Toward a Wearable Biosensor Ecosystem on ROS 2 for Real-time Human-Robot Interaction Systems[*]

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***Abstract*— Wearable biosensors can enable continuous human data capture, facilitating development of real-world human-robot interaction (HRI) systems. However, a lack of standardized libraries and implementations adds extraneous complexity to HRI system designs, and precludes collaboration across disciplines and institutions. Here, we introduce a novel wearable biosensor package for the *Robot Operating System 2* (ROS 2) system. The ROS 2 officially supports real-time computing and multi-robot systems, and thus provides easy-to-use and reliable streaming data from multiple nodes. The package standardizes biosensor HRI integration, lowers the technical barrier of entry, and expands the biosensor ecosystem into the robotics field. Each biosensor package node follows a generalized node and topic structure concentrated on ease of use. Current package capabilities, listed by biosensor, highlight package standardization. Collected example data demonstrate a full integration of each biosensor into ROS 2. We expect that standardization of this biosensors package for ROS 2 will greatly simplify use and cross-collaboration across many disciplines. The wearable biosensor package is made publicly available on GitHub at `https://github.com/SMARTlab-Purdue/ros2-foxy-wearable-biosensors`.**

I. Introduction

Along with the advances in robotics technology and emerging various robot platforms, Human Multi-Robot Interaction (HMRI) systems have been broadly adopted in various real-world applications [1], [2]. The role of a human (e.g., a human operator) in the HMRI system is mainly to physically and remotely deal with unexpected situations/errors and complicated tasks that the robot systems cannot handle due to a lack of experience and hardware specifications, respectively [3]. However, the existence of humans is not always helpful to improve the overall performance of the HMRI system because of the added complexities introduced by widely variable humans [4]. Furthermore, the work performance of the human operator can be indirectly and directly related to the operator's affective state (such as emotional and cognitive states) that can be influenced by the pressure of work or personal circumstances. Finally, the human operator can be easily affected by various factors in the HMRI system, such as the number of robots, working duration, and operator's trust in automation [5].

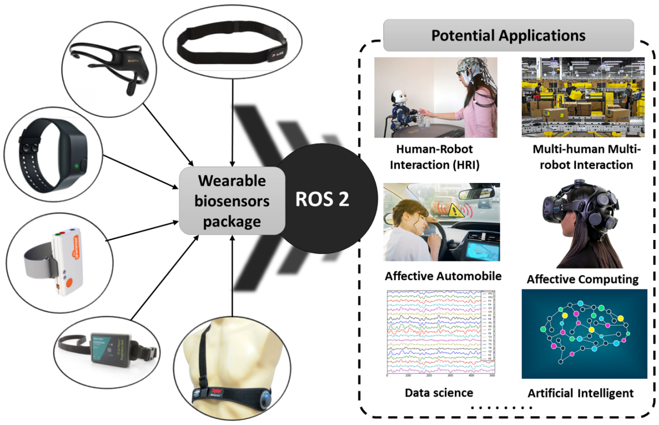

Fig. 1: Examples of the potential applications using the proposed wearable biosensor package.

Several contemporary methods exist to estimate a human's affective states. One of the common ways is to utilize a vision (i.e., camera) sensor to recognize a person's facial expression [6], specific gestures [7], or analyze the human's emotional states through a gait [8]. One potential source of error in camera-based prediction systems, aside from common problems with machine vision systems in general relating to image quality (lighting, exposure, etc), is the reliance on facial expressions that can be voluntarily controlled. Instead of observing biological systems under voluntary control, we propose estimating people's cognitive states from biosignal data. Along with the advances of the smart device and sensor technology, various consumer-available biosensors have been released that have multiple biosensors capable of reading biosignal information, so users can utilize these devices in daily life as auxiliary medical equipment [9] or as a fitness assistant [10]. To learn how to leverage biosignals, numerous studies on how to predict affective states through the wearable biosensor-sourced data are under active development in affective computing fields [11], [12], [13].

In contrast, HRI in the robotics field has still barriers to easily use wearable biosensors as part of a robotic system. In many robotic systems, *Robot Operating System* (ROS) is used as a connectivity layer to manage interactions between many types of hardware and software. Ideally, biosensor data for HRI can be integrated using ROS as a common framework. However, most biosensors do not officially support ROS since each vendor provides vendor-specific binary packages to read and visualize sensor data that limit widespread adoption within the HRI research community.

[*]This paper has not been published in the same form elsewhere.

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Many researchers who want to use the biosensors with ROS, therefore, require additional integration efforts.

In this paper, we introduce a new wearable biosensors package for the ROS 2 system. The ROS 2 supports real-time computing, multi-robot systems and various operating systems (e.g., Windows), and provides easy-to-use, reliable and real-time data streaming from multiple nodes. Thus, the integration of the ROS 2 and the biosensors can expand the role of biosensors in the robotics field. The current version of the package (v0.0.1) supports six wearable biosensors that can be used in real-world HRI research projects without behavioral constraints caused by limited hardware specifications (e.g., wired devices). The supported wearable biosensors are connected to the ROS 2 system, so that researchers who need to use the wearable biosensors in the HRI field can easily obtain a human's physiological data in concert with any other hardware or software nodes supporting ROS 2. To validate our package, we present plots of each sensor's published topics, in metric units. Finally, we present a potential application architecture using this biosensor package with a real-world robotic system.

II. The Robot Operating System 2 (ROS 2)

ROS, a well-known open source middleware for robotics, assists in robotic system development by standardizing subsystem layouts and streamlining sensor communication through predefined communication rules, called standard ROS messages [14]. ROS also provides various common tools for debugging and data visualization, decreasing system development time. Importantly, the ROS framework addresses the challenges and issues with data synchronization from various data formats (e.g., biosensors and image data), operating systems (e.g., Linux, Windows, and macOS), computer languages (e.g., C++, Python, and Java), and other frameworks (e.g., Lab-Streaming Layer (LSL) [15]. Since the introduction of ROS in 2007, the robotics community has been vigorously developing the ROS ecosystem, making it the preeminent framework in the field. However, ROS was initially developed for single robot use, requiring excellent network quality among other limitations. As the robotics and HRI fields expand, the need for real-time systems, for use in multi-robot and HRI research, has arisen.

ROS 2, released in 2017, seeks to overcome many limitations of the initial ROS architecture, such as official support of multi-robot designs [16] and enabling real-time systems via Data Distribution Service (DDS), an open standard connectivity framework [17]. The major features in the ROS 2 are as below:

- Support of real-time computing
- Support of multi-robot Systems
- Multiple nodes running in a process
- Distributed processing
- Flexible network environment
- Support of Windows 10
- Enhanced robot's security

ROS 2 increases accessibility to other disciplines through support for additional operating systems and programming languages, making cross discipline collaborations more realizable [18]. This cross-operating system support is particularly useful for biosensors, where a vendor may have only chosen to support a limited subset of modern operating systems and does not provide communications-level specifications to enable researchers to create an independent interface. While the original version of ROS is fully functional, the additional types of system architectures enabled through ROS 2 provide flexibility to the system designer; typical components of HRI research might include biosensors, processing nodes, actuators, interface nodes, and experimental monitoring, each of which may be running on separate computers and operating systems across continents or in the same room. Given the real-time multicomponent focus of ROS 2 and the rise of biosensor usage in HRI research, a standardized ROS 2 biosensor package is urgently needed.

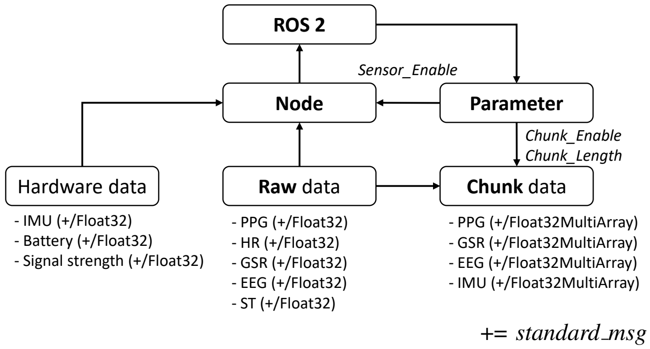


Fig. 2: Generalized structure of ROS 2 nodes in the biosensor package.

III. ROS2 Wearable Biosensor Package

Motivated by the multiple advantages of ROS 2 (Section II), we constructed a new wearable biosensor package for ROS 2 focused on real-time functionality and ease of use, capable of impact in a broad range of research and development areas. The proposed ROS 2 package (v0.0.1) currently supports six popular off-the-shelf wearable biosensors, each with their own node (Fig. 3). We designed the biosensor package with the flexibility to expand to more wearable biosensors as desired. We will keep this package updated and add support for other wearable biosensors according to interest. The package (v0.0.1) is able at: https://github.com/SMARTlab-Purdue/ros2-foxy-wearable-biosensors

A. Wearable Biosensor Framework

Each package node follows a generalized structure, depicted in Fig. 2. We categorized sensor data into three major types, using ROS 2 standard messages and separated per node. Hardware data indicates current battery levels and Bluetooth signal strength. Nodes publish raw data in real-time, with sampling rates based on the individual biosensor hardware specifications. Chunk data, collected per node with predefined lengths, provide end-users with a framework for downstream processing (e.g., feature engineering

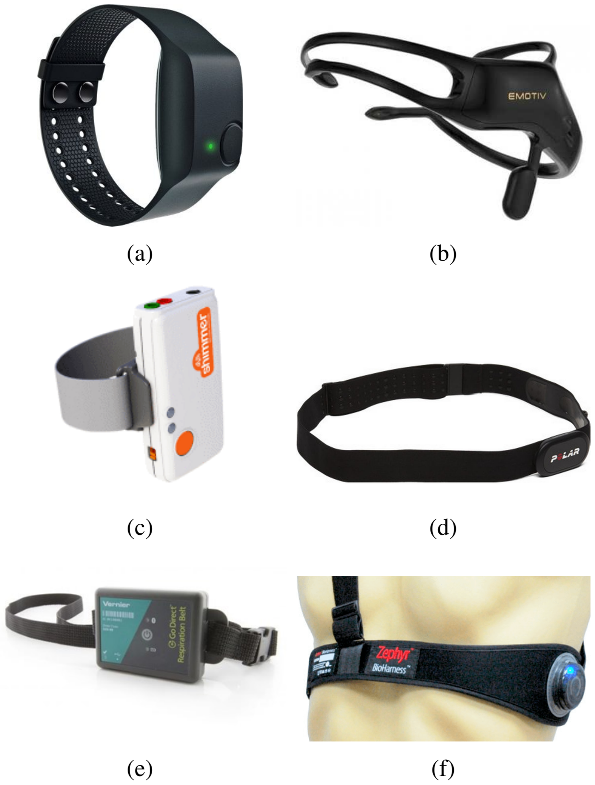

(a) (b) (c) (d) (e) (f)

Fig. 3: A list of the biosensors that the proposed biosensor package currently supports; (a) Empatica E4-wristband [19], (b) EMOTIV Insight-5 Channel Mobile Brainwear [20], (c) Shimmer3 GSR+ Unit [21], (d) Polar H10-Heart rate monitor chest strap [21], (e) Vernier-Go Direct Respiration Belt [22], and (f) Zephyr BioHarness 3 [23]

and Machine Learning (ML) applications). ROS 2 parameters (*Chunk_Enable*, *Chunk_Length*, *Sensor_Enable*) control all three data types. *Sensor_Enable* and *Chunk_Enable* are Boolean data type (i.e., *True* or *False*), while *Chunk_Length* is an integer data type, adjusting data length per topic. Available topics depend on the individual biosensor hardware specifications.

All package topic names follow the following format:

```
/biosensors/<sensor_name>/<data_name>
```

where the *biosensor_name* is the official name of the targeted biosensors (e.g., *empatica_e4*), and *data_name* is the biosignal type (e.g., *PPG_raw* and *PPG_chunk*).

B. Supported Wearable Biosensors

1) Empatica E4 wristband: The Empatica E4 is a wristband with an array of biosensors for monitoring biosignals: Electrodermal Activity (EDA) (or Galvanic Skin Response (GSR)), Blood Volume Pulse (BVP), Inter-Beat-Interval (IBI), Heart Rate (HR), and Skin Temperature (ST), and behavioral monitoring: 3-axis accelerometer [19] (Fig. 3a). However, there is a limitation to directly read biosensor data on the Linux environment since the vendor provides neither SDKs and libraries for Linux operating system nor technical interface documents. Thus, an additional Windows machine and Bluetooth dongle (e.g., Bluegiga Bluetooth Smart Dongle) are required in the current version of the biosensor package in order to stream biosensor data using LSL as mentioned on the Empatica E4 website [24]. The main Linux machine having the ROS 2 system converts the LSL data into ROS 2 topics in real-time. The Empatica E4 node provides topics as depicted on Table I, and the Fig. 4a is an example of the published data.

TABLE I: List of available topic names on the Empatica E4 Node.

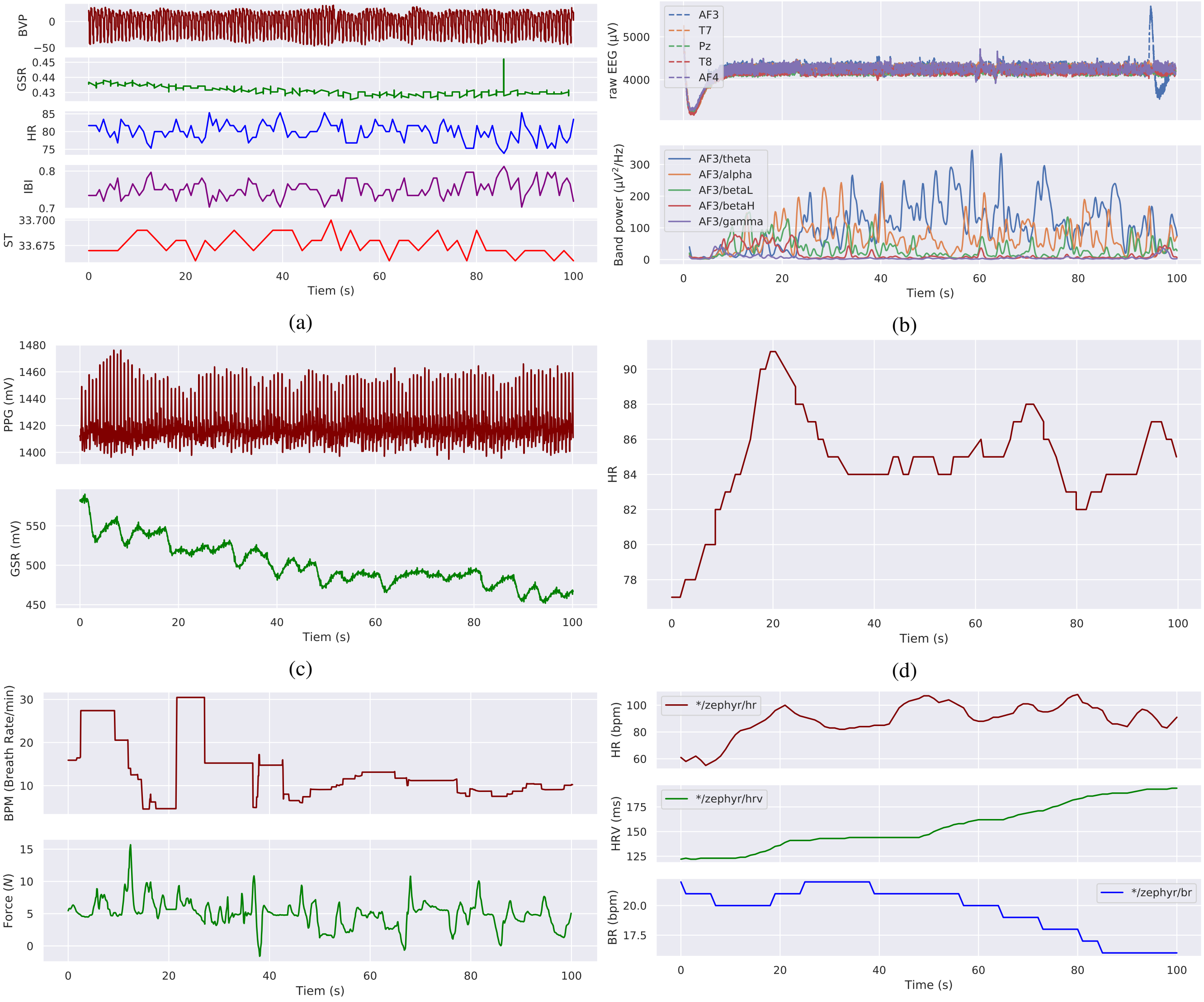
Name	Type	Topic name	Topic type
Raw BVP	raw	*/bvp	+/Float32
BVP Waveform	chunk	*/bvp_chunk	+/Float32MultiArray
Raw GSR	raw	*/gsr	+/Float32
GSR Waveform	chunk	*/gsr_chunk	+/Float32MultiArray
Raw ST	raw	*/st	+/Float32
ST Waveform	chunk	*/st_chunk	+/Float32MultiArray
Raw HR	raw	*/hr	+/Float32
Raw IBI	raw	*/ibi	+/Float32
Accelerometer	hardware	*/acc	+/Float32MultiArray
Battery	hardware	*/bat	+/Float32
Event button	hardware	*/tag	+/Empty

*= /biosensor/empatica_e4 and += standard_msg.

2) Emotiv Insight: Emotiv Insight is a wearable headset capable of reading 8 channels Electroencephalography (EEG) signals (e.g., AF3, AF4, T7, T8, and Pz) (Fig. 3b). The sampling rate of each channel is 128 samples per second with 14 bits resolution. It has an 9-axis inertial measurement unit (IMU) sensor to detect head motions [20]. Since it has a lightweight and user-friendly design, many affective researchers utilize it to measure the EEG signal from a human body [25].

However, there is a limitation to stream and read raw EEG data from the sensor without the Emotive Pro License, so the developers who want to use the Emotiv Insight device should have an Emotiv Pro license from Emotiv website [26]. Thus, we developed this Emotiv node with the Emotiv Pro license. For activating the Emotive Insight node, the main machine should be installed the EMOTIV App for Linux from `https://www.emotiv.com/my-account/downloads/`, then connected with the Emotiv Insight. The Emotiv Insight node provides topics as depicted in Table II, where the band power includes the alpha, low beta, high beta, gamma, and theta bands, and the performance metrics are estimated by the Emotiv software that includes six metrics (defined by Emotiv): Stress (RUI), Engagement (ENG), interest (VAL), Excitement (EXC), Focus (FOC), and Relaxation (MED) [27]. Fig. 4b is an example of the published data.

3) Shimmer3-GSR Unit+: The Shimmer3-GSR+ Unit is a wearable biosensor to measure GSR and Photoplethysmography (PPG) signals from the fingers or skins, converting to estimate HR [21] (Fig. 3c). The Shimmer3-GSR node provides topics as depicted on Table III. Fig. 4c is an example of the published data.



(a)

(b)

(c)

(d)

(e)

(f)

Fig. 4: Collected biosignals from the published ROS 2 topic data; (a) Empatica E4, (b) Emotive Insight, (c)Shimmer3-GSR Unit+, (d) Polar H10, (e) Vernier Respiration Belt, and (f) Zephyr Bioharness.

TABLE II: List of available topic names on the Emotiv Insight Node.

Name	Type	Topic name	Topic type
EEG	raw	*/eeg*	*+/Float32MultiArray*
EEG Waveform	chunk	*/eeg_chunk*	*+/Float32MultiArray*
Band power	raw	*/pow*	*+/Float32MultiArray*
Band power Waveform	chunk	*/pow_chunk*	*+/Float32MultiArray*
Performance metrics	raw	*/met*	*+/Float32MultiArray*
Motion	hardware	*/mot*	*+/Float32MultiArray*
Device status	hardware	*/dev*	*+/Float32MultiArray*

*= */biosensor/emotiv_insight* and += *standard_msg*.

4) Polar H10: The Polar H10 is a wearable heart rate biosensor and attached on the chest (Fig. 3d). It is mostly used for fitness objectives to read HR with 1Hz sampling time [28]. The Polar H10 node provides topics as depicted in Table IV. Fig. 4d is an example of the published data.

TABLE III: List of available topic names on the Shimmer3-GSR Node.

Name	Type	Topic name	Topic type
GSR	raw	*/gsr*	*+/Float32*
GSR Waveform	chunk	*/gsr_chunk*	*+/Float32MultiArray*
PPG	raw	*/ppg*	*+/Float32*
PPG Waveform	chunk	*/ppg_chunk*	*+/Float32MultiArray*

*= */biosensor/shimmer3_gsr* and += *standard_msg*.

5) Vernier Respiration Belt: The Vernier Respiration Belt is a wearable biosensor to measures human respiration rate from around the chest via Bluetooth (Fig. 3e). It is capable of measure from 0 to 50 N with 0.01 N resolution and breaths per minute (BPM) with 50 Hz sample rate [22]. The Vernier Respiration belt node provides topics as depicted on Table V. Fig. 4e is an example of the published data.

TABLE IV: List of available topic names on the Polar H10 Node.

Name	Type	Topic name	Topic type
Raw HR	raw	**/polar_h10/hr*	*+/Float32*

*= */biosensor* and += *standard_msg*.

TABLE V: List of available topic names on the Vernier Respiration Belt Node.

Name	Type	Topic name	Topic type
Raw BPM	raw	**/bpm*	*+/Float32*
BPM Waveform	chunk	**/bpm_chunk*	*+/Float32MultiArray*
Raw Force	raw	**/force*	*+/Float32*
Force Waveform	chunk	**/force_chunk*	*+/Float32MultiArray*

*= */biosensor/veriner_respiration_belt* and += *standard_msg*.

6) *Zephyr Bioharness:* The Zephyr Bioharness is a chest strap sensor designed for dynamic movement activities [23] (Fig. 3f). The Bioharness is capable of publishing output summary data (e.g., heart rate, acceleration) at 1 Hz. Raw ECG (FRQ = 256 Hz, Samples per msg = 63) and breathing (FRQ = 1.008 Hz, Samples per msg = 18) waveforms can be used in more advanced feature engineering. Currently, the Zephyr node provides topics as depicted in Table VI. Fig. 4f is an example of the published data.

IV. Potential Application

A standardized biosensor package for ROS 2 will play a vital role in HMRI research. One of the potential applications is the configuration of a HMRI processing framework as illustrated in Fig. 5. The system could monitor multiple human and robot states [29], [30] and adjust individual task allocations as needed [31], [32]. A system designed for such use could consist of four discrete elements: 1) human and robot condition monitoring, 2) feature extraction from raw data, 3) data storage using ROS2bag, and 4) evaluation, which would include action adjustments and data visualization. Biosensor data would provide human physiological and behavioral observations, while various operation parameters (e.g. battery level, encoder positions, and internal temperature) would provide insight into the real-time robot states. New or existing libraries (for example, pyphysio [33], NeuroKit2 [34], and BioSPPy [35]) would extract physiologically relevant features. A ML model could use the collected data as input and produce an adjustment to the current system. By using ROS 2's recording system, all subscribed/published data can be stored in a single ROS2bag file with synchronized timestamps between measurements, simplifying data analysis and management [29].

V. Conclusion and Future work

In this paper, we introduced a new package to integrate wearable biosensors into the ROS 2 ecosystem that can facilitate to easily measure and utilize the predicted human's affective states (such as emotional and cognitive states) on the HRI and HMRI applications. Each node of the package communicates using ROS 2 in real-time, a distinct advantage of ROS 2. The proposed package (v0.0.1) currently contains six off-the-shelf wearable biosensors. A generalized node and topic layout govern each node's structure. The ROS 2 parameters control published topic information, such as biosensor data channel activation and chunk data length. To demonstrate the performance of the biosensor package, we presented representative data set examples collected from each sensor using ROS 2.

In the future, we intend to integrate more wearable biosensors and topics in accordance with community or industry interest and welcome outside contribution as the ROS 2 ecosystem expands. We plan to keep this package up-to-date and create a Docker image for an even easier environment initialization. Thus, as robotics research becomes more interdisciplinary and complex, we will position this package to be a fundamental resource for the HRI community by providing standardized tools and a minimal barrier to entry. We look forward to the future innovations this package will foster.

TABLE VI: List of available topic names on the Zephyr Node.

Name	Type	Topic name	Topic type
Raw HR	raw	**/hr*	*+/uint8*
Raw HRV	raw	**/hrv*	*+/uint16*
ECG Waveform	chunk	**/ecg_chunk*	*+/Float32MultiArray*
Raw BR	raw	**/br*	*+/Float32*
BR Waveform	chunk	**/br_chunk*	*+/Float32MultiArray*

*= */biosensor/zephyr* and += *standard_msg*.

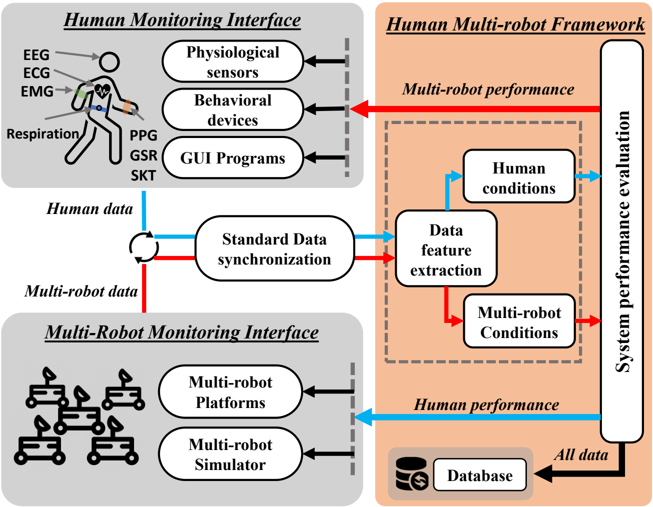


Fig. 5: A potential application for HMRI systems [30].

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