CAES Lab Cyber-Physical System Lower-Limb Prosthesis Literature Review:

A Preliminary Literature Review

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CAES Lab Cyber-Physical System and Prostheses, A Literature Review

Abstract
Recently there has been an increase in the amount of research and interest towards Powered Prosthetics (PP) and the Cyber-Physical Systems (CPS) that are guiding them. As both embedded systems and the means to power them become more available, the unique challenges of developing powered lower-extremity prostheses becomes more manageable. Therefore, the goal of this paper is to review the advancements specifically from 2010 to 2015 regarding CPSs and their applications towards transfemoral and transtibial prostheses. Included in this review of the current literature are the specific algorithms used for both predictive and reactive knee and ankle joint adjustments as well as the type of control theories used to implement these methods. With these algorithms, this paper will also go into several different embedded and server hardware and software solutions that have been developed to drive these algorithms and control methodologies. This literature review will allow researchers to examine the current state of CPS and how they are being implemented in lower-extremity prostheses.

1. Introduction
Human-in-the-Loop Cyber-Physical Systems (HiLCPS) is a rapidly expanding multidisciplinary area of study as embedded systems become more performant and begin meeting the unique challenges that a HiLCPS presents (Schirner et al., 2013). This specific type of Cyber-Physical System (CPS) augments and extends the user, the human, and their environment through the use of an embedded system. This complicated interface creates many difficulties that only recently researchers have been able to start tackling. Lower-extremity prosthesis (LEP) need to have a higher accuracy rate and robustness than upper-extremity prosthesis as typically lower-body movements are important to the safety of the user whereas upper-extremity prostheses are not held in this same factor (Huang et al., 2010). There are three main difficulties that researchers collectively face when implementing a CPS for a LEP. These difficulties include:

• Low-Latency hardware/software responses when undergoing state transitions.
• Minimizing user gait corrections, keeping as natural of a gait as possible.
• Obtaining viable measurements showing user intentions from damaged muscle and tendons.

These issues have led to multiple different hardware and software solutions to maximize strengths against these particular difficulties. These software solutions often create other problems, such as increasing latency due to an increase in complexity.

Recently there has been an increase in the amount of research and interest towards Powered Prosthetics (PP) and the Cyber-Physical Systems (CPS) that are guiding them. As both embedded systems and the means to power them become more available, the unique challenges of developing powered lower-extremity prostheses becomes more manageable. Therefore, the goal of this paper is to review the advancements specifically from 2010 to 2015 regarding CPSs and their applications towards transfemoral and transtibial prostheses. Included in this review of the current literature are the specific algorithms used for both predictive and reactive knee and ankle joint adjustments as well as the type of control theories used to implement these methods. With these algorithms this paper will also go into several different
embedded and server hardware and software solutions that have been developed to drive these algorithms and control methodologies. This literature review will allow researchers to examine the current state of CPS and how they are being implemented in lower-extremity prostheses.

A Cyber-Physical System’s hardware demands specific design principles to guide how the system will interact with the physical aspect of the system. There are two main Model Predictive Control (MPC) methods used to implement CPSs in prostheses, Continuous-Control Set (CCS) and Finite-Control Set (FCS) (Rodriguez, 2013). These two control systems have distinct advantages and disadvantages that are continually addressed with new research implementations. To further study CPSs and prosthesis design we need to analyze these features of each control theory and how they interact with the embedded system itself.

The rest of this paper will be organized as follow. In Section 2 a description and methodology of choosing research and conference papers is given. Section 3 will go into detail about several different control theories used in the system. Section 4 will be split into differing algorithms that support the control theories in how they deal with the walking human gait. Section 5 will go into hardware implementation of these theories. Finally, Section 6 will conclude the paper.

2. Research Choice Methodology

For this preliminary literature review we have chosen 25 defining and important research and conference papers from 1997 to 2015, with 22 specific research and conference papers directly on CPS implementations from 2010 to 2015. We found these articles through online database searches involving Cyber-Physical Systems and lower-limb Prosthesis and then standalone searches for different Control Theory applications to get a further and complete understanding.

No research or conference papers were found on Cyber Physical System implementations for lower-limb prostheses from 2009 and earlier. The first research of this type began in 2010 by University of Rhode Island (Huang et al.). Since this research is new, many of this research has been done by similar groups. 7 of the 22 CPS papers are published by researchers from University of Rhode Island, with 4 of the 22 papers also being published from Cleveland State University. Many of these authors have also branched out to separate research groups in the five years that this literature review mainly spans.

This paper covers both conference papers (8 out of 22) and journal articles (16 out of 25) with the last source being a book from 1997 on control theories (Franklin, 1997). The reason why conference papers are prevalent in this field is perhaps because this area of study has been rapidly moving. In University of Rhode Island’s case, much of their research has been trying to solve the same problem in multiple ways. Because of this, this type of research strategy is more suited towards presentations at conferences to begin sharing ideas towards other complete solutions.

3. Control Theory Methodology

There are several different control methods that have sprung up in determining which methodology is best suited for a cyber-physical system (CPS) implemented in a prosthesis. However, some such control methods are not new to prosthesis research in general. The
proportional-integral-derivative (PID) controller has first appeared in the 1890s, and has been a typical method employed by CPS as well as other embedded systems (Franklin, 1997). Aspects of this controller has been used in recent research, specifically the proportional-derivative controller (PD), even though it’s weaknesses in adaptability is being realized (Zhao, 2015).

More commonly, there are two significant Model Predictive Control (MPC) methods employed in prosthesis research that this section will dive into: Continuous Control Set and Finite-Control Set (Rodriguez et al., 2013). These two methods are the most commonly found methods in controlling prostheses currently.

### 3.1 Finite-Control Set

Many researchers have opted to implement a finite-set machine (FSM) methodology to control different transitional states that occurs when switching from different prosthetic exercises. Some of these states that are tested include: sit-to-standing, standing-to-sit, walking, and ascending/descending stairs. A FSM will keep methodologies for the current state of the prosthetic (e.g. Sitting) and wait until it receives input from whatever state switching algorithm employed to change its current state to something else (e.g. Sitting to standing) (Rodriguez, 2013). Aspects of a FSM have been regularly used in almost all prosthetic studies shown in this literature review.

To begin, Researchers Alvarez-Alvarez et al. have developed a seven state FSM to model the human gait while walking on level ground (2012). This research is specifically attempting to create a genetic algorithm (GA) to both model and predict gait movements. This is recognized as the first time that an intelligent GA has been used to model this behavior. In this research, which is often cited by prostheses research, the gait is considered to be cyclic with an interval determined by the same heel striking the ground. These seven stages are split as follows: Left Swing Phase, Left Stance phase, Left Foot Single Support, Double Limb Support, and the corresponding Right leg phases (Alvarez-Alvarez et al., 2012). In some cases, researchers have chosen to simplify this to two states of the prostheses, being the prosthesis while planted, and the prosthesis swinging (Zhao et al., 2015). This has also led to two different types of prostheses, those that are assistive and powered throughout the gait and those that rely on the user powering the prosthetic itself during the swing phase (Bellman et al., 2010).

Research at University of Rhode Island have begun developing a FSM to model the different state switches of different lower-limb related activities such as sitting-to-standing and walking in a transfemoral prosthesis (Huang et al., 2010). This CPS uses a neural-machine interface (NMI) to collect electromyographic (EMG) signals from the user to register intent to switch states. The majority of URI’s research comprises of developing this algorithm to aid the FSM’s transitional states with requirements of having high accuracy and low-latency. High accuracy is much more important to lower-limb prosthetics than upper-limb prosthetics, as since lower-body movements tend to be cyclic and protect the user from injuring themselves, which is something that upper-limb prosthetics generally do not deal with (Huang et al., 2010). URI’s research modeled their FSM with two states, sitting and standing. Further research has been done by URI to expand this to both walking and stair ascent/descent, however, these further studies altered both hardware and software implementations so they deserve separate mention.
Transtibial prostheses FSMs have also been developed beginning with Dr. Eilenberg et al., who have designed states to be determined by measured reacted ankle torques (2010). This FSM has a similar two state structure to that of a transfemoral prosthesis, containing both stance and swing states. During the stance state the ankle is changed dynamically from a controlled plantar flexion to powered plantar flexion in a single state, three stage process. Ankle movement is considered difficult to account for in transfemoral prostheses, as the muscles typically used in determining transtibial prostheses are absent. This alters many designs for ankle movement if the research is applied towards a transfemoral prosthetic, which may find it necessary to lower the amount of states.

Research during the same timeline by Dr. Ataken et al., simplified their FSM model by only creating three states, one each for sitting, standing, and walking (2010). However, sub-states were created for all, which increased the complexity of the walking stage from 2 states in previous studies to 5 states currently. Transitions were based on live measurements of both foot load, ankle angles, and knee velocities. In conclusion, they found 100% accuracy in recognizing intent and transitions but also experienced higher delay of 500-800ms. This degree of latency is claimed to be too high, where even 400ms of delay is considered perceptible and could risk the prosthetic functionally messing up and causing a fall (Zhang et al., 2010).

3.2 Continuous-Control Set
The difficulty of implementing a Continuous Control Set (CCS) is far greater than implementing a Finite-Control Set (FCS) due to it’s continuous, and not discrete, nature. Continuously recording and managing data leads to extra challenges in managing a prosthesis’s movement. Primarily, the first difficulty that a continuous data design imposes (Which in extent, is true in some way for all CPS) is how to handle data noise (Lozovyy et al., 2011). Handling this inherent problem demands assistive algorithms to figure out how data gets read and employed. These algorithms, called evolutionary algorithms (EA), are multidisciplinary in nature and are created to manage how a prosthesis interacts with noisy environmental data (Lozovyy et al., 2011). There are two specific groups, off-line and on-line, of EAs that are employed in all CPS powered prostheses. Off-line EAs in prostheses are managed outside of the embedded CPS itself, while on-line systems are managed directly in the CPS itself. Off-line testing is often easier, but a proper Hardware-in-the-Loop (HiL) system emulator provides many benefits such as reduced testing time, ability to analyze real-use situations, and ability to manage real-time data (Kinsky et al., 2011).

With these challenges brought forth by a continuous system, researchers, such as those at University of Rhode Island, have combined both continuous and discrete data measurements in their CPS interfaces to lower both complexity and manage the disadvantages brought forth by continuous measurements (Huang et al., 2010). These algorithms and other research, like said before, will be explained in Section 4.

3.3 PD Controller
Proportional-Integral-Derivative (PID) controllers have been around for over a century, first appearing in nautical ships (Franklin, 1997). A PID controller may contain just the proportional and derivative aspects of the design (PD) and this specific type of controller is seen in some control method implementations. PD implementations greatest strengths lay in that they do
not require accurate model data to function, as its purpose is independent from its user (Zhao et al., 2015). However, this can lead to some difficulties as many powered prosthetics may need to be altered to the user as expressed in Dr. Zhao’s et al. conference proceedings (2015). However, for simple trials a PD controller is an accessible solution to get certain aspects of a powered prosthetic working.

A PD system was utilized as a controller for researchers Aghasadeghi et al. who have researched the parameters needed for a learning impedance controller (2013). The PD controller was used to monitor and react to the walking gait cycle split into four phases. During these phases, two measurements are required to analyze prosthetic reactions which are measured and given to the PD controller. The first aspect that the controller requires is tracking the joint trajectories in proportion to the velocity of the user. This is called impedance. Secondly, these measurements are calculated against the user’s own physical characteristics. As a result, these measurements and controller algorithm creates a parameter rule set that defines how a prosthetic should react during each phase of the gait cycle. This research was seen as successful, but limited by its testing which was not robust. Uneven surfaces as well as other common situations were not tested, so a PD system may not be able to handle more intricate environments.

Researchers at Texas A&M have compared three different control methods and their affect on things such as torque on joints, walking speed, and power consumption. The three control methods compared are as follows: PD, PD and Impedance, and finally MIQP and Impedance. Impedance and MIQP controllers will have their results discussed in 3.4 and 4.5 respectively. For the PD controllers, they were found to be inferior to the combination MIQP in all measured fields. The PD controller put higher torque and power draw over the newly created MIQP controller, and as such did not yield any direct benefits in using a PD design for a CPS powered prosthetic implementation.

3.4 Impedance Controller

Impedance controller by design rely on taking in a position (commonly in the form of a vector) and outputting a force. For prosthesis, impedance control is often implemented at some level in the control schema. For an impedance controller to work, it needs assistance from another form of controller, be it a PD controller or specifically developed MIQP control (Aghasadeghi et al., 2013). Several design challenges sprout up because of this. For one, numerous parameters need to be measured around the specific joint. In Aghasadeghi’s et al. research a total of 12 specific spots were needed to enable control of the joint (2013). Part of this research includes generalizing the locations of these parameters to be measured. However, problems arise when the joint begins moving. Measuring impedance values during the swing portion of the gait is difficult which led to alternatives in the method of implementation for Aghasadeghi’s et al. research. To accommodate for noise during joint movement, an estimation with a Poincare map was used, even though these estimations may not completely account for what is currently happening in reality. In conclusion to this study, it was found to be limited due to this estimation practice. However, this would be solved with further time and broadening the topic to include both the ankle joint as well examining symmetry between a working leg and the prosthesis.
Ankle articulation has been studied before, with research from Dr. Eilenberg et al., who tested one current prosthesis on the market created by the Biomechatronics Group from the MIT Media Lab (2010). This research attempted to further test this powered prosthesis on uneven ground, combining both a FSM and impedance design. This impedance was provided by a spring in the prosthesis that would measure torque from the dorsiflexion of the ankle. This torque, which is the major focus and claim of this study, would provide enough information to determine the environment that the foot is in and react quickly enough to maintain a proper gait. However, this study suffered from high latency which caused both slow reaction and predictability of the prosthesis. This delay made it so several steps needed to be made for an accurate enough decision. Further software and hardware solutions are needed to make this project more feasible.

To further improve this latency and effectiveness of a FSM, researchers Dr. Liu et al. have combined both an impedance reliant system with the aid of Dempster-Shafer based state transition rules (2014). The main benefit that this system provided this area of research is that the Dempster-Shafer rule set does not rely on external sensors. Waiting for external sensors and calculating this information during real time increases the complexity of a control system. It was found during this research that the accuracy of state transitions was still very high, which demands further discussion. An external sensor free system would lessen both the training required to use and put on a prosthesis, which would make the system itself be more accessible.

3.5 Model Independent Quadratic Program MIQP
Research by Texas A&M has led to the creation of a new control model system, called Model Independent Quadratic Program (MIQP) (2015). This control system is a novel quadratic program with a control Lyapunov function (2015). MIQP, with the assistance of Lyapunov, was found to be able to test stability of a system with greater accuracy and lower power use than tested PD systems. The Lyapunov functions are used to determine the state of the prosthesis. A particular state is considered stable if measured parameters do not detect any changes. Once sufficient parameters have been changed, the system goes under instability and MIQP then functions to begin powering this state transition. In conclusion, this was considered to be a novel method when included with typical impedance systems and found to have many advantages over older methods in terms of both power consumption and accuracy.

4. Algorithms
To preface this particular part of the review, the scope of what determines an algorithm needs to be made. Overall, an algorithm itself encompasses the entire CPS, however in this section we will be discussing differing algorithms used in conjunction with the FSM model that are implemented to help aid the prosthesis. We will specifically examine different evolutionary and genetic algorithms (EA, GA) that are used to pinpoint state switches in the FSM.

To begin this research, a past literature review from 2012 has been prepared comparing different methods used to control lower-extremity prostheses, exo-skeletons, and other robotic systems (Jiménez-Fabán et al.). In this review 27 of the 33 studies used a FSM, or several FSMs, to model a cyber-physical system in a prostheses related project. Using a FSM is a popular model to determine control patterns of a prosthesis because it is necessary for a prosthesis to
be multifunctional and adaptable. Generally, the solution to create adaptability comes from mechanical or electromyographic (EMG) signals, or a combination of the two. To parse this information (e.g. Impedance) external sensors are often used. However, using this information to determine reactions and predictions require the use of an algorithm (e.g. GAs, EAs) to determine this.

4.1 Biogeography-Based Optimization (BBC)

One such algorithm, Biogeography-Based Optimization (BBO) was created to directly handle the noise that occurs in real world use of a powered device. This optimization algorithm was applied towards a physical system for the first time by Cleveland State University (Lozovyy et al., 2011). In this research, BBO was used to aid a proportional-derivative (PD) controller in a robotic environment. While these research is not directly related to a powered prosthetic lower-limb, it is important as later on this study’s findings proved the feasibility that BBO is capable of optimizing control parameters. In a proof of concept run done by Lozovyy et al., it was found that after ten generations of training time that the error rate dropped by 65%. This quick training is paramount to successfully creating a prosthesis for users who may have altered gaits that need a specialized solution.

The first study to use this BBO research in a prosthetic was also done by researchers in Cleveland State University (Wilmot et al., 2013). In this transfemoral prosthetic implementation they created a semi-active CPS using BBO to drive their open-loop control system. As such in Aghasadeghi’s research, 12 parameters were used to monitor the state of the knee (2013). Before the BBO was towards the prosthesis, manual alterations were made to create a control system. These alterations were done in simulation and altered things such as a stubbing the toe of the prosthesis. However, with lack of complete ankle control, this research implies that the user may use their hip to alter the gait. However, user corrections to their gait can turn into long-lasting issues, such as osteoporosis (Davis, 2014). The BBO in this study holds two separate models that are kept in history. One of these models is the previous generation, and the second model is the newer one actively being used. Each aspect of the generations can change up to at most 5%, which allows for mutations and reductions in cost functions used. This research was proven to be successful, as in Wilmot’s robot testing stage they had proven near-optimized performance after testing. However, this was done in simulation by a walking robot, and human testing needs to be done to test gait changes.

New research shown at the American Control Conference have provided insight on how the ground reduction force (GRF) can be used in an BBO to optimize the gait of an amputee. A standard market-available prosthetic was used to test these algorithms, the Microlite S Knee, and was modified to include sensors for this algorithm to work. BBO in this implementation worked in two phases, with one phase determining vertical displacement of the prosthesis in comparison to the thigh angle. The second phase takes continuous measurements from the vertical parameters of the hip. With these phases, BBO can begin its job to further optimize initial parameters. A walking robot was used to test these optimizations, and it was found that there was a 62% lower measurement of GRF than initial conditions. With this information the research was considered successful, however it is not known if GRF is the best way to determine a correct gait.
4.2 Linear Discriminant Analysis (LDA)

Linear Discriminant Analysis has been widely used as an algorithm for assisting upper-extremity powered prosthetics and as such has since been transferred over to lower-extremity prosthetics (Huang et al., 2010). Research at University of Rhode Island have used LDA to implement a CPS in a transfemoral prosthesis in conjunction with their neural-machine interface (NMI). In order for an LDA to work, it will classify observed continuous data and compare it to each specific posteriori probability that is held constantly. LDA will attempt to maximize this probability. In this specific research, four of these constant probabilities were used to help determine state switches in their FSM model. In conclusion, the researchers found inaccuracies directly in their sit-to-stand and stand-to-sit transitions. These could be fixed with more computations, but latency begins to be too high for this to be useful. More intricate algorithms was determined to be needed for their LDA implementation.

In a later study by researchers at University of Rhode Island they attempted to fix earlier problems with an LDA model by utilizing hardware solutions from an Intel Atom (Hernandez et al., 2013). In another new addition, the FSM model was dropped and switched to a neuromuscular-mechanical fusion support vector machine (SVM). With this new model, the research continued by only testing detection of state switches. In conclusion, they found that they had a 20ms response time with 99.94% accuracy while using less than 11% of the Intel Atom’s potential. Continued research needs to be completed on whether or not this system can also control leg movement and analyze incoming EMG signals as this was not present in the current design.

4.3 Fuzzy Logic

The use of fuzzy logic has been used to assist FSM in determining gait patterns and state switches in a few current prosthetic research studies. In research done by Alvarez-Alvarez et al., a genetic fuzzy logic system has been implemented to determine different gait structures (2012). A knowledge base of initial parameters is needed for a fuzzy system to work correctly, which in this study is taken into account by using existing genetic algorithms to determine these initial states, then the switch to the fuzzy system will be made. If this worked, a fuzzy set of if-then logic would result in extremely fast computational time while still being comprehensive. In this study, a series of models are created and shared to correctly model the human gait. This particular research can be transferred over to prosthetic research as modeling the walking gait is one of the overarching difficulties that this research faces. This particular research was successful in modeling the human gait by expanding the FSM by including these genetic algorithms and fuzzy logic.

5. Hardware Implementations

Hardware of the embedded system is a contributing factor to the difficulty of implementing a powered prosthesis. This is due to the number of calculations needed to determine states and phases that the prosthesis needs to switch to or manage. There have been numerous different CPS implementations using several different families of embedded systems. In this literature review, we will examine the three most commonly found in this field, which based on the collected articles are determined to be using a graphical processing unit (GPU), a Field Programmable Gate Array (FPGA) and then consumer-grade embedded systems. The choice of
embedded system design is due to the choice in control methodology and algorithms used, as performance and low-latency requirements of prosthesis research is a major challenge of the system itself.

### 5.1 Graphical Processing Unit (GPU)

While GPUs are typically not seen in embedded systems due to their generally higher power requirements and typically PCI-Express interface (Xiaorong et al., 2012) it was initially used in 2010 by researchers at University of Rhode Island (Huang et al., 2010) with continued research by the same team in 2011 (Zhang et al.). The GPU has recently had more use in embedded systems due to advancements lowering their costs and their typically low cost to performance for certain computations (Zhang et al., 2011). Specifically, if a prosthetic implementation used GAs and impedance as its control methodology the outputs of these such algorithms are typically in the form multi-dimensional vectors. GPUs are often designed to model this magnitude of vectors, so they may be able to outperform similar CPUs.

In research done by University of Rhode Island a 4 multiprocessor 32 core GPU, the NVIDIA 9500GT, was used in comparison towards a typical embedded microcontroller, the Freescale MPC5566. Since the GPU was not able to be embedded due to hardware limitations so far, its calculations were done in a server transmitted to the prosthetic. The GPU was in charge of taking 7 EMG inputs, totaling up to around 70,000 data points and divided this up into 140x7 matrices, with each one being called a window. It was found that upwards of 500 of these 140x7 matrices could be used to determine state switches accurately, with more windows resulting in slower and less-accurate decisions. Around 400ms of latency was reported, which could be noticeable to the user. This system however was 100% accurate in determining state switches and was determined to be 23 to 39 times faster than the embedded system depending on window size.

### 5.2 Field Programmable Gate Array (FPGA)

A FPGA design shows benefit over the earlier discussed GPU design as an FPGA is easier to embed than a typical GPU system. In this section, we will go over possible design choices and tested implementations for a FPGA in a CPS. A FPGA is an attractive choice overall due to its performance and low cost with maintenance. FPGAs are well suited towards a CPS environment due to the control methods demanding adaptability. First, we will examine FPGAs role in a CPS environment, and then move on to see how it preforms in a prosthetic environment.

Hardware-in-the-Loop (HiL) systems are generally fairly intricate, and as such require a robust method to test, emulate, and be able to manage continuous mechanical and EMG inputs. Researchers Dr. Kinsy et al., have developed a novel architecture implemented on an FPGA that can handle the high number of computations, determinations, and low-latency that a CPS demands (2011). This Multicore Architecture for Real-Time Hybrid Applications (MARTHA) is designed to be general, so that it can be fit to work for a number of CPS implementations. MARTHA’s specific vector machine style cores would translate well towards a lower-body prosthetic. In previous research done by University of Rhode Island they found that a GPU core could quickly and accurately manage the parallel matrix computations that their modeling system needed (Zhang et al., 2012). MARTHA has been shown to be scalable to meet the multiple different computational demands. This opens up MARTHA as a hardware solution for
many of the different previously stated control methods as its computational power can be scaled to meet the different demands of differing algorithms. Research on implementing this system is currently underway.

University of Rhode Island has continued their previous GPU implementation with a general FPGA (Xiaorong et al., 2012). Their CPS is split between two different sections, a microcontroller and an FPGA. The microcontroller manages all input data and sends these parameters to the FPGA which will then compute and decode these signals. There are also multiple stages of how the FPGA is used, one being offline with the other is online. Offline training involves routing all measurements that the amputee user acts out to an external memory. The base patterns are then calculated here. When it comes to online training, data is not able to be stored due to the limited memory. This limits the capabilities of learning in this specific FPGA device. However, with the specific pattern recognition algorithms (based on earlier research using GRFs as it’s controlling parameter) the system was still able to maintain 98% training accuracy. When compared to a MATLAB implementation on a desktop computer (Intel i3, 3.2GHz, 6GB DDR3 RAM) the FPGA was able to measure 30 times faster than the higher powered desktop PC. The inputs that these two pieces of hardware was dealing with was the same matrix computations dealt with in URI’s earlier research. The inputs these systems were dealing with included 7 EMG and 6 mechanical input parameters. This shows the initial success of a parallel FPGA design. However, reliability and consistency has not yet been tested with a full working system, so further research still needs to be completed.

5.3 Other Embedded System Implementations

Research completed by Dr. Davis et al. has used a private company, dSpace, as their hardware and software solution for optimizing their control parameters surrounding ground reduction forces (GRFs) (2014). For their control system, a standardized first-order sliding mode controller (SMC) was used in conjunction with dSpace’s hardware solutions. Another piece of software, Simulink, was used to reference the parameters and control tuning methods of the prosthetic leg during testing. Direct information on the performance of this system was neglected during the research, so required latency measurements and other performance requirements were not talked about during this study. Further research is needed to determine this solution’s capabilities.

Dr. Henandez et al., has researched the computational power of a consumer chip, the Intel Atom, and how it fares in predicting mode transitions in a FSM (2013). This type of solution would carry benefits over an FPGA solution if it showed similar performance as it would be simpler to maintain. However, this test was limited as it did not cover all of the computations needed in a fully assistive prosthetic device. For what it did test, it experienced only 20ms of latency to determine a state switch with 99.94% accuracy. The Intel Atom computational load only measured less than 10.62%. While this has not been further tested for true parallel computing that would have to come later with the addition of determining positional vectors through impedance, Dr. Hernandez claimed that this demonstrated the feasibility of a consumer level chip that could be scaled and expanded towards a complete solution with a neural-machine interface in a FSM.
6. Conclusion

Research so far has been limited. Lower-extremity powered prostheses have only just been starting to becoming an accessible reality. The first research on this began in 2010 and has had an upward trend in the number of research available since then. In this literature review, we have gone over different control methods used, supportive training genetic and evolutionary algorithms, and a few computational hardware solutions for Cyber-Physical Systems in a lower-limb prosthetic.

One general observation that is made from this collected research is that there exist a few unique possibilities in terms of both hardware and control methodologies that could power such a system. However, the testing of all research collected has been limited. Only a single collected article involved uneven-ground real use testing. Many available research has only been able to have access to able-bodied users to test their prosthetic as well as only a limited number of them. In order for a powered prosthetic to become a true solution, further testing needs to be done. With the addition of uneven ground or other unique terrain this will increase the computations required in the typically applied FSM model. Researchers who wish to begin testing prostheses should have these performance requirements in mind. Overall, it has been shown that current hardware has been capable of meeting these performance requirements. Measured latency, however, has generally been on verge of becoming a problem that could cause mechanical failure of the prosthetic (Zhang et al., 2011). Extra computations from a more robust system could push that over the edge, so hardware choice and implementation still is a problematic factor.

Overall, CPS implementations is still a new topic in lower-extremity powered prostheses. There is a wide range of questions that still need to be answered on the route to a complete solution. In this literature review we have gone over several different types of solutions that serve as a basis and entry point for this research field.
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A Preliminary Annotated Bibliography

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Aghasadeghi et al., have researched one approach to designing a correct implementation of a dynamic impedance controlled system for a lower-limb prosthesis. These specific parameters used in an impedance controlled system were discovered through examining able-bodied walking and using that velocity/position data to determine correctly how a prosthetic should act. This testing was able to work with both an abled-bodied person using a prosthetic. This way, testing could be compared to real-use data to see if it was matching what was actually happening. This research split up the gait on level ground of the user into four stages, heel strike, mid stance, heel lift, and full knee extension. More testing is needed on uneven surfaces as well as stairs to create more impedance parameters.


Purportedly the first time that a genetic algorithm (GA) has been combined with fuzzy logic to model the human gait, researchers here have examined multiple test subjects and created a fuzzy algorithm that could apply for further research. This type of state-machine is ideal for modeling the human gait because of this specific type of system can introduce many variables for which creating an equation set can prove to be difficult and challenging. A fuzzy logic if-then tree simplifies this and calls for easy additions to new variables. This research was seen as to be successful but it has not yet been applied to a medical setting, which is the researchers intended purpose.


In this study there was a comparison between four popular powered knee joints that tested safety, energy reduction, and gait alterations. The four knee joints used had some collective differences, with the main defining factor being whether or not all steps of the gait were powered. In some prosthetics only the swing movement of the gait is actually powered, while in others there is a much more constant assistance. It was found that none truly decrease the amount of energy required for a user to manage a prosthetic. However, the C-Leg had tangible benefits in both safety and keeping the gait as normal as possible compared to the others.

Researchers Ron Davis et al. have mainly developed a new type of prosthetic testing robot that correctly emulates the movements of a human hip. This was found to be necessary because one of the largest problems for prosthesis is their need for much more work from the user (up to 65% more energy spent on moving the leg compared to normal) that causes problems such as osteoporosis. With this new testing process, a new prosthetic was created with typical biogeography based optimization (BBO) software made to minimize the ground reaction force (GRF) that the researchers were using as a guideline for accuracy.


While the research specifically regards upper-extremity prosthetics, researchers at University of New Brunswick and Carleton University ask and answer the question of what are the possible myoelectric information that we can extract out of existing muscles to power a prosthesis. The system developed also is able to create a feature set that handles the information given to discriminate against different types of movement in similar muscles. This is helpful as certain patterns can be found in movement that the CPS could then guess about what to do next, improving latency and relying less on EMG data.


For transtibial prosthetics the issue of actively reacting to and predicating changes in a non-uniform environment is the critical question. Researchers Eilenberg et al. are using an ankle prosthetic created by from the MIT Media Laboratory to test if this particular prosthetic along with finite-state machine system is capable of being used in mixed terrain. These states are triggered by drops in ankle torque which would signify that a differing surface has been stepped on. The researchers Eilenberg et al. concluded that they were not successful in switching fast enough as their software and hardware required several steps to change.


Researchers from Sharif University of Technology have both reflected on previous gait pattern research of transfemoral prosthetics and compared different adjustments that the user has to make. In conclusion, there were major differences in terms of effort required from the hip to manage the prosthetic system. This extra effort required from the
amputee user over an able-bodied person leads to further problems such as osteoporosis and other joint problems.


Provides background on different control systems such as Proportional, Integral, and Derivative control systems (PID). This type of control loop system is paramount to the history of CPSs as well as its current applications. PID systems can include one or all of the controllers, and as such rely on feedback around the plant to determine results.


In University of Rhode Island’s previous study, they implemented a FPGA design to meet the constraints of the neural machine interface (NMI) design and while found success in performance the complexity was too high for implementation. Switching over to a consumer processor, the Intel Atom, they managed to collect both mechanical and EMG data utilizing only 10.62% of the chip and in a 20ms window response time with a 99.94% accuracy rating for predicting mode transitions. In the research’s conclusion, a low power consumer chip with extra computational room is an attractive option to create a single-chip solution. More research needs to be done to include real-time impedance based leg control, EMG motion artifact detection, and a signal trust assessment to be a full solution.


Researchers at University of Rhode Island have begun developing an embedded CPS to begin controlling artificial legs of transfemoral patients in a finite-state system (FSM) involving sit-to-stand and stand-to-sit transitions. What this research found is that more accuracy is artificial leg systems, as any error rate gets compounded quickly and can lead to injury unlike artificial arms. In their embedded system they found that using a dedicated graphics card to perform testing was substantially faster than their CPU server. This is an important discovery as speed of training is important to the learning process of amputees.

Continued research by University of Rhode Island has developed more testing further increase the accuracy of a neural-machine interface in a cyber-physical system. The software used to test this relied on creating a virtual reality to emulate the movements that it believed the user intended it to do. This system, which combines information received from neuromuscular and mechanical information is an improvement over either system’s information alone. However, they did not expand the research past sitting-to-standing and standing-to-sitting which as noted, would be necessary for further real use applications. The research again found microcontroller units were too slow for use in this system, having a noticeable 400ms delay.


Continued research by University of Rhode Island have developed a FPGA and microcontroller design for CPS transfemoral prosthetic device. In their past research, they found that a GPU with CUDA support had many magnitudes of a speedup over a traditional PC. However, with both energy and hardware limitations of having a portable GPU this type of system could not be correctly implemented in an embedded device. The FPGA design using the same EMG pattern recognition (PR) to determine state switches still maintained 98.99% accuracy found in the CPU implementation and found a 7x speed increase in the training phase of the algorithm and a more than 30x for the testing phase.


Researchers at University of Mons have prepared a review of the literature surrounding different control schemas of prosthetics, focusing on the different algorithms available for lower-limb prosthetics as well as different methods of retrieving data for these algorithms. Specifically, this paper focuses on biomechanical, EMG, peripheral nervous system and central nervous system signals to adapt to these changes. The majority of the control schemes made for prosthetics are finite state systems, however a few separate systems have been created such as a manual and on-off system. These systems depend on external supervision from the user to tell the prosthetic what state it should go in, either by button or switch on the forefoot. These are seen as more accessible to implement but are not very good at reacting to unique situations or keeping the user’s gait constant.

Researchers Kinsy et al. have developed a FPGA multicore design, MARTHA, that can be placed in a low-latency and low-power demanding CPS. This type of implementation, with explicit regard for vector style manipulations offers great benefit towards a powered electronic prosthetic system. In comparison with other research, such as University of Rhode Island, a GPU is magnitudes faster at virtual simulations over a typical processor. MARTHA I/II can take advantage of the transfemoral prosthesis’s computational problems while still maintaining a low-power footprint. In the paper’s conclusion, a heterogeneous embedded system could fit into the unique challenges that a CPS offers.


Researchers Lawson et al. are attempting to correct the altered gait that occurs in passive prosthetics when they are ascending and descending stairs. This powered prosthesis is using a four-state finite state model controller to manage each aspect of the ascending/descending the staircase which include the forefoot strike, stance knee flexion, swing flexion, and finally the swing extension. The results of this prosthetics testing concluded that they had significant improvements over a passive prosthetic and as such would result in approved gait and lessen the potential injuries that could occur.


Researchers at Cleveland State University have developed an engineering test for the biogeography-based optimization (BBO) algorithm. While the algorithm itself is not specifically made for prosthetics, in this case it was applied for robots, it is integral to a few prosthetic designs that use this algorithm to help with their CPS. BBO is a type of evolutionary algorithm (EA) that is necessary and the backbone of many CPSs. This specific research focuses on the capabilities of a BBO driven device in a noisy environment. Conclusions to the research imply that with their conventional feedback control system in controlling their test robots they found that the BBO driven devices were successful and source code/algorithms is available for this project.


Researchers Liu et al. begin testing a finite state impedance controlled system with and Dempster-Shafer Theory transition rules (DST) to accurately handle state switches. Implementing DST in a finite state control system is an alternative to other research done
with a biogeography based optimization (BBO) scheme. The results they found are significant as while external sensors would achieve more accurate results, DST was able to reliably handle transitions without any aid from external sensors, which in comparison is what the hard threshold (HT) alternative system was doing. This is important in an embedded system for both ease of use and keeping a system at low power.


Researchers Rodriguez et al. have considered that Model Predictive Control (MPC) is the most important tool that process control has to offer today. MPC is found to have several different control techniques that it can apply, such as fuzzy, adaptive, sliding mode, and predictive control schemas. Towards power electronics, it is found that there are too main classifications of techniques, such as a Continuous Control Set and Finite Control Set. In this review, it was found that MPC is a very strong contender for an option in the field of controlling power electronics and should be considered a staple in this research.


Schirner et al. introduce the term Human-in-the-Loop Cyber Physical System (HilCPS) which brings forth the entirety of powered prosthetic research. This research sets forth the idea that more intrinsic tools are needed to create a cyber physical system such as EMG/ECG/EEG data then a physical manifestation of an action like a computer mouse. This type of human interface is exclaimed in the article to be necessary for such a system like a prosthetic as it requires low-latency and as passive as possible decision making from the user.


Researchers Varol et al. proclaim to be the first in combining both a system for a powered ankle and knee joint prosthetic using a finite state impedance controller with a Gaussian Mixture Model (GMM) to determine what state the prosthetic currently is in. This research includes testing on switching between three activities, sitting, standing, and walking, and references both the transition and state switches that occurs in each. One novel technique they employed was the use of votes to register the accuracy of the state switch. These votes were time constrained so that each action only took a certain amount of time to reduce inconsistency. However, previous research has claimed that their measured latency of 800ms+ is too high to accurately react to a situation.

This review of the literature has begun to realize a shift in the applications of Model Predictive Control (MPC) as it has recently broadened its uses towards power electronics. In the past, it has successfully been used for things such as uninterruptable power supplies. Now, with the advent of powerful microprocessors this type of control schema can be applied towards multivariable real word problems. This literature review focuses on new adaptations of this control schema in reference to power consumption and other power loads. This is important for a powered prosthetic system and its need for low energy consumption.


Researchers from Cleveland State University are looking into the mechanics of a powered transfemoral prosthetic. The problem with most leg prosthetics currently is that they significantly change the gait of the user, and this will cause hip problems later on. CSU Researchers aim to fix this by using a set of two hydraulic systems that operate a cylinder actuator. In turn this should make a prosthetic both more manageable and discrete. A new open-loop control method was also created using a microcontroller implementation, which was stated as biogeography based optimization and uses simple genetic algorithms along with Fourier series to power the control system. However, previous research from Rhode Island University stated that they found this MATLAB style implementation to be too slow.


In further real-time expanded testing by both researchers at University of Rhode Island as well as Nunnery Orthotics & Prosthetic Technologies have found a decrease in response time latency as well as an increase in the number of available states that the prosthetic is able to switch from. The main challenge that is still unsolved from this research in general is found to be whether or not there is enough EMG data from the surrounding muscles to accurately aid mechanical driven data. In conclusion, they found latency results to be between 80-323ms available leeway for the prosthetic to begin reacting and a 98.36% success rate for recognizing level-ground walking, stair ascent/descent, sitting and standing. These results slightly differ from previous test subjects which infer that this is successful results can still be dependent on the user.

Continued research again from University of Rhode Island have continued testing their EMG pattern recognition design this time with a GPU implementation instead of an FPGA implementation. The Neural Machine interface design combines both physically determined information and neuromuscular information to figure out what state the prosthetic should be in. This specific part of URI’s research found that they had high accuracy in determining the sitting and standing states of their prosthetic during testing, and that the GPU’s speed was once again much more powerful then a typical server PC. However, previously completed research by the same research team found that the GPU was not able to be fully embedded so an FPGA system was necessary.


Researchers at Texas A&M study the nonlinear aspect of CPSs from bipedal robots and transfer the information learned towards a transfemoral CPS prosthetic. The end result of this research is that it has developed a reference to Inertial Measurement Units (IMUs) that will act as a basis for defining the movements of the prosthetic. IMUs, in addition with the control Lyapunov function (CPF) applied towards a Quadratic Program (QPs) will define how the prosthetic reacts to real world events. In conclusion, Texas A&M successfully built a nonlinear real-time controller that could walk with a much more normal gait than other prosthetics.
## List of Acronyms and Abbreviations

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>BBO</td>
<td>Biogeography Based Optimization</td>
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<tr>
<td>CCS</td>
<td>Continuous-Control Set</td>
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<tr>
<td>CPS</td>
<td>Cyber-Physical System</td>
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<tr>
<td>CPF</td>
<td>Control Lyapunov Function</td>
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<tr>
<td>CUDA</td>
<td>Compute Unified Device Architecture</td>
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<tr>
<td>DST</td>
<td>Dempster-Schafer Theory</td>
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<tr>
<td>EA</td>
<td>Evolutionary Algorithm</td>
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<tr>
<td>FCS</td>
<td>Finite-Control Set</td>
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<tr>
<td>FFSM</td>
<td>Fuzzy Finite State Machines</td>
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<tr>
<td>FPGA</td>
<td>Field Programmable Gate Array</td>
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<tr>
<td>FSM</td>
<td>Field State Machine</td>
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<tr>
<td>GA</td>
<td>Genetic Algorithm</td>
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<tr>
<td>GMM</td>
<td>Gaussian Mixture Model</td>
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<tr>
<td>GRF</td>
<td>Ground Reduction Force</td>
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<tr>
<td>HGM</td>
<td>Human Gait Modeling</td>
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<tr>
<td>HiL</td>
<td>Hardware-in-the-Loop</td>
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<tr>
<td>HiLCP</td>
<td>Human-in-the-Loop Cyber Physical System</td>
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<tr>
<td>HT</td>
<td>Hard Threshold (System)</td>
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<tr>
<td>IMU</td>
<td>Inertial Measurement Units</td>
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<tr>
<td>LEP</td>
<td>Lower-Extremity Prosthetic</td>
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<tr>
<td>MARTHA</td>
<td>Multicore Architecture for Real-Time Hybrid Applications</td>
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<tr>
<td>MIQP</td>
<td>Model Independent Quadratic Program</td>
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<tr>
<td>MPC</td>
<td>Model Predictive Control</td>
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<tr>
<td>QP</td>
<td>Quadratic Function</td>
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<tr>
<td>SMC</td>
<td>Sliding Mode Controller</td>
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<td>SVM</td>
<td>Support Vector Machine</td>
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