{-3} . Which is significantly higher than silicon (2.3 g cm^{-3}). Sputtered AlScN thin film is proposed as a piezoelectric material. Compared to AlN it provides higher piezoelectric coefficients with an only slightly larger relative permittivity of $\epsilon_r = 13$ compared to $\epsilon_r = 9.0$ of AlN. In AlScN typical scandium concentrations vary from 24 to 30 % [4]. With higher concentrations showing better electrical characteristics. In the present model $\text{Al}_{71}\text{Sc}_{29}\text{N}$ with a piezoelectric coefficient of $d_{31} = -5.92 \text{ pC N}^{-1}$ is implemented.

4 Concept evaluation

To evaluate the power output of multiple designs of the spring-spring harvester, a combination of linear and non-linear methods is used. As a performance metric a figure of merit (*FOM*) is derived, from the peak power output of a piezoelectric energy harvester.

$$P_{max} = \left(\frac{V_0}{2}\right)^2 \cdot \omega C \quad (2)$$

With C and ω being constant in a given geometry. For comparison of designs with similar eigenfrequencies, ω can be omitted. The capacitance C is modelled as a rectangular plate. The material and thickness remain constant ($\epsilon_r = \text{const}, d = \text{const}$), thus the *FOM* can be simplified to equation 3.

$$FOM = V_0^2(w \cdot h) \quad (3)$$

Designs are derived via a combination of methods. Initially, a parameter space is defined, which constrains the design variability. Minimum feature sizes are set to ensure manufacturability of the device, e.g. the minimum spring width is $20 \mu\text{m}$. A parameter optimization is performed within the design space using the Nelder-Mead method with the *FOM* as an objective function. Optimization was implemented using the COMSOL optimization module.

Manual design rules are derived from the results of the optimization, to further reduce the design space. The smaller design space is then used for a second optimization step, again applying the Nelder-Mead method. This approach is used to identify six harvester designs with a total footprint between 0.47 and 0.90 cm^2 . These designs are evaluated more extensively.

Every design is subjected to a sequence of three in-plane pulses, each with a duration of 110 ms and peak acceleration of 100 g . An optimum resistive load is assumed and the average power output is calculated. Figure 7 presents the results for six optimized designs with P marking the average power output during the full simulation period and P_{3P} being the average power output during the last pulse only.

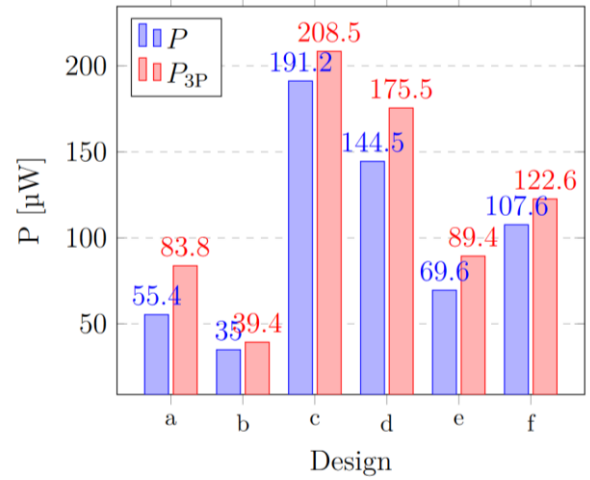


Figure 7 Average power output of designs during transient simulation

From the results shown in Figure 7 and the given harvester geometries, the corresponding power densities are calculated.

Table 1 Design overview

Design	f_0	Surface Area	Power Density
	Hz	cm^2	W cm^{-2}
a	258	0.90	0.61
b	643	0.60	0.59
c	350	0.89	2.14
d	632	0.59	2.43
e	654	0.59	2.27
f	852	0.47	2.50

5 Conclusions and Outlook

Nonlinear EH supports stability improvements and as shown in this paper, enables broad frequency excitations. Adapting the traditional cantilever harvester can yield such advantageous properties. Designing for in-plane excitation and adding suspensions at the cantilever support gives additional design freedom that allows to control the nonlinear characteristics. The rotation of the plate creates comparatively large stresses and voltages in the piezoelectric layer, with comparably small out-of-plane deflections of the device. Combining this approach with modern piezoelectric materials like AlScN and the Powder MEMS technology

further increases the power output of the device, while maintaining the microstructuring fabrication approach. The concept has been evaluated by deriving multiple test designs that have been extensively simulated. A combination of stationary, harmonic and transient test cases have been defined and simulated. A peak RMS power output of 208 μW (design c) has been observed for 100 g shocks. The harvester shall be fabricated and tested in a laboratory setting. Especially the quality factor is of interest. For the current simulation the quality factor is estimated from similarly sized piezoelectric EH. Long term tests are of interest as well, to estimate the lifetime of the device and identify mechanical weak points of the design.

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Advancing Piezoelectric MEMS Energy Harvesting: Design-Independent Resonance Frequency Tuning and Magnetic Interaction

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Abstract

Adjusting a MEMS harvester to a specific use case often requires the adaptation of the resonance frequency which ultimately requires design changes and costly MEMS processing modifications. A novel powder-based processing technique referred to as PowderMEMS allows the integration of pure and mixed powder materials on wafer level. This approach allows altering the tip mass and thus the resonance frequency without altering the design. Additionally, the integration of magnetic materials enables contactless energy harvesting through magnetic interaction. In this study, a MEMS energy harvester with integrated NdFeB magnets is presented and the potential for adjusting the resonance frequency by using mixtures of powders is discussed. In addition, the stability of such devices under thermal cycling is investigated.

1 Introduction

Energy harvesting devices, particularly MEMS vibrational energy harvesters, are discussed to power the increasing energy demand of IoT devices for years [1]. One of the most promising approaches is the use of piezoelectric MEMS energy harvesters due to their high power density [2].

Such devices are commonly composed of a silicon beam with a thin layer of piezoelectric material deposited on top and a silicon tip mass. These harvesters typically exhibit a limited frequency range and a fixed resonance frequency that is determined by their design. This limits their application range since for each individual use case the resonance frequency needs to be adapted. Accordingly, to adjust the resonance frequency for a specific use case, design changes and costly MEMS processing modifications are required.

For macroscopic systems to adapt the resonance frequency, different solutions were proposed including sliding masses [3] or damping the system by external magnetic fields [4]. However, these techniques can hardly be transferred to MEMS systems. Active tuning using split electrode has been employed as a strategy for MEMS devices [5]. In this case the primary electrode was used for harvesting while to the secondary electrode a voltage is actively applied to alter the stiffness of the cantilever. However, achieving a net increase in power output through such technologies is questionable [5].

This article presents a MEMS energy harvester, to which a technique for integrating pure and mixed powders at the wafer level is applied. This technique is referred to as PowderMEMS and is in detail described elsewhere [6].

Due to the integration of NdFeB into the tip, firstly the resonance frequency of the MEMS harvester is reduced compared to conventional pure silicon tip masses. Secondly, due to magnetic interaction translational and rotational energy can be harvested.

FEM simulations are performed to highlight that powder mixtures allows adjusting the resonance frequency without making design modifications and thus create energy harvesters tailored to a specific use case.

2 Experimental

The here presented MEMS energy harvester have been processed on 8-inch silicon wafers. The harvester consists of a trapezoidal cantilever made of 39 μm thick polycrystalline silicon with 2 μm AlN thin films deposited on top. At the tip cavities were etched by deep reactive ion etching. The cavities were filled with NdFeB powder and solidified by depositing Al_2O_3 using atomic layer deposition. Afterwards the cantilever was released. A detailed description of the process can be found elsewhere [7].

A typical MEMS energy harvester made of trapezoidal cantilever and NdFeB powder embedded in the tip mass is depicted in **Figure 1a**. For reference, length and width of critical dimensions of the device are highlighted and summarized in **Table 1**.

For determining the resonance frequencies finite element method (FEM) simulations have been performed using COMSOL Multiphysics 6.2.

To excite the harvester magnetically a wheel was modified with 32 N52 NdFeB rod magnets (1.7 mm diameter, 6.6 mm length). The magnets were placed in blind holes within the wheel and secured with a 1 mm thick aluminum cover. To measure the open-circuit harvester, an oscilloscope

(Tektronix MDO3034) was used. The MEMS energy harvester was bonded on a PCB and fastened to a 3-axis translation stage (Thorlabs) (see **Figure 1b**).

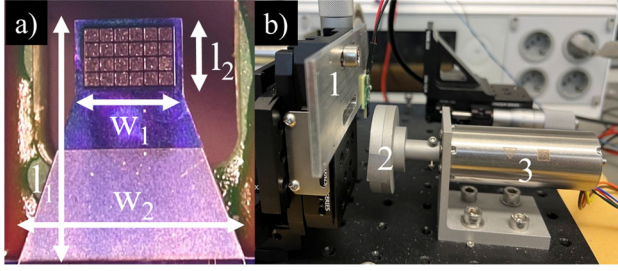


Figure 1 a) MEMS energy harvesting with embedded NdFeB powder magnets in the tip; b) Measurement setup to excite the MEMS energy harvester. The holder with a mounted chip, the wheel with embedded magnets and the dc-motor are highlighted by the numbers 1, 2 and 3, respectively.

Table 1 Design dimension of the MEMS energy harvesters according to **Figure 1**

length l_1	length l_2	width w_1	width w_2
3.45 mm	1 mm	1.5 mm	3.2 mm

To verify the stability of the PowderMEMS structures and the MEMS in general thermal cyclic shock tests have been performed using a Weiss Technik TS 60 temperature shock test chamber. In **Table 2** the parameters of the testing procedure can be found. An impedance analyser (Keysight E4990A) has been used to measure the admittance before and after thermal cycling.

Table 2 Parameters used for thermal cycling experiments.

Number of cycles	Dwell time	Maximum temperature	Minimum temperature
10	10 min	150 °C	-55 °C

3 Results

3.1 Resonant magnetic excitation

Using the experimental setup described in chapter 2, the harvester was magnetically excited at 4 mm distance between excitation source and harvester. **Figure 2** depicts the open-circuit voltage measured with respect to excitation frequency. According to these measurements the resonance frequency is 1667 Hz. Based on the obtained resonance frequency, the filling factor of NdFeB was calculated to be 38 %.

Comparing these results with the calculated resonance frequency of samples featuring a pure silicon tip mass, a decrease of the resonance frequency is expected. Specifically, the resonance frequency for an energy harvester of the same design with a pure silicon tip mass would be 1732.7 Hz. By adjusting the ratio of silicon to NdFeB content, the resonance frequency can be adapted between these two extreme points. This could be achieved by simply

changing the etch depth during the creation of cavities for the PowderMEMS structure.

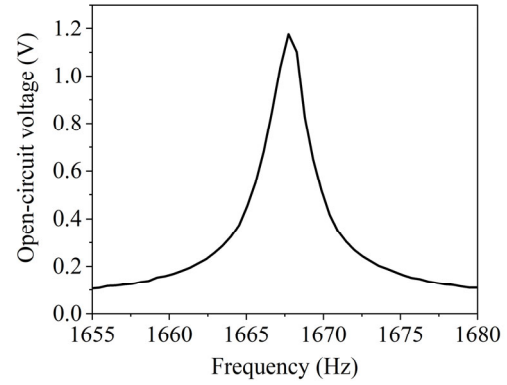


Figure 2 Open-circuit voltage independence of the excitation frequency.

3.2 Adjusting the resonance frequency using powder mixtures

In addition to NdFeB, other powders can also be incorporated, such as tungsten and silica particles. According to the discussion before, tungsten, with its density of 19.28 g/cm³, significantly reduces the resonance frequency compared to pure silicon samples. On the other hand, silica, with a density of 2.65 g/cm³, increases the resonance frequency. Considering the same design and a 38 % filling factor, calculated resonance frequency for pure tungsten and pure silica powder corresponds to 1310 Hz and 1937 Hz, respectively. Thus, the resonance frequency can be tuned with a mixture of the two powders. **Figure 3** illustrates the calculated resonance frequency, obtained through FEM analysis, for different ratios of tungsten and silica powder mixtures. By adjusting the ratio of these two powders, the resonance frequency can be fine-tuned by up to 600 Hz.

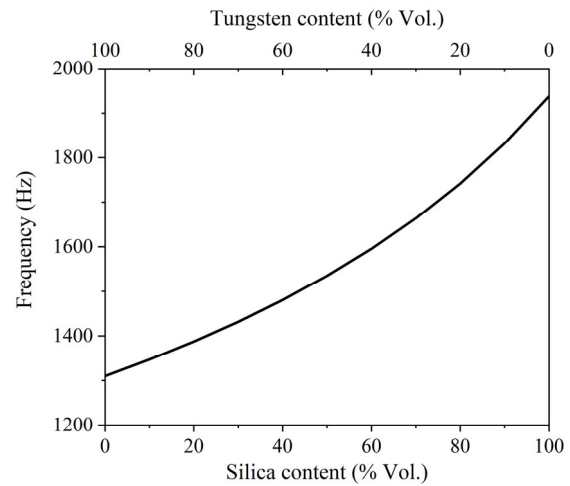


Figure 3 Calculated resonance frequency for varying content of silica and tungsten powder, assuming a total filling factor of 38%.

3.3 Thermal stability

Thermal cycling tests have been performed on samples bonded to PCBs according to the parameters given in **Table 2**. The impedance and the phase were determined by an

impedance analyser. In **Figure 4** the results of the measured admittance before (BTC) and after thermal cycling (ATC) are depicted for a typical sample. No significant changes are observed. The measured resonance frequency is not altered, indicating that the PowderMEMS structure is still intact. Furthermore, it can be concluded that the dielectric materials and the wire bonds are largely unaffected by the thermal cycling procedure.

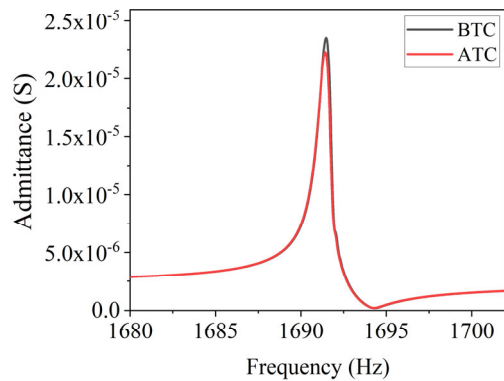


Figure 4 Measured admittance before (BTC) and after thermal cycling (ATC).

4 Conclusion

The integration of NdFeB by the PowderMEMS process allows to magnetically excite the here used MEMS energy harvester. This capability enhances its versatility and potential for efficient energy harvesting. Furthermore, the option to use different powders and integration of powder mixtures open up possibilities for optimizing the harvester's design and tailoring its resonance frequency to specific application requirements. Additionally, thermal cycling tests confirm the thermal stability of the harvester, with no significant changes observed in the measured admittance. This highlights the robustness of the MEMS energy harvester and the PowderMEMS structure.

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