Wearable
Devices

A Wearable Devices Ltd.
White paper

Designing a neural input wristband for extended reality experiences

June 2023

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PREFACE

Please feel free to reach out to Wearable Devices Ltd. at WhitePaper@wearabledevices.co.il if you would like to provide feedback, corrections, engage in discussion, or share ideas regarding this publication. Please note that the use of the content in this white paper is subject to the limitations outlined in the agreement that readers accepted when downloading this document from the company's website.

EXECUTIVE SUMMARY

This white paper discusses the importance of a proper wearable neural interface design for controlling an external device. A neural input interface translates intended movements into digital commands. It must be designed to ensure functionality, accuracy, and comfort for all users.

Detecting finger movements that are exceedingly subtle is one of the foremost challenges for neural interfaces. This challenge is particularly critical when the user is multitasking or operating a digital device while on-the-go. Providing an accurate input that prevents false positives across various user physiologies is a driver for the entire XR insustry.

When developing a wearable neural interface, there are always tradeoffs between functionality, accuracy, and product design. It is crucial to take a system-engineering approach that considers all the different components of the sensor, the algorithm compute requirements, and the product form factor. We analyze the requirements for such parameters as reach, accuracy, latency, MAC, number of electrodes, and device geometry.

The technology pillars used in the creation of a neural interface can be categorized into three types – hardware, software, and humanware, which is the method of adding a human facet with the main goal of making it as functional, natural, and intuitive as possible. This approach ensures that the device not only meets the user needs but also exceeds the expectations in terms of comfort, usability, durability, and overall satisfaction.

With thousands of users testing and over 100 companies who bought the Mudra neural input dev-kit, Wearable Devices Ltd. has developed the Mudra Band, an aftermarket accessory band for the Apple Watch. It allows users to operate the entire Apple ecosystem through touchless subtle finger movements and hand gestures. With its Air-Touch functionality that allows users to naturally input control and intuitively switch between devices, we believe the Mudra Band is shaping and the landscape standard for the extended reality input and interaction.

FORWARD LOOKING STATEMENT

This White Paper contains “forward-looking statements” within the meaning of Section 27A of the Securities Act of 1933, as amended, and Section 21E of the Securities Exchange Act of 1934, as amended, that are intended to be covered by the “safe harbor” created by those sections. Forward-looking statements, which are based on certain assumptions and describe our future plans, strategies and expectations, can generally be identified by the use of forward-looking terms such as “believe,” “expect,” “may,” “should,” “could,” “seek,” “intend,” “plan,” “goal,” “estimate,” “anticipate” or other comparable terms. For example, we are using forward-looking statements when we discuss advantages and benefits of our Mudra Band and our Mudra technology, our belief that the Mudra Band is shaping and the landscape standard for the extended reality input and interaction and our mission to shape to shape the input landscape for extended reality. All statements other than statements of historical facts included in this White Paper regarding our strategies, prospects, financial condition, operations, costs, plans and objectives are forward-looking statements. Forward-looking statements are neither historical facts nor assurances of future performance. Instead, they are based only on our current beliefs, expectations and assumptions regarding the future of our business, future plans and strategies, projections, anticipated events and trends, the economy and other future conditions. Because forward-looking statements relate to the future, they are subject to inherent uncertainties, risks and changes in circumstances that are difficult to predict and many of which are outside of our control. Our actual results and financial condition may differ materially from those indicated in the forward-looking statements. Therefore, you should not rely on any of these forward-looking statements. Important factors that could cause our actual results and financial condition to differ materially from those indicated in the forward-looking statements include, among others, the following: our use of proceeds from the offering; the trading of our ordinary shares or warrants and the development of a liquid trading market; our ability to successfully market our products and services; the acceptance of our products and services by customers; our continued ability to pay operating costs and ability to meet demand for our products and services; the amount and nature of competition from other security and telecom products and services; the effects of changes in the cybersecurity and telecom markets; our ability to successfully develop new products and services; our success establishing and maintaining collaborative, strategic alliance agreements, licensing and supplier arrangements; our ability to comply with applicable regulations; and the other risks and uncertainties described in our annual report on Form 20-F for the year ended December 31, 2022, filed on March 22, 2023 and our other filings with the SEC. We undertake no obligation to publicly update any forward-looking statement, whether written or oral, that may be made from time to time, whether as a result of new information, future developments or otherwise

INTRODUCTION

The global wearable technology market was valued at USD 61.30 billion in 2022 and is expected to expand at a compound annual growth rate of 14.6% from 2023 to 2030. Wearable computing is reshaping business processes and consumer entertainment patterns. The pace of technological advancements is always dictated by user interfaces. The input method for wearable computing will have to be re-invented as well.

A neural input interface is one of the most challenging tasks in our time. Neurotech, brain- computer interfaces and brain-machine interfaces promise more natural, intuitive, and effortless interaction. Delivering a functional, accurate, and elegant non-invasive interface is the epitome for the next computing platform, with thousands of brain neuroscientists, machine learning and artificial intelligence researchers, multi-disciplinary engineers, UX/UI designers, and human factors experts focused on solving the challenge.

Augmented Reality glasses and Virtual Reality headsets are gaining traction in business and consumer markets, yet still lack an effective hands-free and touchless command input. A wearable with point and click and drag and drop functionality, free from hand held constraints, provides the optimized input for the next wearable computing platform, whether as an after-market accessory or integrated into existing devices.

Defining Neural Interface Requirements

When designing a neural input solution, multiple factors must be addressed, including user physiology, user intention and task, user attention and awareness, environment conditions, and more. These parameters calculate the abstract requirements for a wearable input wristband.

The device features are influenced by the input functionality, the way the interactions are performed, and the controlled device output type. Out of the box accuracy, the onboarding process, a user-tailored calibration, and a comfortable, elegant, and fashionable device is a must for user willingness adoption to wear and use.

The device's technical specification is determined by hundreds of design considerations and decisions dictated by the sensor specification and the algorithmic system characteristics and attributes.

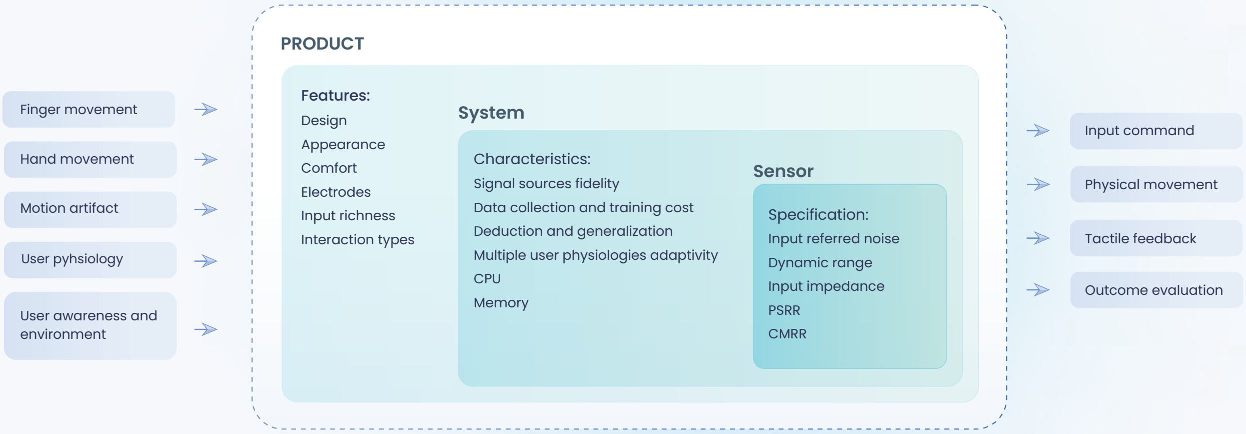

Figure 1: Requirements flow (partial list)

When integrating certain elements of hardware and/or software into a third-party device, further constraints on the specification may arise.

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[1] Grand View Research, Wearable Technology Market Size, Share & Trends Analysis Report 2023-2030

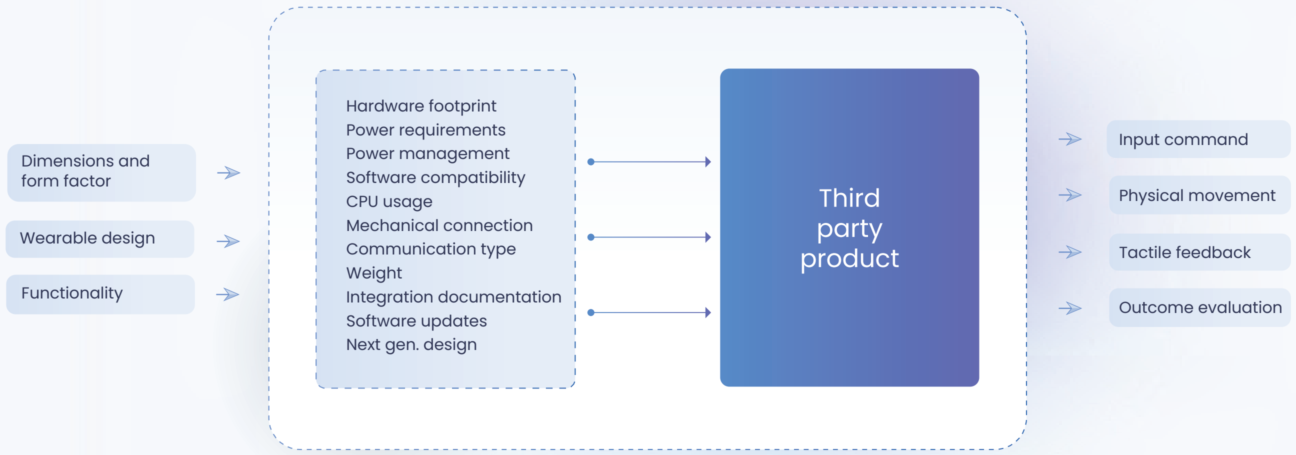

Figure 2: Integration Design Considerations

Basic Human-Computer Interaction (HCI) is conveyed through user input and computer output, by means of a user interface and an interaction device. The user forms an intent, expressed by selecting and executing an input action. The computer interprets the input command and presents the output result, which the user perceives to evaluate the outcome.

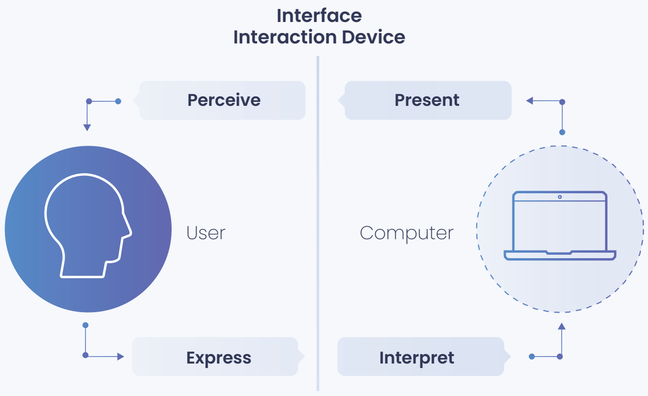

Figure 3: Human-Computer Interaction

The user's biological process begins with the brain sending an action potential indicating an intended movement. This signal travels down the spinal cord and activates the nervous system, which in turn triggers the appropriate muscle groups to execute such a movement. To issue digital commands, the user engages with an interface or device, which may include a keyboard, mouse, touchscreen, pointing device, gesture recognition system, or character device.

There exists a substantial difference of several orders of magnitude between the amount of information humans input and output. Input is gathered through various sensory channels such as visual, auditory, and proprioception, utilizing organs such as the eyes, ears, and hands. Conversely, the output generated by humans is slow and necessitates significant muscular activity to execute even rudimentary input commands.

The goal of a natural interface is to bridge this gap between human input and output to enable computer interaction that is both effortless and as natural and intuitive as real-life experience.

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[2] Norman, D. A, (1984) Stages and levels in human-machine interaction. Int. J. Man-Machine Studies (1984), 21, 365-375

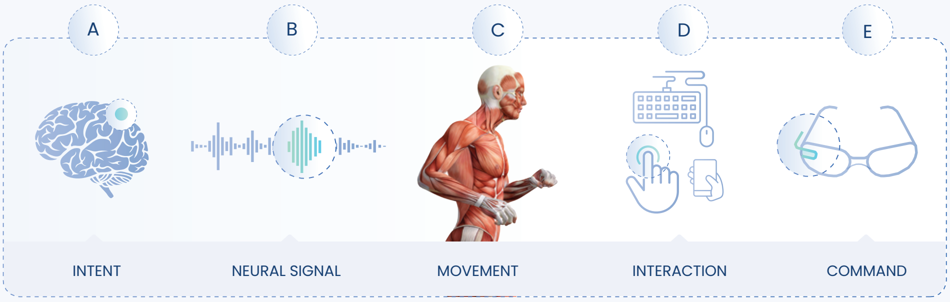

Figure 4: The command flow from intent to move to digital command

Currently, mechanical transducers like computer mice and touchpads are being used as input devices. During the interaction with these input devices, the human body typically activates fourteen muscles to control hand and finger movements.

The evolution of computers into wearable devices has opened up new possibilities for interaction design, resulting in the emergence of novel interaction techniques. To facilitate these new forms of interaction, it is crucial to develop new interfaces that are specifically designed to support them.

Typically, while using a personal computer, an individual tends to lean forward in contrast to interacting with a smartphone, where a more relaxed posture is adopted. Nevertheless, with augmented or virtual reality technology, spatial posture necessitates diverse interaction scenarios which typically require quick on-the-go gesture based commands.

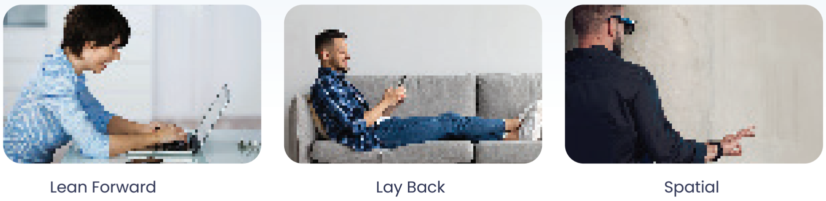
Lean Forward
Lay Back
Spatial

Figure 5: body postures when interacting with computers

When using current interfaces with novel computer devices, a user may encounter limitations that hinder the ability to optimize the user experience. Therefore, it is essential to re-evaluate how to interact with wearable computers, empowering such devices them to interpret human intentions instead of requiring the user to conform to their limitations. The process of translating natural movements into digital commands is hindered by handling a physical gadget.

A neural interface eliminates the need for mechanical transducers by utilizing the phenomena of ionic exchange between our body and a bio-potential sensor, resulting in a natural and intuitive user experience. This type of interface allows for instantaneous, hands-free, touchless, and immersive interactions. The development of novel compute devices devices leads to new forms of interaction, which, in turn, require the design of new interfaces that enable quicker control and offer completely new input methods.

New computers and related technologies will prioritize the user and place them back at the center of the interaction. Conventional methods adopted from previous compute devices introduce unproductive and needless constraints. experience, bringing back the human to the center of interaction.

GUI, UX and UI

A Human Interface Device (HID) is traditionally categorized as a pointing device or a character device, the former is used to input position, motion, and pressure, and the latter is used to input text. Finger tracking technology is utilized to track the position of fingers and hands, both for generating a 3D representation and for discrete input, and so do newer technologies, such as voice and computer vision based gesture recognition.

An analogy can be drawn between digital command input and car driving. Some interaction types require high cognitive load and precise physical movements, while other interactions can be performed while multi-tasking with low cognitive effort.

- In-line text editing requires precise and tight movements, which is similar to the way a driver must maneuver in a crowded parking lot. Both activities require a lean-forward posture and a great deal of focus to achieve the desired outcome.
- Browsing through icons is a relatively simple task that can be performed with ease, much like driving on urban roads. Both activities can be performed in a laid-back posture and with low cognitive load.
- Finally, selecting a large, highlighted icon using mid-air hand gestures is similar to highway driving, necessitating low cognitive load. In both cases, the movements are broader and more relaxed, allowing the user to navigate through space with intuitively and efficiency.

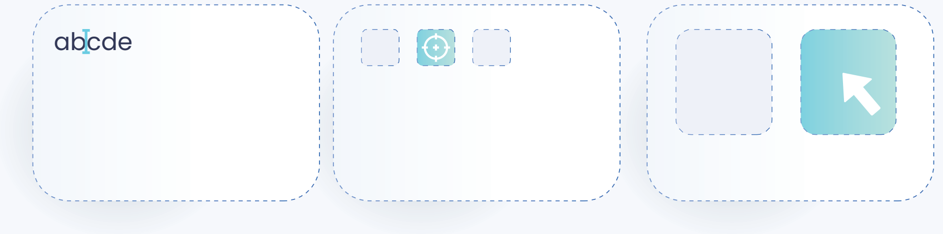

Figure 6: Types of interactions and their GUI characteristics

In this context, Fitts'-law ratios and numeric-value approximation are often used to quantify the cognitive demands of various motor HCI tasks, such as moving a mouse cursor to a target location or clicking on a specific button. A quantitative analysis of the Difficulty Index (ID) for the above scenarios where the Distance (D) is at the same value clearly emphasizes the analogy of cognitive load while leaning forward.

GUI design considerations for face-worn devices must address a natural spatial interaction posture. The GUI design should favor decreasing the cognitive load by providing simple, natural and intuitive input with a low Index of Difficulty.

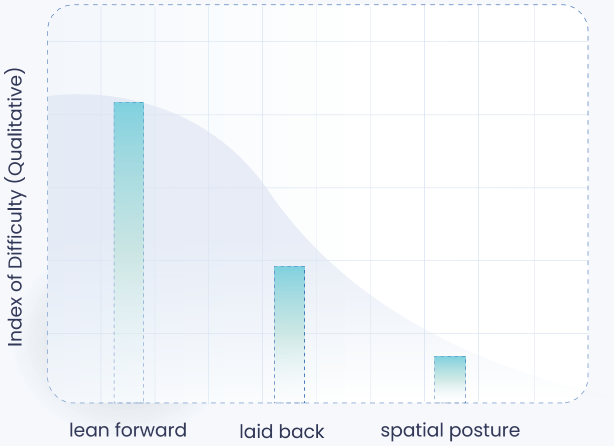

Figure 7: Qualitative evaluation of Index of Difficulty

Source: Wearable Devices Ltd.

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[3] Fitts, P. M. The information capacity of the human motor system in controlling the amplitude of movement, Journal of Experimental Psychology, 47(6), 381–391

HCI – NEW TAXONOMY FRAMEWORK

Human-Computer Interaction is viewed mainly through the prism of the Human Input Device and puts the interface type – be it a mouse, a touchscreen, or a keyboard – ahead of the user experience. We believe that the user-experience, and the user's needs and motivations should lead the discussion.

Neural input devices and Brain-Computer Interfaces (BCI) are still in the emerging development state and may not be mature enough to be standardized. System-level aspects of Brain-Machine Interface (BMI) such as user-needs and performance assessment are not yet the subject of established standards. We offer a framework for defining the scope of a neural input interface.

The framework describes and categorizes the interaction levels of users, based on the type of activity the user is performing. The user functionality includes navigating to a certain location; interacting with a digital element; and being aware of location, motion, direction, action and result.

We propose a simplified framework and taxonomy that defines the levels of interaction using four parameters: (i) Hand-held/Hands-free, (ii) Hands-on/Touchless, (iii) Big vs. small physical movements, and (iv) the time it takes to input the command and receive feedback. As seen in the table below, this creates six product categories covering the entire spectrum of neural input interfaces. We believe these definitions should serve engineers, product managers, designers, and customers – it should be clear to all stakeholders.

	HCI Level 0	**HCI Level 1**	**HCI Level 2**	**HCI Level 3**	**HCI Level 4**	**HCI Level 5**
What characterizes user interaction?	You use coarse palm, hand, and finger movements. You must physically hold or touch the device interface when you input commands.			You use subtle finger movement or non-visible muscle movement. The interaction is hands-free and touchless. You become the interface.		
	Your expression flow runs as follows: (a) movement intent through (b) Neural signal, (c) muscle movement, (d) Input interaction, and ends with digital command (e).			You use movement intent to command action through neural signals and subtle or no muscle movement.		Your movement intent immediately turns into command action.
	Touch and muscle-based interactions			Intent and neural-centered commands		
How does the user interact with the interface?	Keystrokes	* Point and click * Drag and drop	* Finger tap * Finger dragging	* mid-air gestures * Finger movement and fingertip pressure	Minute to non-detectable movements	Direct Brain to Device interaction
Device examples	* On/Off button * Switch / Toggle * Navigation arrow	* Computer mouse * Joystick * Game controller	* Touchpad * Touchscreen * Directional pad	* Wrist wearable * Gesture sensor	* Wearable * Invasive	* Wearable * Invasive

Figure 8: A new framework for neural-based interfaces
Source: Wearable Devices Ltd.

Performing a "slide to unlock" input command will be fulfilled by expressing the following states, as shown in figure 4: it starts with a movement intent that generates a neural signal that manifests in a muscle movement, followed by a physical interaction and than ends with the digital command. Only in a HCI Level 5 interaction does the movement intent immediately turn into a digital command. On all other levels the time it takes to perform input is the same regardless of physical movement size.

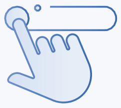

Figure 9: Slide to unlock gesture

Wearable, Touchless and Hands-Free are XR's MVP

Neural input is a promising market with significant potential for Extended Reality. Like any new market, it requires a clear definition of the Minimum Viable Product (MVP). Defining an MVP can reduce complexity of the functionality and form-factor, and emphasize the real value of the technology rather than generating inflated expectations.

As wearable computing becomes ubiquitous, users will be immersed in XR and the metaverse through a pair of face-worn devices that overlay digital data and holograms into a real-world view. Satisfactory interaction with these elements requires features such as point and click and drag and drop, which allow the user to input spatial commands into the device, in a discreet, natural and intuitive way.

While this input functionality simplifies the full potential of neural interfaces, it can be extended to interaction with additional devices beyond touch, such as Smart TV, a computer, a tablet and a mobile phone, indoors or outdoors. Switching and toggling between connected devices with a smooth handoff and transition from controlling one device to another is crucial for a seamless immersive user experience in extended realities and ambient computing.

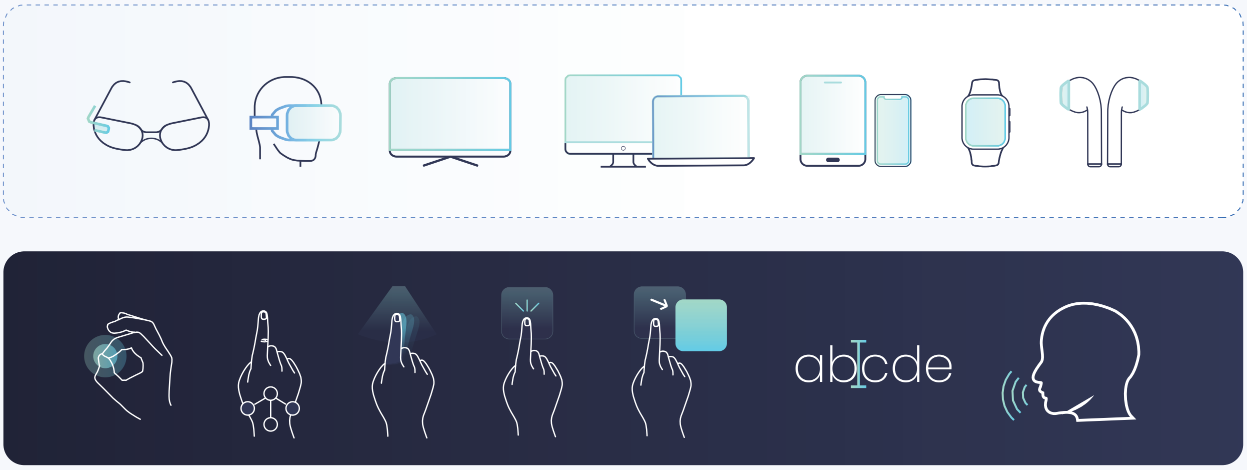

Figure 10 : Device types and interaction methods

In section 3, we discuss **sensor fusion** and compare keyboard, gaming controller, gesture camera, bio-potential sensors, and surface nerve conductance. In section 4, we elaborate on **balancing functionality, accuracy and device form factor,** and emphasize the interdependency of hardware, software and humanware. In section 5, we discuss **neural interface specification** for the sensor, the system and the product. In section 6, we present the **Mudra Band** neural input product, which is based on insights gathered from testing thousands of users wearing our Mudra neural input technology. In section 7, we preview how **SNC signals** can be utilized in multiple additional industries and use-cases.

SENSOR FUSION

Decoding the hand and finger intent movement requires sensor fusion. We need sensors that know what the movement of the fingers are, what the movement of the wrist is, and what the absolute true position of the hand is in relation to the body. Decoding the user's movement and intent depends on the correct sensors because each sensor has advantages and disadvantages.

As the accuracy and functionality capabilities of the multi-capacitive touch sensor grew, it gradually became ubiquitous and replaced the traditional physical keyboard and mouse. Gesture recognition sensors and wearables are now common input methods for gaming consoles and smart glasses. Sensing technologies for Human-Computer Interactions have progressed from remote punch cards to hand-held devices and nowadays wearable input methods are common.

The pace of technological advancements has always been dictated by user interfaces.

An input device consists of a sensor and a signal condition unit to create a transducer. The transducer converts a physical quantity into a digital electrical quantity, which can be used to input commands. The input device may be static, dynamic, or worn on the body.

Any sensor that reacts to a physical phenomenon can be used for input. In this context, sensors can be classified as external or internal. External sensors measure non-electrical quantities such as force, movement, pressure, and torque. External sensor examples include a mouse, keyboard, and touchpad.

Internal sensors measure electrical signals such as resistance, capacity, photonics, ionization, and magnetism. These signals can originate in the user as bio-potentials, or in the user surroundings. Internal sensor examples are EMG, EEG, PPG, and SNC.

Because all sensor types have limitations, sensor fusion improves the probability that there will always be a sensor that performs well in any given situation. Each sensor must work independently without any interaction between them. Thus, correct decisions always will be made, regardless of user physiology or scenario conditions that are challenging for a certain sensor type.

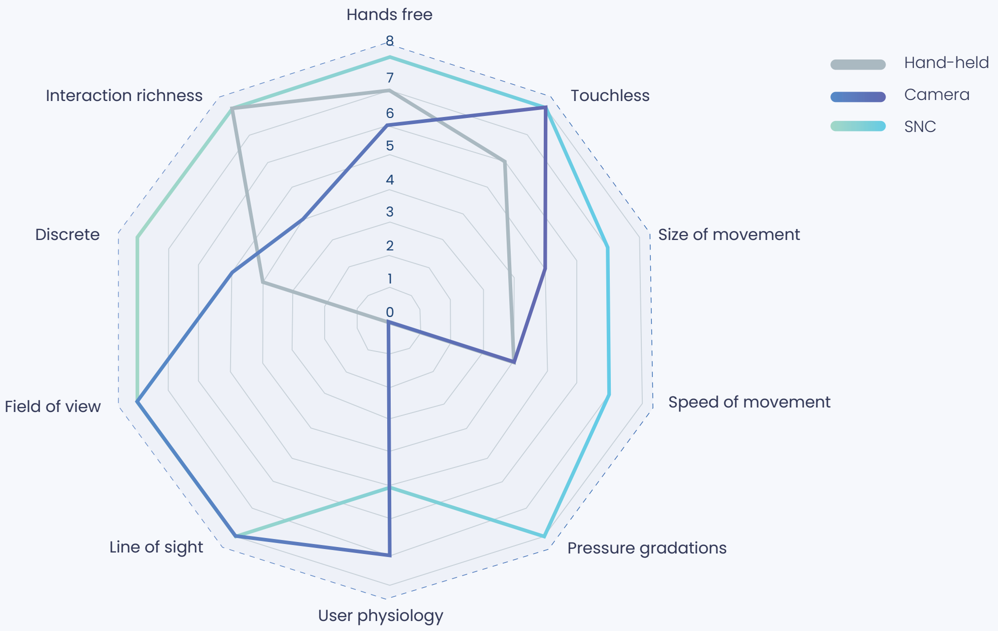

Figure 11: Hand held, Camera, and SNC interface performance across different dimensions

Source: Wearable Devices Ltd.

Keyboard and Mouse

The keyboard is a static input device that uses external sensors to detect the pressing of keys. It is advantageous for typing text and entering numerical data. However, it has limited functionality when it comes to gesture recognition and other forms of input.

The mouse is a dynamic input device that uses external sensors to detect movement and click actions. It is advantageous for precise cursor control and graphical user interface interactions. However, it requires a flat surface to operate and has limited functionality when it comes to gesture recognition. Both input devices require a static physical surface, limiting the user's mobility, thus making them less suitable for compact or portable devices and mobile interactions.

Touchpad and Touchscreen

Touchpads are dynamic input devices to detect finger movement and gestures. They are commonly used in laptops and other portable devices. They offer a compact and intuitive interface for cursor control and gesture recognition. However, they can be less precise than a mouse an have limited functionality when it comes to inputting text or numerical data.

Touchscreen is a display technology that enables direct interaction touching or tapping on the screen. Using multitouch gestures and swipe actions, touchscreens enhance speed and efficiency. However, they lack tactile feedback and can lead to accidental taps. Prolonged usage may cause physical strain, and screen visibility can be affected by fingerprints.

Gaming Controller

Gaming controllers are specialized input devices designed for gaming consoles. They typically use a combination of external and internal sensors to detect button presses, joystick movement, and orientation. They offer a wide range of input options and are advantageous for gaming. However, they can be complex to use and require a learning curve.

Gesture Camera

Gesture cameras use internal sensors, such as infrared sensors and cameras, to track hand and body movements and recognize gestures. They offer a hands-free interaction for controlling and interacting. They offer a more natural interface for users and are accurate in recognizing movements. However, they require a clear line-of-sight and can be affected by lighting or temperature conditions, or physical obstructions. They also operate on a limited field-of-view, and users may need to learn specific gestures to use them effectively. They require fairly expensive hardware, development costs and increase the form factor if integrated on a wearable device, with high battery consumption and compute resources.

Voice

Voice activation offers a hands-free and eyes-free interface for controlling devices and can be useful in situations where hands are occupied or when visual attention is required.. However, it can be affected by ambient noise or accents, users may need to learn specific voice commands to use it effectively, and it is not discreet and draws attention to the user in public spaces.

Bio-Potential Sensors

Some examples of internal sensors used in wearables are EEG, EMG, PPG, and SNC sensors.
EEG (Electroencephalography) sensors measure electrical activity from the brain. EEG sensors can be used to detect and interpret brain-wave patterns, which can be used as input signals for controlling devices or interacting with virtual environments. The advantages of EEG sensors are that they can be highly accurate in recognizing brain activity. However, they require a high level of expertise to interpret the signals, and they can be affected by external noise.
EMG (electromyography) sensors measure electrical activity in the muscles. EMG sensors can be used to detect muscle movements and gestures, which can be used as input signals for controlling devices.

They offer a natural and intuitive interface for users, and they can be highly accurate in recognizing muscle activity. However, they can be affected by external noise, which can interfere with the accuracy of the signals they measure. Additionally, interpreting EMG signals requires a high level of expertise, which can make them difficult for non-experts to use. Finally, EMG sensors require users to wear sensors on their skin, which may be uncomfortable for some and limit their use in certain applications.

PPG (photoplethysmography) measures blood volume changes via reflected light. The advantages of PPG sensors are that they are non-invasive and can provide real-time monitoring of physiological signals. However, PPG sensors can be affected by external factors such as temperature and humidity, which can lead to inaccurate measurements. Additionally, they may require calibration to ensure accurate readings, and their accuracy can be affected by certain medical conditions.

Surface Nerve Conductance

SNC (Surface Nerve Conductance) sensors react to ions, via the process of ionic exchange and react to innervation picked up mostly by wrist movements. The advantages of this sensor type are that they offer a non-invasive and convenient way to track physiological signals, they can measure pressure gradations, and they can be highly accurate in detecting changes in the body. However, various sources of noise can affect the accuracy of SNC such as humidity and sweat, they may require calibration to ensure accurate measurements, and they may also require constant physical contact with the skin.

SNC and IMU Sensors Fusion

Consider an example of a “swipe left” gesture; it starts with a slight tap of the index finger on the thumb and then keeping fingertip pressure while moving the wrist to the left, thus dragging a icon from the right to the left and releasing the fingertip pressure at the end of the hand motion. Figure 12 below shows the signals obtained by three SNC sensors (top graph) and IMU accelerometers (bottom graph). To verify the true physical contact of the index with the thumb, a physical conductive fabric is worn on the tips of each finger as ground truth (the dashed line).

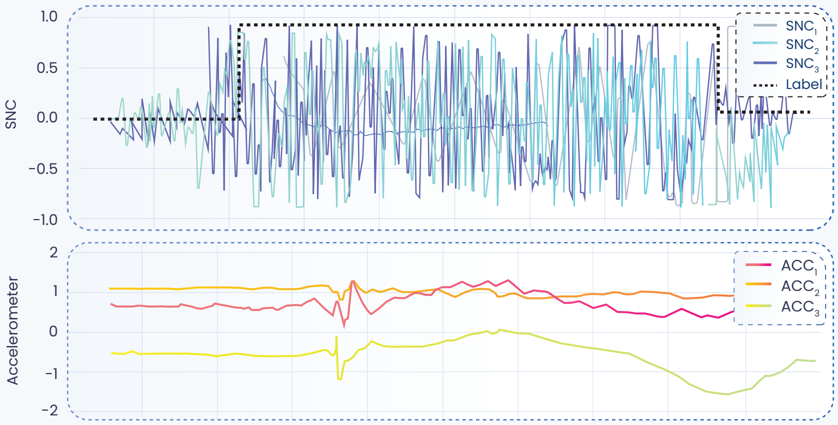

Figure 12: SNC and IMU signals for a swipe left gesture

The SNC sensor properties are characterized by a noisy yet swift response. The sensor array reacts to pressure before physical contact between the two fingers is registered. However, SNR (signal-noise ratio) is low in all electrodes; there is white contact noise in the electrode of SNC1 sensor as it is slightly detached from the skin. SNC signals are responsive, yet noisy.

IMU acceleration has inverse properties. While IMU sensor response exhibits higher latency, its SNR is higher. At around ~1900ms a high frequency component is indicative of the tap, while low frequency components are indicative of a dragging motion. Also, hand motion continues following the release of the fingertip pressure, decelerating more slowly.

We would like to exploit the strengths of such sensors and therefore we need sensor fusion to extract all the information available for the highest possible accuracy and reach.

BALANCING FUNCTIONALITY, ACCURACY AND DESIGN

When developing a wearable neural interface, there is always a tradeoff between functionality, accuracy, and design:

- Functionality – determining the scope of features and capabilities and the input types it offers
- Accuracy – an input method that is reliable and provides high accuracy of the intended functionality for all types of user physiology
- Design – a wearable interface that is comfortable, durable, stylish, and fits a user's daily routine

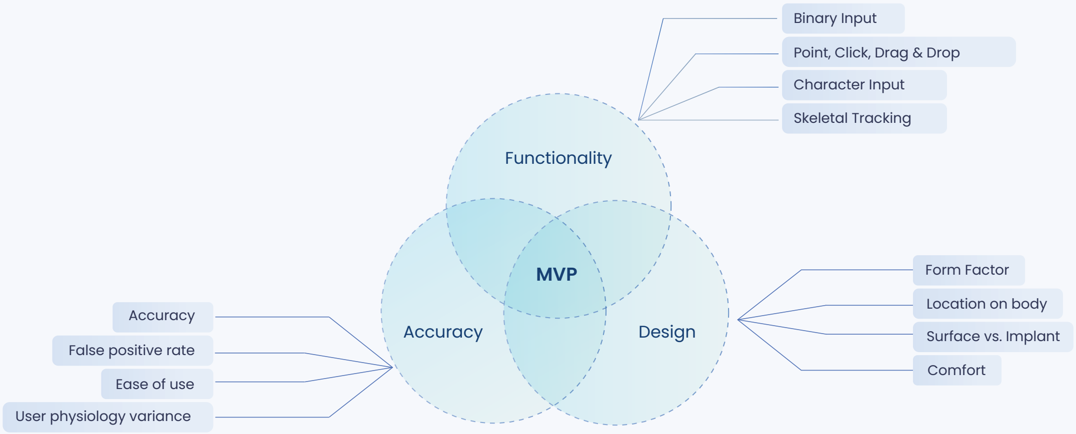

Figure 13: Functionality, accuracy, and design scope

Hundreds of trade-offs need to be balanced with multiple contradicting features: weight, size, materials, ergonomics, and user experience must be balanced with type and number of gestures, ease of interactions, suitability to multiple user physiologies, and more.

To create a successful consumer-level neural interface product, it is crucial to take a systemic approach that considers all the different components of the product. This includes the sensors, which are responsible for detecting and recording neural signal activity, the algorithm system that interprets this data and translates it into meaningful feedback for the user, and the hardware that enables the device to function and be worn comfortably.

Careful selection, design, and integration of the sensors, system algorithm, and hardware is critical for creating a device that is both effective and user-friendly. Ultimately, the success of the device will depend on its ability to accurately detect and interpret neural activity and provide meaningful feedback that enhances the user's experience.

A System-Engineering Approach

A neural input device specification must first address three fundamental aspects:
the user, the wearable product, and the interfacing area between the user and the product. The technologies used can be categorized into three levels – hardware, software, and humanware, which is the method of adding a human facet into the development of hardware and software.

Within these categories exist six layers with very high interdependency between each layer to adjacent layers and developing similar solutions requires expertise in each individual layer.

- **Hardware** device consists of band design, form factor, and materials. Interfacing hardware includes electrode geometry, material, and arrangement. The sensor is mounted on a miniaturized flex-rigid dynamic PCB with electronic components
- **Software** cross-platform software engine; artificial intelligence learning algorithms; the algorithm runs on low computer power wearables and digital devices with limited CPU and memory
- **Humanware** and user experience – hand and finger movements, the functions that bind to these interactions, and the way the user performs them

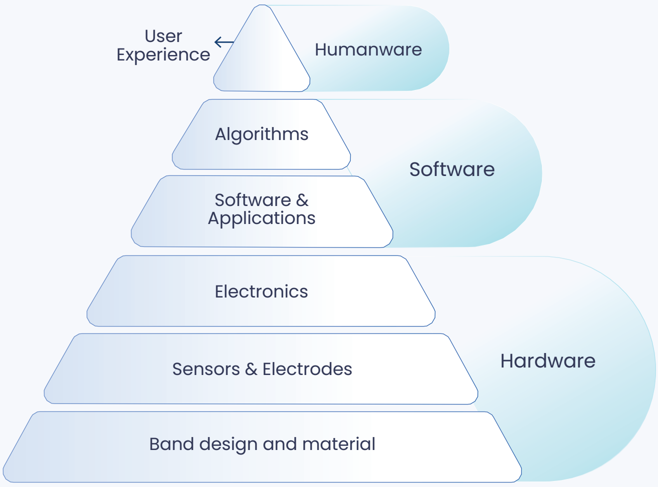

Figure 14: Vertically integrated platform

The hardware and software must emphasize natural, intuitive, easy-to-use user experience and user interface humanware. The design process must be approached from a bottom-up perspective, starting with the user experience. By starting with these aspects, the design process can focus on creating a product that is both functional and user-friendly.
Factors such as the size and shape of the device, the materials used in its construction, and the way in which the user interacts with it must be considered. This approach ensures that the device not only meets the user's needs but also exceeds their expectations in terms of comfort, usability, and overall satisfaction.

Device location on the body

The wristband’s electrodes are placed on the inner wrist area. This location allows for a convenient and accessible source for capturing and interpreting neural signals, which can then be used to control various devices and systems. Furthermore, it can be connected to a smartwatch easily and does not interfere with existing sensors on the caseback of the watch.

Fashionable

A wristband form-factor is both functional and fashionable. It supports multiple stylish designs to make it an attractive accessory.

Comfortable

The wristband is made of soft and flexible bio-compatible materials that ensure a comfortable fit for extended all-day wear.

Surface vs. Implant Device

Unlike some other neural input devices that require invasive implantation procedures, a neural input wearable is a surface-level device. This means that it does not require any surgical procedures, making it a safer and far-more accessible option for the mass consumer market. Additionally, a surface-level design can be easily removed and replaced if needed.

For a neural input device specifically, such as those used to control prosthetics or assistive technologies, there are some additional pros and cons to consider for wearables vs. implants:

Wearables:

Pros:

- Non-invasive, meaning they do not require surgery or implantation into the body
- Can be easily removed or replaced if needed
- Generally, less expensive than implants

Cons:

- Limited in their ability to detect neural signals with high precision and accuracy
- May be subject to interference from external factors, such as movement or electromagnetic fields
- Limited in terms of the types of signals they can detect and interpret

Implants:

Pros:

- Able to detect neural signals with high precision and accuracy
- Not subject to interference from external factors
- Can provide a more permanent and reliable neural input

Cons:

- Invasive, requiring surgery or implantation into the body
- May pose risks such as infection, rejection, or damage to surrounding tissue
- Expensive

NEURAL INTERFACE – SPECIFICATION GUIDELINES

Successful commercialization of a deep technology neural interface requires a delicate balance of three essential components: cutting-edge sensors, advanced processing systems, and user-friendly products.

Achieving this balance is crucial, and it depends on ensuring that these components work seamlessly together. The sensor's responsibility is to collect valuable data, which is then processed by the system to create actionable insights. The product integrates the sensor and processing system, enabling a smooth and intuitive user experience. Neglecting any of these components can lead to a suboptimal product and a less-than-optimal user experience. Therefore, it's vital to ensure that each component meets the necessary specifications and is seamlessly integrated with the others.

Sensor specification parameters are relatively straightforward and are well established. The sensor is connected to an electrode touching the skin surface area and needs to provide high SNR and a wide dynamic range. The SNR directly affects the ability to correctly decipher the neural signal pattern and correlate it with intent.

Sensor specification parameters[4]:

- Input-referred noise – should be as low as possible
- Dynamic Range (DNR)– should be wide enough to work on a large user population
- Input Impedance – should be high
- Common-mode rejection ratio (CMRR) – should have high linearity
- Power-supply rejection ratio (PSRR) – only relevant for regulated power supplies

System specification parameters:

- Reach: Determines the effective user base that the device works properly straight out of the box, based on component quality, sensor accuracy, and user physiology
- Accuracy: Reflects the ability to recognize and interpret user inputs, accounting for intra-class and inter-class variability
- Latency: Measures the delay between user input and device response, including algorithm processing and transmission time, important for high-precision tasks
- MAC: Represents the computing power required for neural network algorithms, measured in Multiply and Accumulate (MAC) operations, essential for evaluating the feasibility of wearable devices with limited computing power

Product specification parameters:

- Number of electrodes: affected by the number of source signals and the available body surface area
- Band dimensions: need to be acceptable and common with available market products, whether as an after-market product or if integrating certain aspects of the technology into an existing watch band

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[4] Zhang, M., Tang, Z., Liu, X. et al. Electronic neural interfaces. Nat Electron 3, 191–200 (2020)

Reach

Reach can be defined as the number of users to which the interface will effectively provide the promised functionality. High reach is essential for the product to work right out of the box for a large proportion of the users. Reach should support a large variety of user wrist sizes and user physiologies. Reach should enable signal detection in an electrode detachment scenario, in which the electrode becomes intermittently unattached from the wrist skin area. The minimum reach is 90%.

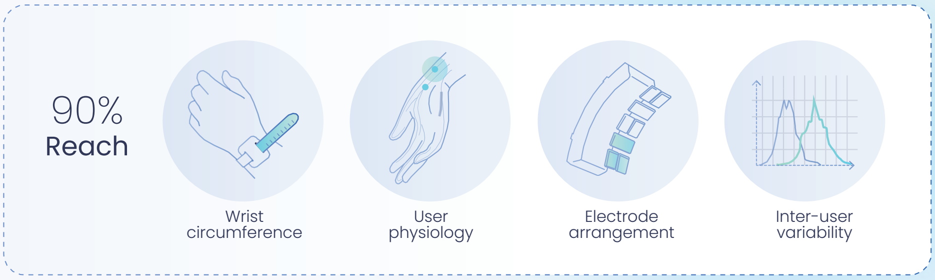

Figure 15: Reach design considerations

The percentage of users who can successfully operate the device functionality will depend on various factors, such as wrist size, wrist and hand physiology, and the electrode design arrangement, which determine whether the electrodes keep a constant snug fit with the wrist skin area when the user performs a finger movement. The electrodes are fixed but user-physiologies are unique, and the sensors end up in unpredictable configurations. In general, the success rate of any wearable input interface will vary from one user to another.

Human skin impedance, muscle structure, and wrist size will all affect the bio-potential sensor signal pattern. If and when an electrode is detached from the skin when the user preforms a certain finger movement, the signal pattern will look different from the normal expected signal pattern, thus affecting the prediction of the system.

In Figure 16, the bottom segment depicts a scenario in which the electrodes of sensors Snc2 and Snc3 detach from the skin. The actual pressure measurement at the fingertip (black-color line) differs from the algorithmic prediction of the system (yellow-color line), as seen on the top of Figure 16.

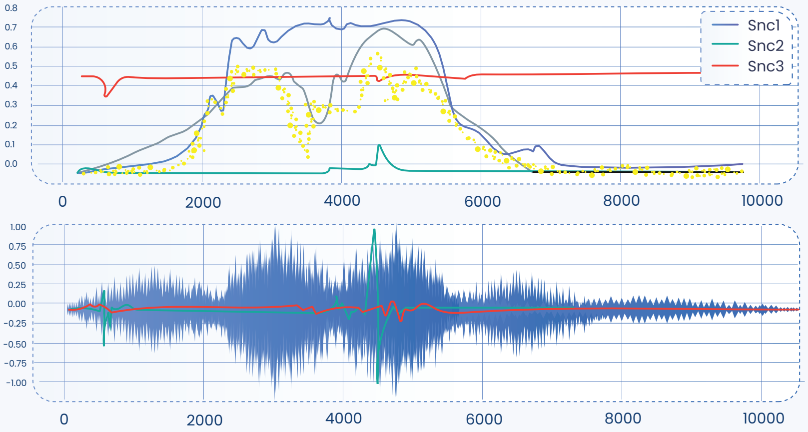

Figure 16: Actual finger movement (black line) vs. system prediction (yellow line)

The challenge of using neural information as input to a classification algorithm differs from vision-based classification methods, which are more common in deep learning. A neural-signal based classifier cannot accurately describe all users without adaptation.

Figure 17 shows a distribution of accuracy without calibration procedures. Accuracy will vary across different users. Most will be able to effectively control a neural input interface, but not all.

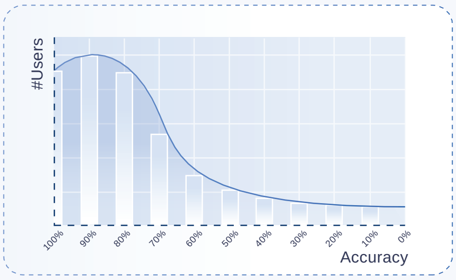

Figure 17: Accuracy will vary across different users (illustration)

Besides the detachment challenge, there exists the challenge of inter user-variability. In the extreme case, a user may have a completely opposite signal pattern signatures (for example, a thumb movement may look like an index finger movement of a different user), which is also known as **contradicting reactions.**

To overcome such challenges, a calibration algorithm procedure can be introduced. The user provides a small sample set of each relevant gesture. Using this data, a classifier algorithm “tunes” the neural network weights to the specific user physiology.

Achieving high reach requires an arrangement of hardware design and algorithm architecture for the defined functionality. Reach for a neural input wristband should be at least 90% of the designated intended user base.

Accuracy

Accuracy reflects the ability to recognize and interpret user inputs, that is to correctly classify a user’s finger movement with the correlating signal pattern and the intended gesture. The algorithms should account for intra-class and inter-class variability. If random or constant false positive are above the acceptable error rate, the user will not trust the interface, and usage and adoption will decrease accordingly.

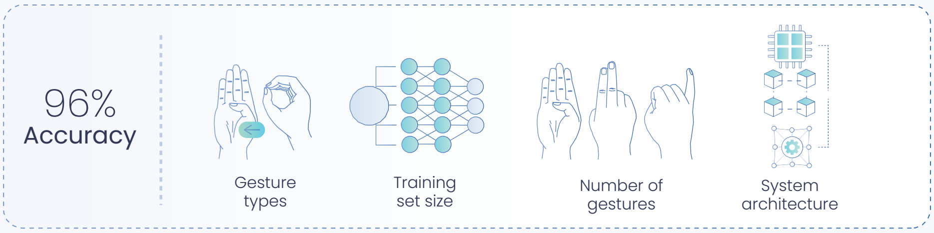

Figure 18: Accuracy considerations

A simplistic definition of accuracy does not suffice to explain a typical usage scenario of a neural interface. For example, if a certain intended or non-intended finger movement, e.g. “pinky tap”, always triggers a false positive (FP), a user will tend to “mistrust” such a classifier. Even if such movement occurs rarely, the user will not trust the interface’s accuracy for executing a command. Another accuracy challenge is correctly classifying an intended finger movement with the signal pattern it generates, i.e., a user performs a” tap”, and the algorithm correctly classifies it as the intended gesture.

There are two different sources of statistical variability which affect the overall accuracy. The first is **intra-class variability** inherent in a specific gesture, which can be described as “how many different ways the system maps a specific user gesture?”

The second aspect is **inter-class variability,** which can be described as the effective choice of a set of gestures that “sufficiently differ” from one another (i.e. each gesture has some unique pattern). This implies that such a gesture set forms a unique mapped space, and each gesture is easily distinguished from another. False positives may not necessarily form a “cluster”, as noise presents many different “signatures” and will dominate most of the feature space, as seen in Figure 19.

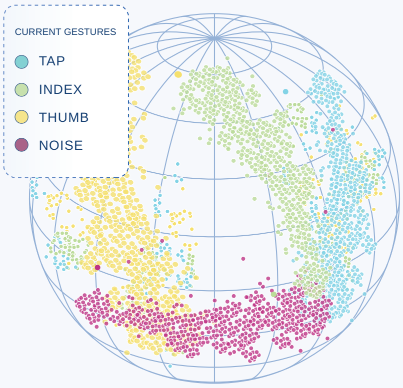

Figure 19: User-gesture variability mapping (illustration)

To address inter-class variability, a set of gestures are performed and composed of a labeled database (each gesture is recorded alongside its conditions, for example in a seated position). In Figure 20(I) multiple users' samples for two gestures are illustrated by a square and a circle. The feature space dimensions are not separated enough for high classification accuracy. (II) illustrates the same gestures for a specific user after applying a fast adaptation algorithm. (III) illustrates noise, or FP, as the red triangle, which may occupy at any point in the feature space.

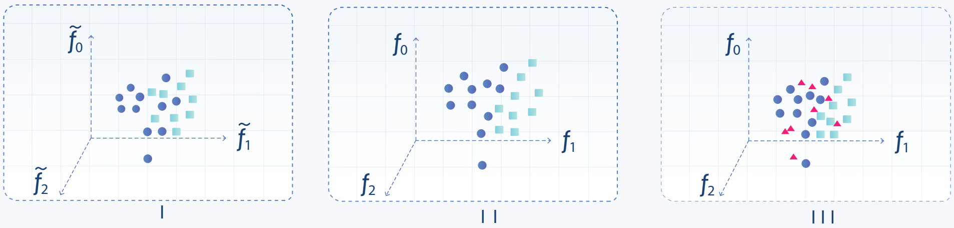

Figure 20: Inter-class variability mapped to various dimensions

A mapping algorithm, embedding from the sensor space to a low dimensional feature space, which satisfies the above conditions can be formed effectively by specific neural network architectures. A gesture set must be "sufficiently separable", which implies a cross-user accuracy of over 96%.

While a typical usage scenario may last only a few minutes, users expect a very low false positive rate of FP_Rate<0.5 per hour, on average. Above all, the gesture set needs to be natural and intuitive for the user to perform.

Achieving high accuracy requires an algorithm architecture approach which takes into account intra-class variability, inter-class variability, false positives, and motion artifacts, for natural and intuitive gestures. Accuracy for a neural input wristband should be at least 96% for a user within the designated user base.

Latency

Latency is defined as a delay, or the elapsed time after a digital command is performed following a user input gesture. It is essentially the time the device takes to execute a command. High latency causes time delay which makes the command lag after the input, causing low interface response. Generally, an acceptable latency is anywhere around 40 – 60 milliseconds. Acceptable latency for touch-based interfaces is typically 50ms.[5]
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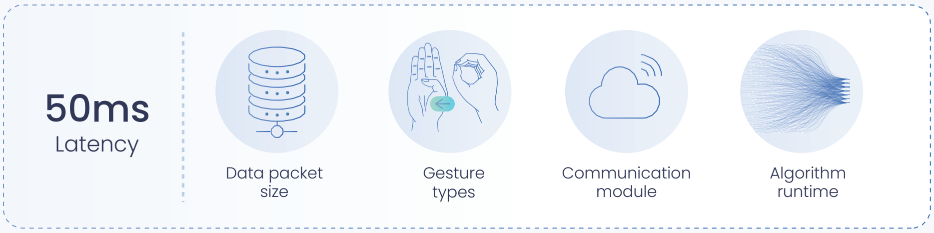

Figure 21: Latency considerations

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[5] Albert Ng, Julian Lepinski, et al, Designing for low-latency direct-touch input, UIST: Proceedings of the 25th annual ACM symposium on User interface software and technology, Pages 453-464, 2012

Latency time includes both algorithm-induced latency and transmission time to send a data packet from the interface to a digital device. Some tasks are more sensitive to high latency than others. For example, drag-and-drop input - which is a continuous gesture that takes longer than a discrete "tap" gesture - will be sensitive to high latency. Data packet size is determined by the number of sensors and the sensor sampling rate. Transmission time is determined by the communication module and its bandwidth.

Additionally, certain algorithm classes, typically those which utilize a form of "memory" or use a series of measurements observed over time (e.g. Kalman filters), inherently react slower to certain inputs than others. These types of algorithms may be essential for providing high accuracy.

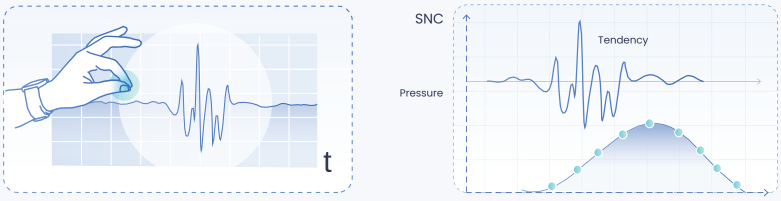

Figure 22: Latency for a continuous interaction

For continuous type interactions, the use of an external sensor is needed for gathering user sample data and for denoting the times a user presses fingers together. These external sensor readings provide the data label as a ground truth. Using such a custom dataset allows for quick and effective "pixel-perfect" acquisition (highly accurate segmentation without too much label noise).

Continuous gestures also pose a difficulty for training convolutional neural networks. Certain movements may go on indefinitely, thus the use of fixed window size is not efficient (for example, using a convnet for detecting a car when only a small part of the car is provided). More effective aggregation of data, such as using RNNs with back propagation in time to learn user operation such as drag & drop can minimize such latency using optimization.

An interface should have low latency. Since computation and memory bandwidth are constrained in low-power computing devices, care must be used while designing the system to meet user expectations, accounting for both discrete and continuous gestures. Latency for input device should be below 50msec to ensure high responsiveness, precision, and intuitive interaction.

MAC

MAC is a number denoting the total amount of Multiply and Accumulate operations. It provides a metric for evaluating processing and memory requirement of an algorithm. The higher the MAC is, the more processing power is required from the compute unit. It is important to perform major parts of the computations on the interface devices itself for minimal response time and for saving bandwidth.

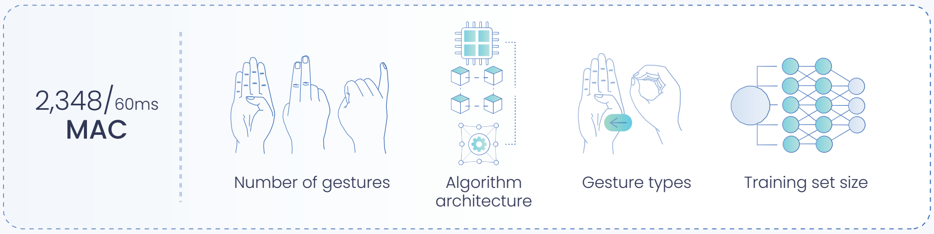

Figure 23: MAC considerations

Wearables with System-on-a-chip (SoC) face CPU limitations. The sensor sampling rate and algorithm architecture determine the total MAC operations per second. MAC requirements can vary greatly based on sensor type and sampling rates, ranging from a few units to significant differences. We will use a 60-millisecond time frame for the MAC figure value. The MAC metric helps to evaluate the suitability of a computational graph for a neural input method. MAC is calculated as the sum of weighted computations involving input samples and weights derived from supervised learning optimization methods (neural net). It encompasses memory extraction and mathematical computations on the input.

Neural networks and computational graphs present dual challenges: compute time on CPU/GPU/NPU and memory usage. These resources are highly restricted in low-power wearables, where edge devices handle computing and local processing of packet data instead of relying on remote servers.

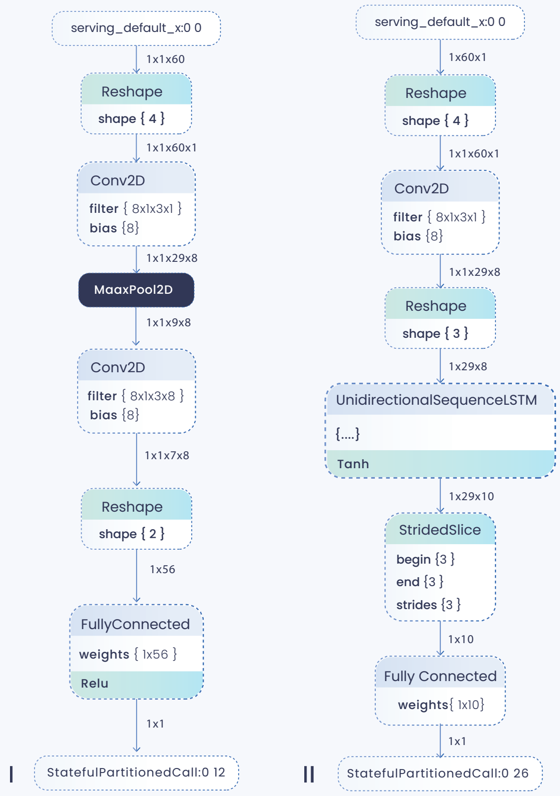

Figure 24:
Two possible architectures for neural networks

IFigure 24, (I) depicts a a 3-layer convolutional neural net, 2 conv layer, with 1 fully connected layer which has a total of 2,348 MAC operations per 60ms. (II) depicts a 3-layer neural net with convolution, LSTM and a fully connected layer with a total of 822 MAC operations per 60ms of sensor data.

As reference, the tables in Figure 25 summarize the number of parameters (Params), multiply and accumulate operations[6](Madd), for modern computer vision-based classifiers.

Network	mAP	Params	MAdd	CPU
SSD300[34]	23.2	36.1M	35.2B	-
SSD512[34]	26.8	36.1M	99.5B	-
YOLOV2[35]	21.6	50.1M	17.5B	-
MNet V1 + SSDLite	22.2	5.1M	1.3B	270ms
MNet V2 + SSDLite	22.2	4.3M	0.8B	200ms

Network	Top 1	Params	MAdd	CPU
MobileNetV1	70.6	4.2M	575M	113ms
ShuffleNet (1.5)	71.5	3.4M	292M	
ShuffleNet (x2)	73.7	5.4M	524M	
NasNet-A	74.0	5.3M	564M	183ms
MobileNetV2	72.0	3.4M	300M	75ms
MobileNetV2 (1.4)	74.7	6.9M	585M	143ms

Figure 25: Compute timetable for vision-based classifiers

We show that typical neural nets designed for computer vision are orders of magnitude more computationally expensive than sensor based AI. Multiply and Accumulate operations (MAC, MAD) are "bottom line" metrics for resource-constrained classifiers and regressors, especially for fixed point signal processing. Since both CPU usage and memory bandwidth are limited in low-power wearables, this metric is useful when evaluating the viability of a computational architecture to be used for neural input.

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[6] Sandler, M., Howard, A., Zhu, M., Zhmoginov, A., & Chen, L. C. "MobileNetV2: Inverted Residuals and Linear Bottlenecks." Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition (CVPR), 2018, 4510-4520.

Number of Electrodes

Spatial resolution is crucial in discerning the origins of different signals, especially in a wrist-worn neural interface where distinguishing between the ulnar, median, and radial nerve bundles innervation is important. Insufficient spatial resolution, resulting from a limited number of sensors, hinders the accurate classification of subtle finger movements. Too many electrodes require larger skin area causing the device to be worn above the wrist.

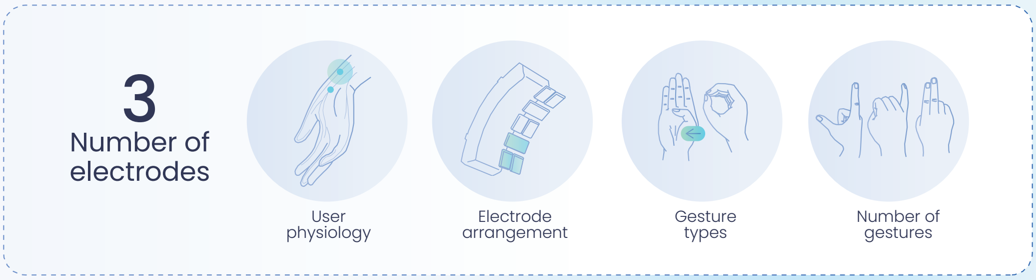

Figure 26: Number of electrodes considerations

While employing a greater number of electrodes may increase the ability to capture muscle signals from the forearm, it could lead to user discomfort during prolonged wear and may discourage user adoption due to unappealing aesthetics. It's worth noting that appearance plays a significant role in user acceptance and satisfaction, especially for wearables. Looks sell.

Unique causes of noise in biopotential sensors include motion and friction artifacts, 50/60Hz power line interference, as well as general electronic noise and other sources of variability. An effective and straightforward approach to mitigate noise is to design a larger surface area electrode. A larger electrode integrates a greater area of signal sources, enhances skin contact, and ultimately improves signal quality.

Two sensors are the minimum for spatial resolution to differentiate noise from finger innervation, especially when the sensor disconnects from the skin. In this condition, one sensor may be in contact with the skin while the other is not, allowing for skin contact conditions to be considered for classification. Two sensors are required for such an application. Three sensors can add to a higher reach, but at the cost of design complexity.

Another key consideration in differential amplification, particularly in differential biopotential sensors, is the common mode interference, such as the noise produced from power-line interference. A common and effective solution is adding a Driven Right Leg (DRL) mechanism to the sensor.

Figure 27: Electrode configuration to support differentiation

There are many more sensor-electrode design considerations, such as electrode materials , inter-electrode distance, and electrode properties. Electrodes touch the user skin and determine the number of signal sources the device will capture; thus the electrode-count and design are of major importance to designing a comfortable and functional wearable interface.

Three electrodes should be sufficient to provide tap, and drag & drop functionality even when an electrode detaches from the skin, and it provides a high accuracy discrete gesture classifier for four gestures, enabling two direction navigation, selection, and back functions.

Wristband Geometry

The dimensions and geometry of the band should closely resemble those of a typical watch strap or wristband wearable. It should be designed to accommodate various hand and wrist movements without causing any discomfort. The band dimensions should not exceed 8mm in thickness and 20mm in width to maintain a sleek and comfortable profile.

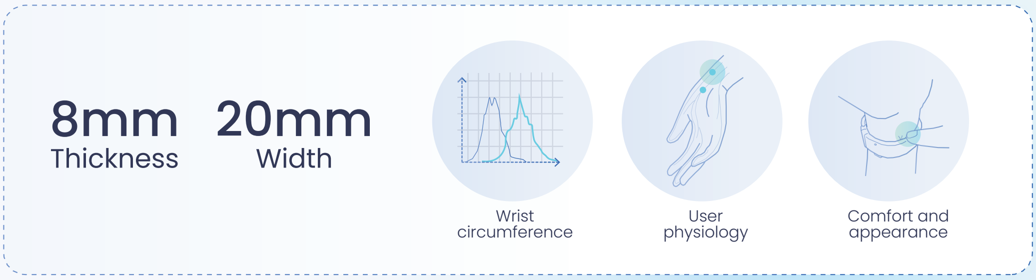

Figure 28: . Wristband geometry considerations

The wrist form factor offers greater comfort and convenience since the wrist is a natural and familiar location for wearing devices. It is more socially acceptable and aesthetically appealing as it resembles a traditional watch band. It can be compatible with existing watches or wristbands, making a watch band attachment a natural extension for wearable accessories and providing improved sensor placement close to the skin surface without interfering with other sensors. It may also provide more accurate and reliable readings of biopotential signals from subtle finger movements.

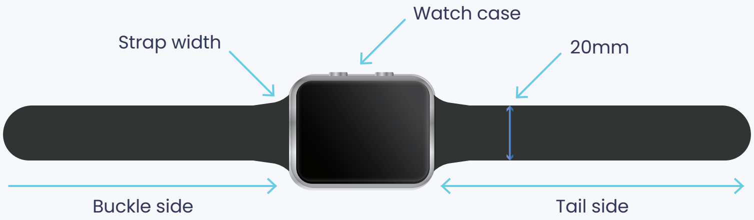

Figure 29: Typical watch strap geometry

A band's geometry is typically designed using the form-follows-function design philosophy. This approach involves considering common usage scenarios, such as laying the wrist on a surface while. The material used for the band should possess key attributes such as flexibility, durability, and biocompatibility.

Integrating flexible electronics into the band poses considerable practical challenges. A bracelet that is bendable, malleable, durable, and biocompatible is still an active field of research. With respect to practical design considerations of band geometry, different kinds of physical stress exist.

Consider the challenge of bending and elongation. Each incurs different stress conditions on the band. When a band contains both rigid and flexible electronics it is susceptible to several types of physical stress. For example, elongation may incur high stress on the flex-rigid connectivity. In general, the design is limited to a certain radius of flexion.

Adequate protection is necessary to safeguard the electronics from physical damage and moisture. One such solution is to over-mold the band thus covering the electronics with silicon-type materials which adds to band thickness.

Another design consideration of band geometry is for integrating aspects of the technology into an existing smart watch band. Some components may be redundant which may lead to new PCB layout, and new functionality requirements, band dimensions, and power and communication connections may necessitate new algorithms and mechanical design. Keeping band geometry dimensioning as ubiquitous as possible requires high interdependency of design in the hardware, software and functionality.

MUDRA BAND – SIMPLY CONTROL EVERYTHING

Mudra Band for Apple Watch

Mudra Band, an aftermarket wearable, enables users to operate products across Apple's entire ecosystem using intuitive and subtle finger movements and gestures without the need for physical touch.

The Mudra Band's Air-Touch functionality supports point and click and drag and drop functionality. It seamlessly switches between connected devices like iPhone, iPad, Mac computer, and Apple TV, smart glasses, and various mobile gaming devices.

The Mudra Band functionality continues to be extensively tested and approved by a global community of thousands of Apple enthusiasts.

The Mudra technology offers an AI-powered touchless sensing wearable for any Bluetooth connected device and operating system.

Mudra technology gestures can be tailored per specific use-case; it was designed first-hand for easy integration of hardware and software modules into existing wrist wearables, smartwatches, AR glasses, VR headsets, and connected electronic devices.

Mudra technology supports the use of discrete gestures, continuous gestures, and air-touch gestures:

- Discrete gestures. Moving a single finger or softly tapping the finger or thumb.
- Continuous gestures. Applying various gradations of fingertip pressure to manipulate digital objects.
- Air-touch gestures. Combining discrete and continuous gestures with hand and forearm movements such as "slide-to-unlock".

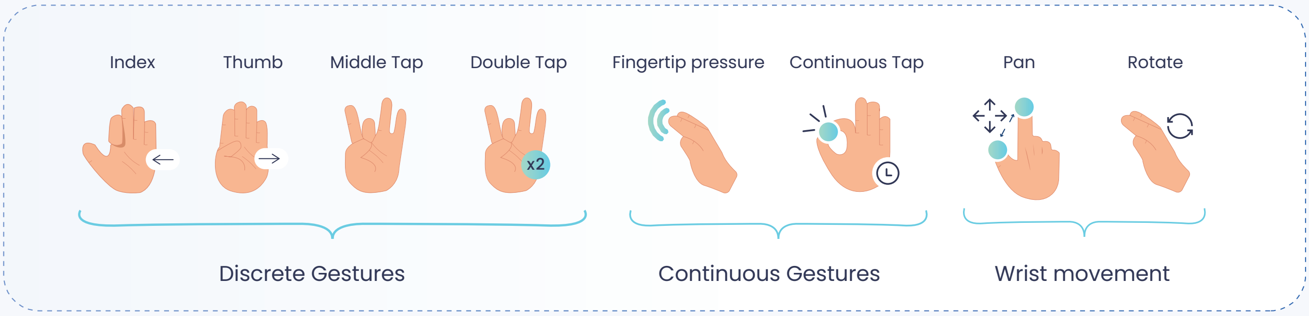

Figure 30: Mudra Band interaction types and input gestures examples

With its unparalleled market advantage, and the ability to tailor specific gestures, it provides an immersive, natural, and intuitive input to support our mission of shaping the input landscape for extended reality.

BEYOND INPUT: SNC AS A NEW BIO-POTENTIAL

The human wrist is interesting. Humans have been gracing their wrists for over thousands of years. Nerve bundles and arteries pass directly beneath the skin thus it is possible to sense the electrical conductance of the nerves and other bodily functions and collect valuable data.

The wrist is a prized “real estate” for sensing the human body. Digital wrist-worn accessories, applications, and services form an ecosystem for utilizing bio-potential signals for multiple use cases such as fitness tracking, remote monitoring, and digital input. SNC technology can be utilized in multiple additional use cases which involve tracking hand and finger movements and their correlated neural signals.

Industry 4.0

Manufacturing and assembly lines contain numerous manual tasks that employees repetitively perform. By collecting, monitoring, and analyzing these hand movements it is possible to identify if a certain manual task is performed accurately, thus preventing incurred losses in later stages of production. Inferring employee stress levels, and potentially degrading performance are important for employee wellbeing and health.

The motivations of industrial companies for integrating neural monitoring into their work processes include:

- error prevention for equipment operators to avoid mistakes and defects through monitoring, correcting, drawing attention, or preventing human errors as they occur; and
- process engineering and business activities that continuously improve all functions and involve all employees from senior management to assembly-line workers.

Sports Analytics

Monitoring athlete activity improves peak performance and generates meaningful insights. Practicing a designated routine and performing numerous repetitions of certain hand-instrument interactions can be greatly enhanced by utilizing neural signal tracking with muscle memory movements.
Through the collection and analysis of historical data, sports analytics inform players, coaches, and support staff to facilitate decision-making both during and prior to sporting events. Basketball, golf, baseball, and tennis benefit from improved motor skills developing a more intuitive understanding of the body mechanics for performing various play movements.

Digital Health

A non-invasive wearable device can be used for monitoring and rehabilitation. SNC is a new type of bio-potential signal which may become as common as ECG, EEG, and EMG. The benefits include gamification of a repetitive process in occupational therapy rehabilitation, high-fidelity prosthetics control, digital gesture detection for body-focused repetitive behavior, and the creation of specialized input interfaces for patients with severe motor dysfunctions.

CONCLUSION

In this paper we presented the need for a neural input interface that is accurate and comfortable for Human-Computer Interaction. We presented and explained the main factors affecting neural wristband design and performance, and their interrelation.

A natural interface necessitates the design of a bracelet or wristband form factor, that can be attached to a smartwatch case. Because the wrist is a highly valuable “real-estate”, the design should be comfortable, durable, and fashionable. We postulate that the wrist form factor is optimized for extended reality experiences, and specifically for smart glasses.

Interacting with digital elements on smart glasses necessitates an accurate prediction of user intent; however, this cannot come at the cost of a bulky product with an unacceptable form-factor. Motion artifacts and large user physiology variance reduces system accuracy and performance, resulting in inconsistent input. A neural wristband must be designed to consider dynamic conditions for ensuring ease-of-use.

Careful evaluation of the device’ form factor and functionality should be considered when evaluating a neural input solution, since ease of use and accuracy involves many trade-offs.

ABOUT WEARABLE DEVICES LTD.

Wearable Devices Ltd. (the "Company") is a publicly traded growth company developing AI-based neural input interface technology for the B2C and B2B markets. The Company's flagship product, the Mudra Band for Apple Watch, integrates innovative AI-based technology and algorithms into a functional, stylish wristband that utilizes proprietary sensors to identify subtle finger and wrist movements allowing the user to "touchlessly" interact with connected devices.

The Company also markets a B2B product, the Mudra Inspire, which utilizes the same technology and functions as the Mudra Band and is available to businesses on a licensing basis. Wearable Devices is committed to creating disruptive, industry leading technology that leverages AI and proprietary algorithms, software, and hardware to set the input standard for the Metaverse, one of the most rapidly expanding landscapes in the tech industry.

The Company's common stock trades on the Nasdaq market under the symbol "WLDS".

Headquartered in Israel, the company was founded in March 2014 by Asher Dahan, Guy Wagner, and Leeor Langer, with renowned expertise in analog sensors, signal processing, deep learning and machine learning algorithms, software, and human-computer interaction.

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