Wireless Applications of a Refactored Prosthesis (W.A.R.P.)

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***Abstract* — W.A.R.P. is a project commissioned by Limbitless Solutions with the goal of improving their bionics by redesigning the hardware and rebuilding the software from the ground up. Specifically, with the addition of an inertial measurement unit to detect orientation, solid state relays to power down active motors, fully configurable multi-color LEDs for general aesthetics, a digitally programmable electromyography sensor, external flash memory for data logging, and wireless communication through Bluetooth low energy. Additionally, mobile applications will interface with and be capable of configuring the hardware wirelessly while interfacing with a remote server and web app over the internet.**

***Index Terms* — Bluetooth, Electromyography, Limbitless Solutions, Mobile Applications, Prosthetics, Servers, Wireless communication.**

I. INTRODUCTION

Limbitless Solutions is a non-profit organization founded by Albert Manero in the Spring of 2014 which was created to deliver high quality, inexpensive bionic limbs for use by children in accordance with the ethos, "Nobody should profit from a child in need".

Figure 1 – The Limbitless Solutions Iron Man bionic arm shown as a potential recipient of a W.A.R.P. module

Since its inception the organization has matured and refined the art of creating low cost, 3D printed bionics. A multitude of teams work tirelessly on improving every facet of the design and manufacturing process in order to improve the quality of life for children in need. This experiment started with the basic objective of assisting children by putting into practice engineering techniques taught at the University of Central Florida. Initially, Limbitless produced a bionic arm subsisting of various printed circuit boards interconnected in order to sense electrical impulses within the body. The onboard processor utilized these signals when triggering state changes of the hand, controlled by actuators. The system includes a power source, microcontroller, electromyography (EMG) sensor, electrodes, and a servo motor. Each board was assembled by hand and extremely sensitive to manufacturing defects and external noise. Although the system was enhanced with each iteration, a major overhaul was becoming evidently necessary to put an end to consistent problems. "The Ultimate Bionic Arm" (T.U.B.A.) was a Senior Design team commissioned in the Fall of 2015 to realize a single board solution, addressing many of the original issues. Although T.U.B.A. was largely successful, many technical improvements are still sought after.

The current ambition of the organization is to provide technicians with the capability to wirelessly transfer data and remotely update the microcontroller housed within the bionics. The purpose for including this feature is to streamline the process of providing firmware updates to end-users. Furthermore, a more practical implementation of T.U.B.A. is needed to provide optimal functionality with a limited power supply. Further research and development towards a practical software architecture, advanced hardware, and exceptional human-body interface are the technical challenges Limbitless Solutions aspires to overcome.

After brainstorming in a collaborative effort between the team members and the directors of Limbitless Solutions, the "Wireless Applications for a Refactored Prosthesis" or W.A.R.P. project was established in order to provide a solution to the challenges previously presented. The project will focus on redesigning previous systems to include wireless communication which will be used as a training utility for children in conjunction with the prosthetic device. This new module will double as a controller functioning similarly to the current devices in use, while also acting as a standalone peripheral.

The W.A.R.P. team aims to provide a working wireless architecture while also introducing a new suite of software applications which interface with the device via Bluetooth and the internet. A new printed circuit board will be designed, incorporating the best features of previous implementations and additional sensors which provide the ability to recognize gestures, limit power consumption, and provide a live debugging interface for developers. The final result being a fully integrated hardware and software stack which seamlessly work together to provide a fluid experience to users and technicians alike.

II. GOALS AND OBJECTIVES

The original inspiration for this team's requirements originated from an expressed concern from both Limbitless directors and technicians alike who found the modern calibration mechanism inconvenient. The main goals and objectives for this project include:

A. Utilize the LSR SaBLE-x module which contains a Texas Instruments CC2640 dual ARM Cortex processor as requested by Limbitless Solutions.

B. Wireless Calibration - remotely calibrate and transmit sensor data through Bluetooth low energy.

C. Integrated EMG Sensor:

   a. Reduce footprint size of original EMG layout

   b. Update nominal operating voltage from 5v to 3.3v allowing it to directly interface with the SaBLE-x ADC directly.

   c. Update design to use Texas Instruments ICs in an effort to reduce price and accommodate TI's partnership with Limbitless.

   d. Incorporate a digital potentiometer which can programmatically control the EMG sensor's gain and generate a selectable reference voltage.

D. EMG Triggered Interrupts - utilize the selectable reference voltage generated by the digital potentiometer and EMG output as inputs to an analog comparator to trigger an interrupt within the microcontroller in order to prevent polling the sensor for data; ultimately reducing power consumption.

E. Enable two-way wireless communication between the device and a smartphone

F. Manufacture a compact printed circuit board

G. Wirelessly control multi-color LEDs

H. Implement a method of powering down the servo motors in order to reduce power consumption.

I. Incorporate additional sensors which can provide users with more control over the prosthetic device.

J. Efficiently regulate a 7.4v nominal voltage down to 3.3v for digital logic and 5v in order to power servo motors.

K. Develop a custom mobile application for Android and IOS to wirelessly communicate with the printed circuit board using Bluetooth low energy.

   a. Provide individual user profiles

   b. Wirelessly connect with custom board using BLE

   c. Permit users to enter calibration data to sync with device

   d. Display sensor and log data

L. Configure and deploy a central server which will be accessible over the internet

   a. Design a database backend used to store relevant data

   b. Develop a web API to be utilized by the smartphone in order to effectively interact with the server and database in real-time

   c. Organize an administrative web page through the server for use by Limbitless developers to upload updated code and communicate with their users

   d. Design a simple platform for users to interact with one another and develop a sense of community.

III. SPECIFICATIONS

The W.A.R.P. team worked directly with Limbitless Solutions in order to decide on workable specifications upon which to base the team's design, denoted below.

TABLE 1
HARDWARE SPECIFICATIONS

Description	**Specification**
Price	Under $100 for the final design
Input Voltage	6.5v - 8.5v (7.4v Nominal)
Operating Time	8 - 10 hours
Min Trace Width / Clearance / Via Size	8 mils / 8 mils / 13 mils
Layers	2-4
PCB dimensions	100mm x 100mm x 25mm (Approximately 4in x 4in x 1in)

IV. HARDWARE LAYOUT

The hardware was redesigned with the intention of maximizing the number of features, minimizing power consumption and attempting to use the full power of the SaBLE-x module and BLE to allow the device to be configured dynamically rather than statically at compile time.

The initial breadboard design shown below utilized tools such as the predecessor to the "Myo Ware" EMG sensor as well as a stand in for the final regulator design. This board, although usable, demonstrated to the team the improvement the switch to the new embedded EMG design provided to signal clarity.

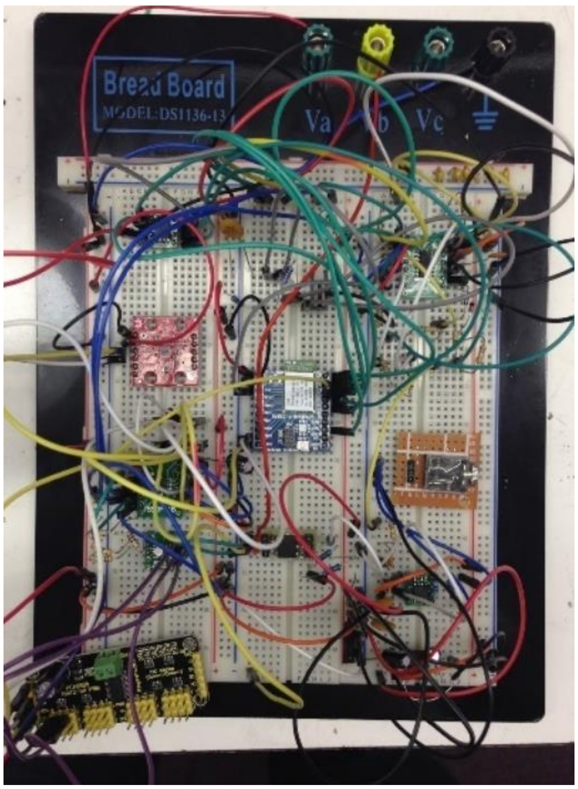
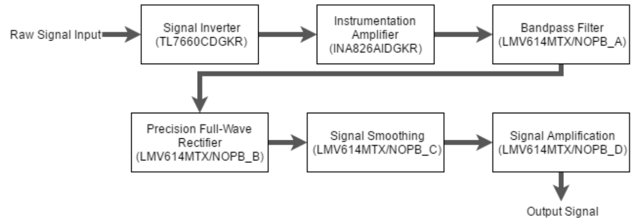


Figure 2 – Functional W.A.R.P. Breadboard

The EMG sensor was successfully updated to use all Texas Instruments chips, effectively reducing the price whilst providing a higher quality, lower noise output. Chips such as the TL7660 voltage inverter, INA826 instrumentation op amp, LMV614 low power general purpose quad op amp, and lastly the TPL0102-100 dual channel digital potentiometer were selected in the design for their superior features and low price. By changing the TL084 from the original open source design to the LMV614, the EMG sensor is now capable of operating using an input voltage as low as 2.5v compared to 5v. This allows it to interface directly with the SaBLE-x module's ADC which cannot tolerate voltages above 3.6v.

The following diagram showcases the W.A.R.P. EMG flow signal processing as well as the parts that represent each section.



A major addition includes the addition of the LSM6DS3 6 axis accelerometer / gyroscope. This device is interfaced using the I2C bus and has programmable interrupts which would allow the primary MCU to remain in low power mode until triggered. This is important since the original designs relied solely on the EMG sensor to decide when to trigger opening and closing the prosthetic hand. The IMU will provide more information which can be provided to the algorithms which make these decisions in software.

This design also incorporates two bright multi-color LEDs (ASMB-TTB0-0A3A2) in which brightness and color can be controlled using a dedicated PWM driver (PCA9685) with high resolution. The goal is for the LED color to be user selectable using the mobile application and change the aesthetics of the prosthetic. Similarly, there are two servo control signals which are generated by the same device and controlled through I2C.

The only stipulation given by Limbitless Solutions as the W.A.R.P. team's sponsor was to attempt to utilize the chip determine by a previous team to be well suited to the Limbitless design. The SaBLE-x chip, which contains an FCC approved trace antenna and a TI CC2640 microprocessor, provides what is required by this team. In particular, the CC2640 contained within the SaBLE-x fits well with the goals of the W.A.R.P. project with its multiple internal communication lines, decent amount of fast access memory for storage, many peripherals to allow for future growth. A layout of the CC26xx architecture can be seen below.

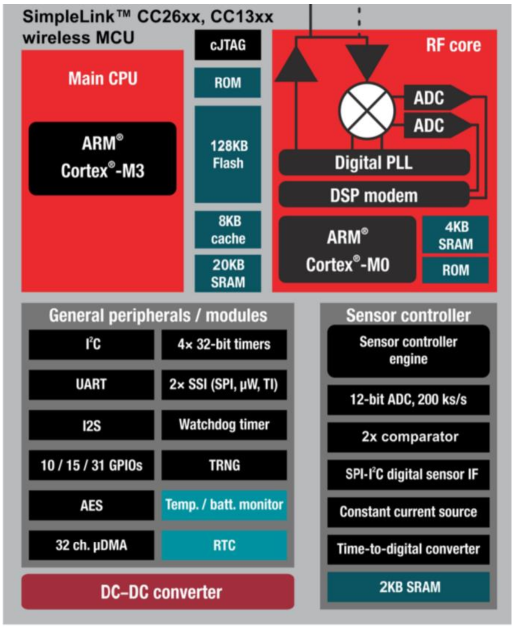


Figure 3 – CC26xx high level architecture overview

The SaBLE-x module being the most important device on the circuit board interfaces with the internal Bluetooth radio, processes sensor data, and interfaces with all the other chips.

Great care was made when routing the traces near this chip as it has very clear instructions such as where copper pours can be placed. This chip is programmed using an XDS100 or XDS200 JTAG Emulator and a 10 pin Cortex debug header was connected to the microcontroller. Similarly, a reset button with a hardware debounce was included in the design for the case where a manual reset is required. Lastly, a 1MB external flash memory was connected through SPI to provide an interface to store external flash images and to store data logs.

This board is expected to be powered by a 2 cell lithium ion battery with a nominal voltage of 7.4v and an expected range of 6.5 - 8.5v. The TPS62745 is used to regulate an output of 3.3v which is used to power all the digital logic. This was chosen due to the low number of passive components required and high efficiency. Additionally, the TPS62130 was selected since it can efficiently produce a regulated voltage between 5 - 6v and up to 3A which is ideal for powering servo motors. To reduce noise, reference designs were followed as closely as possible and shielded inductors were utilized.

The schematic and layout was created using EAGLE CAD 7.6.0. During the course of development, the board layout was run through three separate Design Rule Checks under individual industry standard Design Rules in order to ensure all components conformed to W.A.R.P. specifications. The final fabrication was completed by PCBWay with all non-discrete ICs being soldered onto the PCB by Quality Manufacturing Service. The final set of discrete components were soldered by hand.

As a last note on the hardware architecture, this PCB includes two sets of debug headers which isolate the 3 major subsystems of the board which is: power, digital logic, and EMG. These headers can be shorted together to connect subsystems together or disconnected if there was a fault in the design in order to prevent affecting the remainder of the board. As the first version of the design, the W.A.R.P. team designed it to be 2.25" x 2.25" on a 2-layer board and would like to see future versions be optimized down to 1.75" x 1.75" using a 4-layer board (while also removing the debug headers which will be unnecessary in a production version).

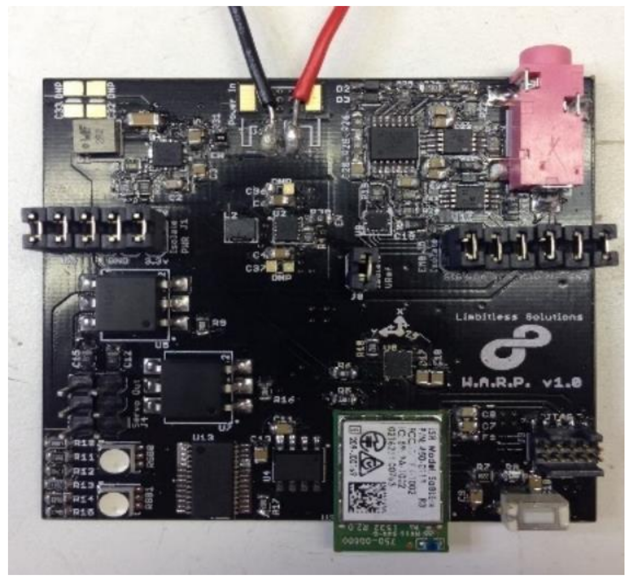


Figure 4 – W.A.R.P. board version 1.0

V. EMBEDDED DESIGN

The code which will be executed on the SaBLE-x, includes but is not limited to the Texas Instruments Real Time Operating System (TI-RTOS) and the TI BLE Stack. This firmware will be used as a framework for the application software to be built on top of. The basic structure for the BLE Profile will be generated by Bluetooth Developer Studio and integrated into the software as an API. The application code will include files which access this API to interface with the BLE Stack and RF Core. Furthermore, this code will interface with the application code to read and set data based on BLE communications.

A large portion of the embedded code will revolve around configuring TI-RTOS peripherals and drivers along with creating tasks (threads) which execute on the embedded device. The UART will need to be configured and linked to the correct GPIO pins to enable serial communication through the USB interface. Hardware interrupts will need to be configured to post data to the correct thread once triggered. Similarly, I2C and SPI drivers will also need to be configured to allow communication on the correct GPIO pins, and tasks to include the handling of data as it is received and when it requires transmission. The driver for the ADC will be configured to ensure the EMG signal is correctly sampled and passed to higher layers of the application layer.

Once the hardware based peripherals are created, semaphores will be utilized to ensure mutual exclusion of shared data between tasks. This will allow each task to execute in parallel and allow resources to be shared securely. With all these functions properly configured and initialized, the device logic will be added which will send high level commands through I2C, SPI, UART, or even BLE. These high level commands will be executed based on a timer, when new data arrives from sensors, or due to hardware based interrupts.

The figures below give a high level technical overview of how the embedded application functions during normal use within the W.A.R.P. system. The individual components are largely self-evident but the ordering of events can be summarized by the following; upon powering on or resetting the system the Boot Image Manager will execute. Upon succeeding the system will initialize the BLE stack followed by the TI-RTOS which will then move the system into its main function initializations.

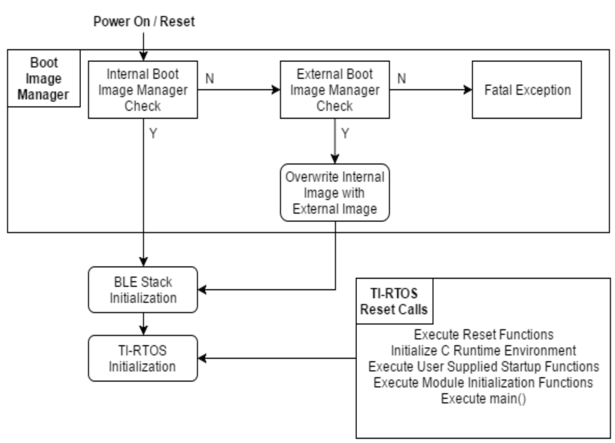


Figure 5 – Power On Bootloader cycle and base initializations flowchart

The main function will handle the majority of the initializations that will be used by the application and will end by starting the BIOS.

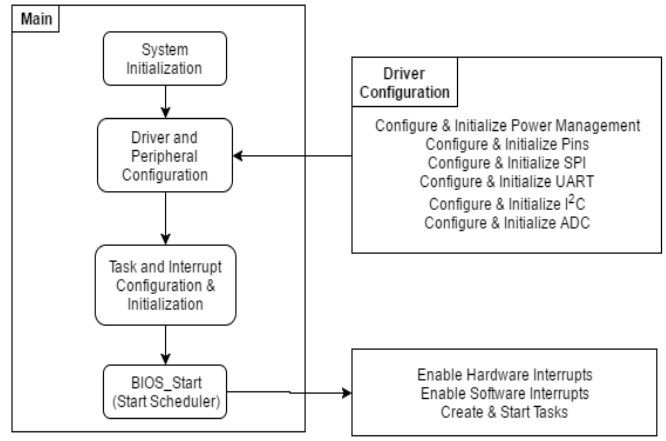


Figure 6 – Main Declarations and Configurations flowchart

Finally, the system moves into the kernel operations which is where the main application programmed by the user resides. In the case of a shutdown even the system will either gracefully exit and power off or abort application execution in the case of fatal exception.

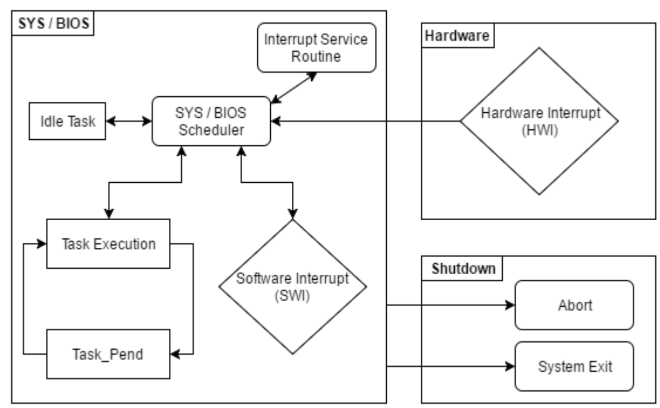


Figure 7 – SYS/BIOS Loop flowchart

VI. BLUETOOTH LOW ENERGY

The method of communication between the embedded processor running the TI-RTOS and the mobile application is Bluetooth low energy (BLE). BLE, also commonly referred to as Bluetooth Smart, is specifically tuned to low power applications in that it allows for many peripheral friendly communication standards. BLE allows for security in transfer of low energy device data whilst maintaining many of the features of normal Bluetooth such as adaptive frequency hopping. The integration of BLE to the W.A.R.P. module is committed through the secondary processor contained within the SaBLE-x MCU, the ARM Cortex M-0, which acts as an encoder/decoder of Bluetooth messages.

VII. HIGH-LEVEL SOFTWARE ARCHITECTURE

The approach taken in developing the mobile, is a combination of the server-client architecture and the publish-subscribe architecture. The mobile application is to interface with the Bluetooth component of the W.A.R.P. module. This will be used to set user input to values on the embedded device. Another feature of the mobile application is providing real-time chat from the user to a Limbitless Solutions team member if any support or questions are required. This is easily divided into three separate sections in effort to minimize constraints between layers.

The higher level software layers have the responsibility of managing connections between users of the W.A.R.P. device and the Limbitless team. Developing a network of any type will include a layer of security to ensure the safety of its users, connections between the server and clients can be secured with Secure Sockets Layer (SSL). This prevents an attack from occurring from an attacker intercepting data from the client and sniffing passed parameters. While ultimately the application will not feature monetary transactions, keys such as passwords could be reused for other services. Taking security a step further, the production application will feature a password less authentication system, this is achieved by the user submitting some form on either the web or mobile application to the server application, there a secret token with an expiration is generated, packed into an email and sent to the user. After which, the user can use this token to sign on. This establishes the initial authentication, a JSON Web Token (JWT) is generated and sent back as a hypertext transfer protocol (HTTP) request. The JWT must be present in all subsequent requests as an Authorization header item. In the case of a websockets (WS) connection needing to be established, the JWT will be sent as string query parameters.

VIII. MOBILE APPLICATIONS

The target platforms for the W.A.R.P. project is both iOS and Android. With this requirement in mind, it was decided to use React Native, a framework that wraps native user interface (UI) calls in JavaScript and allows for cross-platform development. Additionally, the React Native framework and by extension, the React library, provides useful tooling and debugging an application undergoing development as well as declarative syntax. State management is handled via pure functions in an immutable state tree allowing for fast transitions that can be computed using pure functions. Composing the application in this way allows for a portion of code to be shared not only between target mobile platforms but between the web application as well.

The figure below represents the UI in the event of the user contacting a Limbitless admin regarding an issue with his or her device.

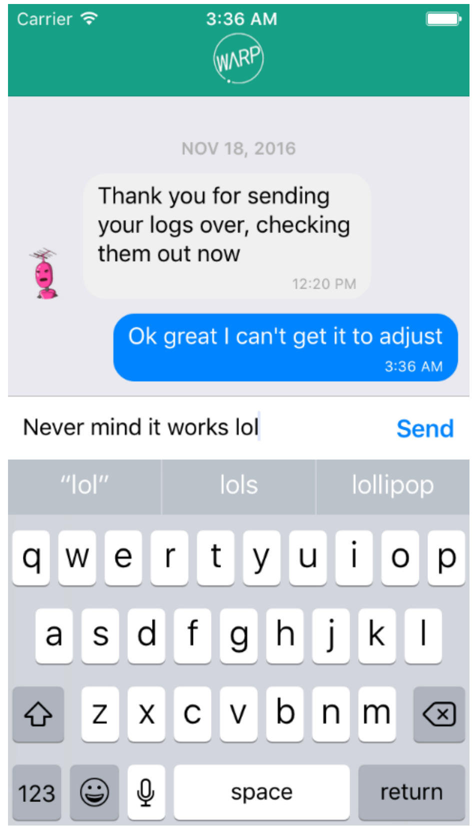


Figure 8 – The W.A.R.P. app in the admin help section

The most ideal environment to handle when communication over the HTTP/WS is JavaScript as, in our case, our responses are serialized in JavaScript Object Notation (JSON). Meaning there is no mental overhead when formulating views for incoming data. This data can easily be mocked and tested over the project's iterations.

While a Bluetooth connection is very much a native feature, system calls can be triggered via appending a listener to a native application emitter, which must be carefully managed as multiple calls in this way without closing a native channel can cause memory to bubble.

IX. WEB APPLICATION

The web application is used as a hub for the administrators of Limbitless Solutions to create new users and attach them to devices as well as provide any requested help or resolve any issues that may arise from using the device. The user may optionally send log files back to the admins to further debug issues. This application was written using the React view library and Redux for state management, with middleware supported via Redux Sagas to manage side-effects.

X. BACKEND SUPPORT

The server application is built on the Open Telecom Platform (OTP), running on the Erlang Virtual Machine. OTP allows for the creation of fault tolerant systems through a series of supervised child processes, when a crashed node is observed, it is replaced with another identical process from a previous state. The Erlang bytecode powering the W.A.R.P. server side application is compiled from Elixir, a much younger language with semantics similar to Erlang, with an additional robust tool system and less dense syntax. Elixir is a functional programming language, providing a different approach in managing mutations through side-effects in comparison to common academic functional languages such as Haskell, where a state monad would manage the manipulation of state. While these languages feature immutable data structures by default, interesting observations can only be made with mutations, in Elixir and Erlang change in state is performed under OTP's using a generic server process (GenServer), allowing for synchronous and asynchronous functions to external resources.

The server side application is doing the heavy lifting for the real time transport protocol, websockets. This can still be managed in a RESTful way, while broadcasting new messages from a given channel (i.e. a POST request to `https://warp-api.herokuapp.com/help_threads/me` with the params: {body: "test, this"} would in turn broadcast a "CREATE_MESSAGE" event to all clients connected to the channel broadcasted to).

The below diagram references the event lifecycle of a message being submitted and broadcasted back to the same client, this would be true for all other connected clients as well.

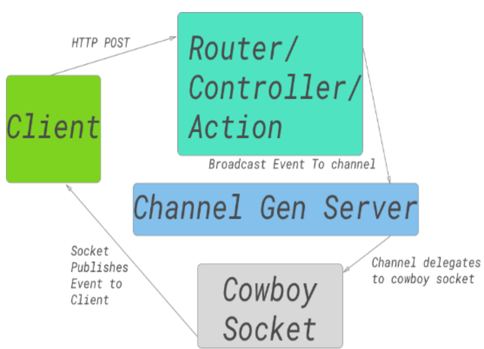


Figure 9 – Message send and acknowledgement in the W.A.R.P. server

Structuring the application this way can give the team some very appealing options. A new endpoint can be creating referencing a specific Help Message Thread called `/help_messages/me/typing` which could in turn broadcast an event letting other clients be informed on other individuals typing messages.

XI. CONCLUSION

The research conducted for this product has created a workable set of electronics and supporting software that can act as a springboard for future development of the Limbitless Solutions design. Included in the final deliverables are a thoroughly tested set of schematics and board designs, a complete bill of materials, functional prototypes and a tool kit with which to build future Limbitless Solutions products. From an overview standpoint the W.A.R.P. module has left Limbitless with the capability of wirelessly controlling their bionic arms and creating an online presence for their users through the W.A.R.P. app. The improvements to the voltage regulators and the addition of isolating solid state relays has improved overall power efficiency and performance. The reduction of the embedded EMG size has made room for a smaller overall board design in future iterations. This paper further touches on the design issues which are involved in creating such a device which is capable of interfacing on a hardware level with multiple LEDs, multiple servo motors, external, and even internal sensors and memory.

The primary goal of this device is to provide the architecture for wireless communication from the transport layer through to the application layer of BLE stack from both the embedded server side, and client side software. Furthermore, the goal is to utilize this communication to demonstrate advanced utilization of this wireless link for use by Limbitless Solutions and their future products.

The Wireless Applications of a Refactored Prosthesis project aims to bridge the divide between the software and hardware used by Limbitless Solutions and hopes this solution will further that goal with a product which will form the basis of their future products and help people everywhere.

ACKNOWLEDGEMENTS

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REFERENCES

[1] C. Andrews, R. Brunkow, W. Mullins, and B. Steiner, "The Ultimate Bionic Arm," Limbitless Solutions. Florida, 2016.

[2] Texas Instruments. (2016, June). SYS/BIOS (TI-RTOS Kernel) User's Guide (v6.46) [Online]. Available: http://www.ti.com/lit/ug/spruex3q/spruex3q.pdf

[3] Texas Instruments. (2016, June). TI-RTOS 2.20 User's Guide (Rev. M) [Online]. Available: http://www.ti.com/lit/ug/spruhd4m/spruhd4m.pdf

[4] S. Monk, *Make Your Own PCBs With EAGLE From Schematic Designs to Finished Boards*, New York: McGraw-Hill Education, 2014.

[5] Cadsoft Computer, *EAGLE Manual Version 7.3*, 4th ed. Florida, 2015.

[6] A. Weiler and A. Pakosta, *High-Speed Layout Guidelines*, 2006.

[7] P. Horowitz and W. Hill, *The Art of Electronics*, 3rd ed. New York, Cambridge University Press, 2015.

[8] J. W. Nilsson and S. A. Riedel, *Electric Circuits*, 10th ed. New Jersey, Pearson, 2015.

THE TEAM

Brandon Ashley: Brandon is Computer Engineering student with a focus in Software Development, who primarily focused his efforts on higher level software design, creating a mobile interface for W.A.R.P. module. Currently employed as a Software Engineer at Zuke Music, a music related startup.

Daniel Mor: Starting in 2011, Daniel has been studying Computer Engineering at The University of Central Florida. Actively involved with the Computer Science community, focusing on programming and Software Engineering with a background in robotics and embedded systems. He has gained experience by participating in various projects through student organizations such as: The UCF Men's Rowing Team, Robotics Club, American Society of Mechanical Engineers (ASME), American Institute of Aeronautics and Astronautics (AIAA), and Limbitless Solutions. He additionally served as Vice President of the Association for Computing Machinery at UCF (ACM) from May 2013 - May 2014 and then President from May 2014 to Jan 2015. Daniel plans to pursue a career which involves the further development, implementation, and integration of both hardware and software.

Niko Tubach: Niko is a Computer Engineering student focused on embedded systems and processor architecture with a Minor in Business Administration. For the W.A.R.P. project, he focused on the Bluetooth communications and assisted in the schematic design for the board. After graduation he will be joining Lockheed Martin as a Software Engineer.