# Introduction

# Related Work

A software architecture for multimodal sensor integration was described in Gonzales-Sanches et al. (2011). The core components of their architecture include sensing devices, specialist agents, a centre agent, and third-party systems. The sensing devices have a one-way communication to their specialist agent, so the specialist agent is receiving data from the sensing device, but the sensing device is not receiving any data from the specialist agent. Each specialist agent has a two-way communication with the centre agent, so the specialist agent can send data to and receive data from the centre agent. The purposes of the communication from the centre agent to a specialist agent include to coordinate sample rates across multiple devices. Similarly, the centre agent has a two-way communication with third-party systems.

Each specialist agent is uniquely designed around the sensing device. The specialist agent has multiple components which perform the following tasks: communicating with the sensor, preliminary processing or reformatting of the data, sending the data to the centre agent. Some manufacturers offer SDKs and/or APIs for one to communicate with the sensor via bluetooth, while others use USB ports. The specialist agent is responsible for reformatting the data so that it is sent in the desired format to the centre agent.

While there exists a specialist agent for each sensor, the architecture uses one centre agent. The centre agent is responsible for communicating with every specialist agent, processing the multimodal data, and communicating to the third-party software. The way in which the centre agent processes the multimodal data can vary by task, but always integrates the multiple data streams to update the current state. The centre agent communicates the current state to the third-party software at a frequency set within the architecture design.

Gonzales-Sanches et al. describe the challenges presented by vastly different sample rates for each sensor and present some options for overcoming these challenges. One example of overcoming the sampling differences is to record the multimodal data as a data table and continue to add a new row anytime any sensor gets new data; the sensor attributes that received new data will be updated in the new row and any sensor attributes that did not receive new data have their previous data included on the new row. The current state can be calculated at any time based on the newest row in the data table. This solution works best for continuity of data but can create misleading interpretations of the data if one sensor has not been updated for a relatively longer period than other sensors, because the interpretation assumes that the data indicated is accurate for that timestamp. Another solution is to adjust the sample rate from the sensors with the highest sample rate so that each sensor collects one sample every time the slowest sensor collects a sample. Both methods can be used successfully but have drawbacks, so it comes to the application of the data and the sensor-types when determining a solution.

(Insert TAG background here)

The University of Arizona’s TAG project’s ongoing research into robotic teaching agents is currently using the LEGO® MINDSTORMS® EV3 robot to drive across a classroom to assist students to interpret geometric shapes. The EV3 robot combines a Wi-Fi-capable EV3 Intelligent Brick to two medium motors each connected to a medium wheel on either side of the EV3 Intelligent Brick (**Figure X – EV3 Configuration**). The TAG project installed a python script onto the EV3 which allows one to send movement commands to the EV3 from a remote computer by communicating using MQTT protocols and leveraging the LEGO® MINDSTORMS® Education EV3 MicroPython SDK (Kumar 2021). The TAG project’s EV3 is designed to move upon receiving an MQTT message in the format of: “MoveTank {left speed} {right speed}”, where “{left speed}” and “{right speed}” are floating point values ranging from 0 to 100 and used to denote the percentage of max speed at which the left and right motors should turn the left and right wheels, respectively. For example, the command “MoveTank 50 50” would prompt the TAG EV3 to power both wheels at 50% max power, therefore resulting in a forward movement. Alternatively, the command “MoveTank 50, 0” would prompt the TAG EV3 to power the left wheel at 50% max power while the right wheel remains stationary, therefore resulting in a spinning motion centered around the right wheel.

(Insert MQTT background here)

The project team was interested in exploring the complex challenge of mapping sensing device data to movement commands for the EV3 using standalone sensors and multimodal sensors.

## EV3 Movement Commands

The team leveraged the software loaded on the TAG EV3 to receive MQTT messages in the form of “MoveTank {left speed} {right speed}” to move the robot, however, the existing movement commands were limited. The researcher enhanced the existing commands by developing the python script “sender\_functions\_TB” which has a variety of pre-formulated messages to send over MQTT for movement commands such as: go straight, stop, go straight for a preset amount of time, move with bi-speed controls, turn around 180-degrees, spin, and spin for a preset amount of time. This python script was developed to be imported by centre agents and to be used to communicate to the third-party software (EV3 robot) to facilitate additional movement commands.

## EEG Signals

The first sensing device the researchers chose was the EMOTIV Insight EEG brainwave detection sensor (“the Insight”). The Insight is a 5-channel EEG with a 1-to-2-minute preparation time and utilizes a proprietary 2.4GHz wireless BLE connection. The relatively fast preparation time and wireless connectivity made the Insight the ideal EEG for the researchers because it would work best for future deployment with children in a classroom setting if integrated with the TAG project. The Insight can stream the raw EEG data directly from the sensors, but it can also stream Performance Metrics (stress, engagement, interest, relaxation, focus, and excitement). The Performance Metric data for each stream is collected as a floating-point value between 0 and 1, where 0 indicates zero value of that metric and 1 means the highest possible value of that metric.

The Insight’s specialist agent architecture incorporates the Emotiv© Cortex API and an adaptation of the “cortex.py” and “sub\_data.py” python scripts from the Emotiv’s Cortex example public GitHub repository (Emotiv 2021). The modified python scripts allowed the researchers to subscribe to the Performance Metrics from the Insight, and the data was immediately sent to the centre agent using MQTT protocol.

The researchers experimented with mapping the Insight’s data into movement commands for the EV3 robot, the researchers developed the centre agent python script, “int\_func\_EEG\_1d\_onMSG.py” to receive the Insight data sent over MQTT from the EEG specialist agent and send a command to the EV3 to move forward, stop, move backward, or stop continuously upon receipt of a message from the EEG specialist agent. The test script worked successfully, so the team built off that script to send movement commands to the EV3 based on the content of the Insight data – not just on the receipt of new data.

The centre agent developed by the researchers to control the movement of the EV3 robot using the Performance Metrics of the Insight EEG is included in the project’s GitHub repository as the python script “int\_func\_EEG\_1d\_Rel.py”. The mapping of the Insight’s Performance Metric data into movement commands for the EV3 robot was utilized by mapping movements in one dimension so the robot moved forwards or backwards during any movements – both wheels were powered to always matching speeds. The speed and direction of the EV3 robot was dictated by the changes in the Insight’s relaxation Performance Metric from the previous sample to the newest. The centre agent stored all Performance Metric values received from the MQTT channel from the Insight’s specialist agent to calculate the change from sample to sample. If the relaxation metric increased, then the EV3 robot was sent a message to move forward; the amount that the EV3 was told to power its left and right motors was calculated by subtracting the previous relaxation value from the current relaxation value, then multiplying by 100. For example, if the relaxation value was 0.50 and then next value was 0.60, then the centre agent would calculate the left and right motor power to be a value of 10 – resulting in the EV3 powering its left and right motors at 10% of maximum power.

The mapping successfully worked as intended, however the researchers quickly noticed that the Insight’s Performance Metrics are difficult to control even if trying deliberately, so the mapping was not very successful as it relates to the participant consciously controlling the speed of the EV3 robot in a one-dimensional case, let alone in a two-dimensional case where there are movement commands for the speed and direction of the robot. However, the researchers determined that the Performance Metrics would likely work well when actively being collected, but the centre agent only triggering movement commands when a metric exceeds a range instead of actively mapping the changes from sample to sample.

Therefore, the researchers sought to bring in another sensor which could compliment the Insight’s Performance Metrics with sensory data that has a participant can tangibly control with little training, so they could use the multimodal sensors in unison to control the EV3 robot.

## Empatica E4 Signals

The second sensor the team integrated into the EV3 movement architecture was the Empatica E4 wristband. The E4 wristband is a medical-grade wearable device that offers real-time physiological data acquisition. Equipped with sensors to monitor blood volume pulse, galvanic skin response, 3-axis accelerometer, and skin temperature, the E4 sensor was an ideal choice for the variety of data streams accessible from the single device and therefore vast variety of applications and movement mapping options.

The E4 can connect to a computer using a BLE-Bluetooth dongle and is worn similar to a standard watch without any nuisances to the wearer. Empatica offers an API for developers to stream the data for their own purposes. In order to do so, one must acquire an API key from Empatica, install the “Empatica Streaming Server”, and connect to the streaming server using Transmission Control Protocol/Internet Protocol (TCP/IP). The researchers’ desire for a wireless sensor with quick set-up time and mild to no nuisances to the wearer, multiple sensors and data streams, and high sample rate made the Empatica E4 wristband a desirable sensor to integrate to their architecture.

The research team built off existing research from the University of Arizona’s SensorLab for streaming E4 data using in a python script but modified to send the data to a centre agent over MQTT (see python script “sub\_data\_E4.py” from the project GitHub). The python script connects to the streaming server with TCP/IP, subscribes to the pre-specified data streams, and receives data message text strings containing data from multiple timestamps and data streams from the streaming service at regular intervals. Additionally, the script transforms each data message text string into a list of dictionary objects with one dictionary object per unique data stream and timestamp and publishes the list of dictionary objects over MQTT to the centre object.

To compliment the Insight EEG’s slower sampling rate and difficult-to-change metrics, the researchers experimented with mapping the E4’s accelerometer data stream to the EV3 robot’s movement controls. “The E4 is equipped with a MEMS type 3-axis accelerometer that measures continuous gravitational force (g) applied to each of the three spatial dimensions (x, y, and z). The scale is limited to +/-2g.” (Empatica 2021). The raw accelerometer data from the E4 is reported as 1/64g, so the raw data values are within the range of -128 to 128. Figure X illustrates the x, y, and z spatial dimensions when the E4 wristband is worn properly. The accelerometers can detect movements and will report those movements relative to the spatial dimensions. Additionally, the accelerometers detect the constant force of the Earth’s gravity, 1g, and the orientation of the wristband dictates the extent to which each spatial dimension detects the components of the background acceleration due to the Earth’s gravity. Figure X.2 illustrates the orientation of the E4 wristband at which the entirety of the background acceleration from Earth’s gravity (“background acceleration”) is registered in one spatial dimension while the other dimensions register 0g.

The researchers mapped the E4’s accelerometer data to the EV3 robot’s movement controls by leveraging the background acceleration recorded for each spatial dimension for different orientations of the E4 wristband. The specialist agent performed the tasks from the python script “sub\_data\_E4.py” as described above, while subscribing to the accelerometer data. The centre agent subscribed to the MQTT messages from the specialist agent to receive the data as a list of dictionary objects for each sample point. Due to the high sample rate, the centre agent used the last datapoint from every message received to process the movement controls. Similarly, the rate at which the specialist agent published to MQTT was controlled and could be easily adjusted for faster or slower response times.

The centre agent for the EV3 movement control mapping relative to the E4 accelerometer data as described above is included in the project GitHub repository as “int\_func\_E4\_3d\_Acc.py”. The centre agent processes the spatial acceleration data and maps the data to movement controls for the EV3 robot using the x and y spatial dimension acceleration data primarily as it’s derived from background acceleration. The acceleration in the y spatial dimension was mapped to control the speed of the EV3, and the acceleration in the x spatial dimension was mapped to control the off-axis acceleration, or direction and extent to turn, for the EV3. When the y spatial dimension’s acceleration is 0, then the EV3 will be stopped. Furthermore, a positive value for the y spatial dimension’s acceleration results in the EV3 powering its wheels forward, and a negative value results in powering its wheels backward. The y spatial dimension controls the maximum power for either of the EV3 motors at any given time, and at least one of the EV3 motors will be powered at that maximum at any given time.

The x spatial dimension reduces the power for one of the wheels while the other is powered at the relative maximum, therefor resulting in off axis acceleration which turns the EV3 to the left or right. When the x spatial dimension’s acceleration is 0, then both wheels will be powered at the maximum power dictated by the acceleration in the y spatial dimension and therefor the EV3 will move in a straight line. However, if the x spatial dimension’s acceleration is less than 0, then the EV3 will power its right wheels at the relative maximum power dictated by the y acceleration and reduce the power to its left wheels, therefore resulting in the EV3 to turn to the left. Similarly, if the x spatial dimension’s acceleration is greater than 0, then the EV3 will power its left wheels at the relative maximum power and reduce the power to its right wheel, therefore resulting in the EV3 to turn to the right.

When the E4 wristband is worn properly, the background acceleration registered in the y spatial dimension of the E4’s accelerometer, and therefore the relative maximum power of the motors, increases when the wearer’s wrist is lower than their elbow; the maximum background acceleration in the y spatial dimension is registered when the wrist is directly below the elbow. Similarly, the background acceleration registered in the y spatial dimension of the E4’s accelerometer becomes negative when the wearer’s wrist is above their elbow; the most negative background acceleration in the y spatial dimension is registered when the wearer’s wrist is directly above their elbow. Alternatively, when the E4 wristband is worn properly on the participant’s left arm, the background acceleration registered in the x spatial dimension of the E4’s accelerometer increases when the arm is rotated clockwise – the user’s left thumb is lower in elevation than their left pinky finger – and therefore results in the EV3 robot to power its left wheels at the relative maximum power while powering its right wheels at reduced power which leads the EV3 to turn to the right. Furthermore, when the E4 wristband is worn properly on the participant’s left arm, the background acceleration detected in the x spatial dimension of the E4’s accelerometer becomes negative when the participant’s left forearm is rotated counterclockwise – so that their left thumb is at a higher elevation than their left pinky finger – and therefore results in the EV3 robot to power its right wheels at the relative maximum power while powering its left wheels at a reduced power which leads the EV3 to turn to the left. The EV3 will turn the most to the left or right when the participant’s forearm is rotated so that their left thumb is directly above their left pinky finger or so that their left thumb is directly below their left pinky finger, respectively.

The centre agent for the EV3 movement control mapping relative to the E4 accelerometer data uses the process described above to calculate the power for the EV3 robot’s left and right motors for each data message received from the MQTT channel with the E4’s specialist agent. Upon calculating the power for the left and right motors, uses the “move\_bispeed” function from the imported python script “sender\_functions\_TB” which sends a message to the EV3 robots MQTT channel – different channel than the one from the specialist agent to the centre agent – in the form of “MoveTank {left speed} {right speed}” using the left and right speeds calculated from the process described above.

The research team found that the mapping procedure did not result in the expected movement commands when the wristband was oriented in a position where both the x and y spatial dimensions would register non-zero values – such as a position where the participant’s wrist was at a 45-degree angle below their elbow and the forearm was semi-rotated clockwise. The described orientation results in positive x and y values, which maps to a forward direction with a turn to the right. However, because the accelerometers are mostly leveraging the background acceleration, 1g, the speed is less than expected for a similar orientation of the wrist below the elbow, but without the forearm rotation. The mapping is more intuitive if the rotation of the forearm does not significantly reduce the speed registered from a similar orientation in the y spatial dimension.

To overcome the issue described above, the researchers implemented additional procedures in centre agent. Specifically, if the absolute value of the x spatial dimension’s acceleration exceeded the absolute value of the y spatial dimension’s acceleration, then the y spatial dimension’s acceleration as used for the calculation of the relative maximum motor power was increased in absolute value to the mean of the x and y spatial dimension’s acceleration, while preserving the sign, positive or negative, of the original y dimensions acceleration. This allowed the EV3 to conduct significant turns with enough speed to carry out the maneuver in a responsive manner.

After implementing the procedures described above, the E4 accelerometer signals were successfully mapped to movement commands for the EV3 robot which could be intuitively used by a participant and had a fast response rate.

## Mapping Multimodal Sensors to Movement Commands

The researchers integrated the above-described processes to map Insight EEG signals and Empatica E4 signals to movement commands for the EV3 robot. The integration process was conducted entirely in the centre agent and therefore did not require any alterations to the specialist agents.

The specialist agents published their data on unique MQTT channels, so the centre agent subscribed to both channels

# Results

# Conclusions

## References

Emotiv. (2021). “cortex-v2-example.” GitHub repository, https://github.com/Emotiv/cortex-v2-example/tree/master/python

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