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Designing Electronics for an Artificial Leg

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Designing Electronics for an Artificial Leg

Cover Page Footnote

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1. Introduction

1.1 History of Prostheses

Before the introduction of microprocessor-controlled knees, prosthetic legs caused many problems for amputees. Past prostheses were stiff and did not emulate a human leg, so the user had to compensate by using unnatural hip motions. These hip motions resulted in two main problems. The first problem was that the unnatural hip movement caused adverse health issues such as osteoporosis and osteoarthritis [3]. The second problem was that the unnatural hip motions required more energy, causing a prosthetic user to be able to take fewer steps than an able-bodied person before becoming fatigued [2].

An initial attempt to remedy the drawbacks of early prosthetics was the introduction of microprocessor legs. The microprocessors use information from sensors mounted on the prosthesis to control the mechanical damping of the prosthesis [1]. The variable damping allowed these legs to swing more during the region of the gait cycle when the leg is not in contact with the ground. Since the leg is able to bend similar to a human leg during the swing (non-contact) phase, the prosthesis user can provide a motion from the hip that more closely matches an able-bodied hip motion. The more natural hip motion reduces the amount of energy required to walk and also reduces stress on bones that lead to further health issues. A picture of one of these commercially-available knees (Össur Mauch® knee) can be seen in Figure 1. Even though microprocessor knees are a great improvement to the quality of life of amputees, research was required to improve prosthesis performance in the region of the gait cycle when the leg is in contact with the ground (stance phase). Since the prosthesis has to support the weight of the user, prostheses tend to stiffen during stance phase. By becoming stiff, the prosthesis is unlikely to collapse under the weight of the user, but does not accurately restore gait trajectories.

Figure 1: An Ossur Mauch knee. This prosthesis acts as a variable damper to restore proper gait during swing phase.

1.2. Current Prosthesis Research

Current global research is trying to improve the emulation of a human leg that microprocessor prostheses have during ground contact. Researchers at multiple universities have studied the possibility of adding motors to prostheses [4], [5], [6]. By adding these motors, prostheses are emulating human muscles because they can actively move the knee and ankle joints. This research is very recent, with only a limited number of commercial legs available. One of the largest problems with these motorized prostheses is that they consume a large amount of energy. The large consumption of energy creates a need for large, heavy batteries and allows for a limited operating time.

Our current research is attempting to reduce the dependence on large batteries to power active prostheses through regenerative braking. Previous studies have shown that the human knee and ankle has times at which it requires power to move and times when power is required to be dissipated through a braking action [7]. These different modes of power operations are similar to an automobile. When a car needs to move forward, the engine supplies power to the wheels. When the car needs to stop, it dissipates energy through the brakes. Instead of wasting this energy as heat through the brakes, regenerative braking cars store this excess energy in batteries. Our research uses the same idea, but applies regenerative braking to a transfemoral (above-knee) prosthetic leg.

The human leg requires braking during many activities throughout the day. A prominent example is walking down stairs. In this activity, the human loses potential energy with each step, which is dissipated as heat through the muscles. Our research has focused on the dissipated energy during normal walking. Over the course of one gait cycle, the human knee has a net dissipation of energy. A graph of the power flow at the knee for typical walking is shown in Figure 2; the positive values represent when the knee requires power and negative values represent when the knee is dissipating power as heat. This power flow is highly beneficial since the human ankle requires more power than it dissipates throughout one gait cycle. By using the excess energy from the knee motor and applying it to the ankle motor, a prosthesis could have a longer operating time.

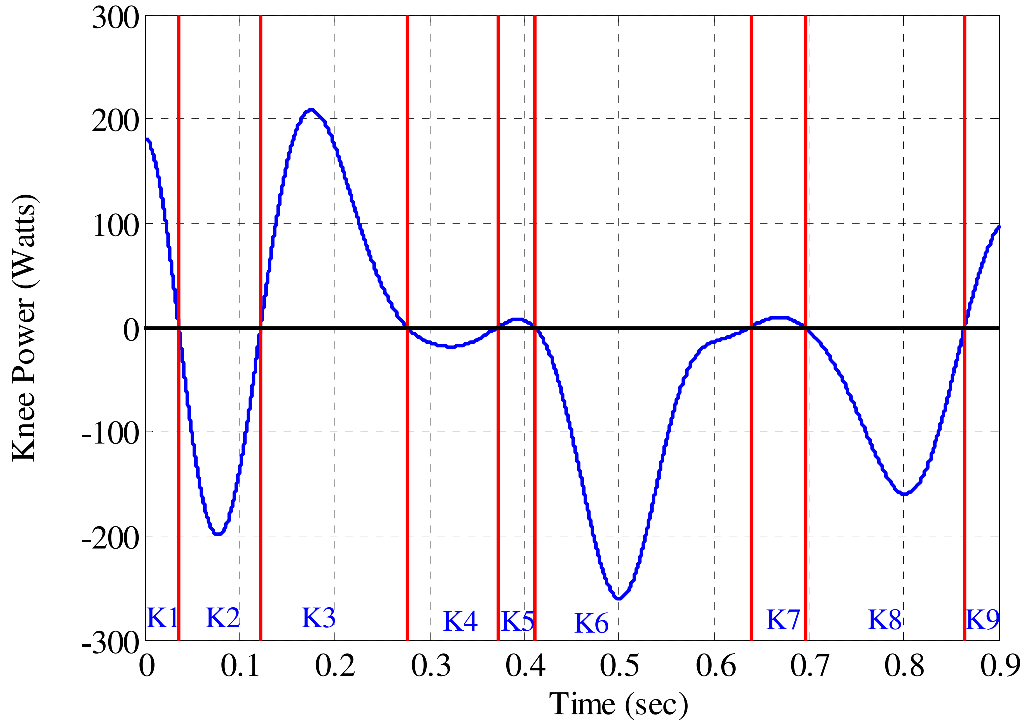

Figure 2: The typical power flow of a human knee during walking. Positive values represent when the knee requires power and negative values represent when the knee is dissipating power.

Capturing the excess energy throughout a gait cycle is accomplished by using the knee and ankle motors as generators. The torque and velocity from the leg is transformed by a mechanical transmission. The output of the transmission causes the motor shaft to turn, which then generates a current in the circuit connected to the motor. The electrical circuit takes the generated current and transforms it into a form that can be stored in supercapacitors. When the prosthesis needs to be powered, the circuit transforms the power from the supercapacitors into a form that can be used by the motors. Supercapacitors were chosen because they can handle large charges at fast rates. An example of a supercapacitor is shown in Figure 3.

Figure 3: A typical supercapacitor found on Digikey's online catalog.

Current research includes simulations of the described prosthesis. After simulations become more refined, our research aims to build and test a prototype of the prosthesis. Testing prostheses on human subjects is a difficult process. We need to ensure that all possible safety measures are in place and get permission from appropriate agencies to be able to begin testing. Testing with human subjects is also difficult because humans, especially amputees, can become fatigued and have inconsistent gait patterns while learning how to walk with a new prosthesis. To avoid these complications, our research will use a human hip robot that was developed during a previous project and is shown in Figure 4. With this robot, we can test the prototype with repeatable motions of the hip and gradually introduce disturbances to the leg. After positive tests with the hip robot, human subject testing will be examined.

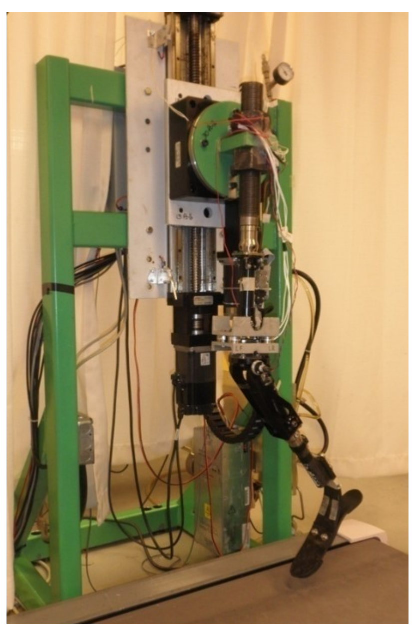

Figure 4: A hip robot testing a prosthesis.

2. Circuit Design

The proposed prosthetic leg is a complicated system that is composed of many smaller subsystems. One particular area of research that is addressed is the electronic circuitry that is required to connect the prosthesis' motors to the supercapactior. This circuit, in addition to the mechanical section of the prosthesis, requires optimization in order to select the components that will give the most regeneration and restore proper knee angle trajectories.

One of the main goals of this research is to capture energy in a supercapacitor when it is available. The need for electronics is due to the requirement of power conversion. The prosthesis circuitry needs to be able to take power from the motor and convert it to a form usable by the supercapacitors. The circuitry must also be able to convert power in the reverse direction (from the supercapacitor to the motor). The current power electronic circuitry is shown in Figure 5.

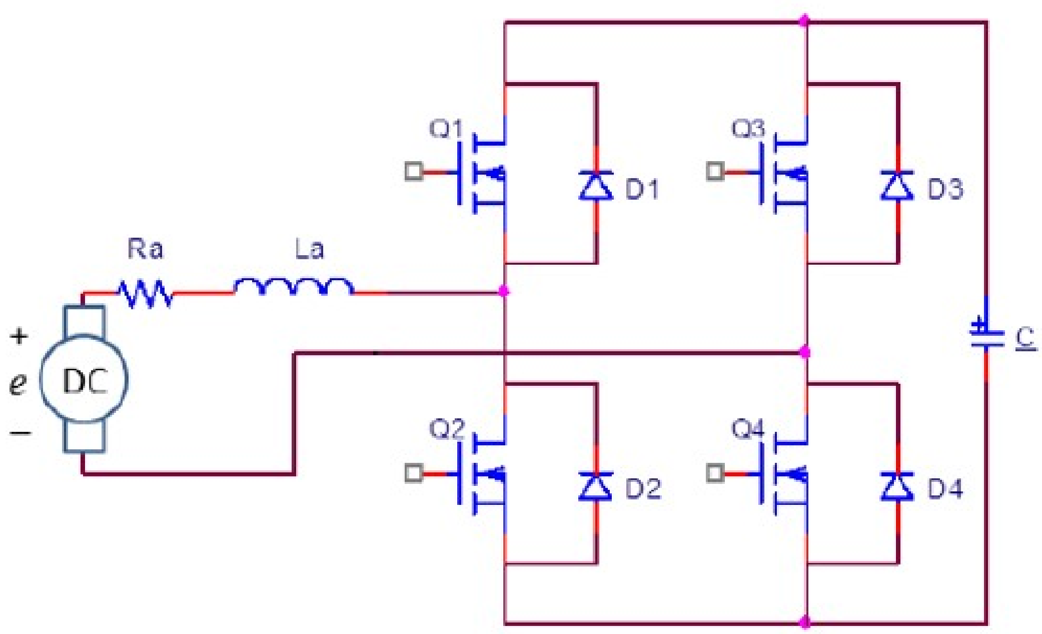

Figure 5: The power electronics circuit used to transform electric power in the prosthesis.

Fundamental laws of physics and circuits are applied to the circuit schematic shown in Figure 5 to obtain a mathematical representation of the circuit. The equations that model the circuit are combined with the equations that model the mechanical system to create a mathematical model of the entire prosthesis. All of the equations are programmed into a simulation through use of the MATLAB® and Simulink® software.

The power electronic circuitry by itself is unable to allow power to flow properly throughout the prosthesis. The power electronics circuitry includes four switches (Q1-Q4 in Figure 5) that determine which way power will flow. A system that triggers the switches at the proper times is developed in this research. Such a system is called a control system, which was also mathematically modeled in the prosthesis simulation.

The control system used in this project is based off of a standard PID controller which is commonly used in industry. The controller compares the simulated knee angle to a reference knee angle and then manipulates the difference between the two trajectories. The controller then send signals to the four switches in the circuit in order to make the prosthesis better match the reference knee angle.

Currently, the prosthesis is simulated through the use of computer programs. The simulations were based on the mathematical representations of physics, circuitry, mechanics, and control. Once the research becomes more refined, prototype hardware will be built. A microcontroller will have to take information from sensors and then control the switches in the power electronic circuitry in real time.

3. Optimization

Everything that is engineered needs to be optimized. Cars need to have high fuel efficiency at a low cost and also be comfortable to drive. A prosthesis also has multiple objectives that need to be met. The prosthesis must replicate human motion trajectories, be able to store a large enough charge to have long operating times, and be cost effective among many other goals. An optimization algorithm is used to select components and control parameters for the system.

Biogeography-based optimization (BBO) is the name of the algorithm that was selected to optimize the prosthesis simulation. This algorithm is based on biogeography, the study of the migration of species [9]. This algorithm treats each electrical / mechanical component and control parameter as a characteristic that composes an individual. Many different combinations of characteristics make many different individuals. The individuals are said to be living on an island.

BBO works by emulating immigration and emigration, having individuals entering and leaving islands. The more desirable an island is, the more likely that it will have a high population of individuals, which means that the island is nearing its population limit. Due to the limited resources, the island will have a high emigration rate as individuals go to other islands and share their good characteristics. Islands with poor resources will have a small population, giving room for immigration to occur. Strong individuals bring their strong characteristics to share in these lightly-populated islands.

Over the course of many generations, individuals moving between islands and sharing desirable characteristics will create a population of desirable individuals. These desirable individuals, which represent a list of electrical / mechanical components and control parameters, will eventually become desirable to the point that the prosthesis will operate in an optimized manner by having proper knee angle tracking and energy regeneration.

To get many generations to share characteristics, BBO takes an initial generation of individuals that had their characteristics selected manually by our research team. BBO then determines how desirable each individual is through the following equation:

$$Desirability = ability\ to\ restore\ knee\ angle\ trajectory + ability\ to\ regenerate\ energy \tag{1}$$

Once the desirability of each individual is calculated, BBO determines the immigration and emigration rates of each island and uses probability to determine which islands selected individuals will emigrate to. Once all individuals are selected to emigrate, or remain on an island, BBO will repeat the process for the newly-created generation.

4. Results

The proposed circuit was optimized with the BBO algorithm. BBO ran for 20 generations and gave a knee angle trajectory shown in Figure 6. The solid blue line represents the reference knee angle that should be followed. The dashed red line shows the knee angle trajectory created from the prosthesis simulation. Over the course of an entire stride, an averaged error of 5.15 degrees is present. The capacitor was able to regenerate energy at some point during the stride when the knee was acting as a brake, but had an overall loss of energy when averaged throughout an entire stride.

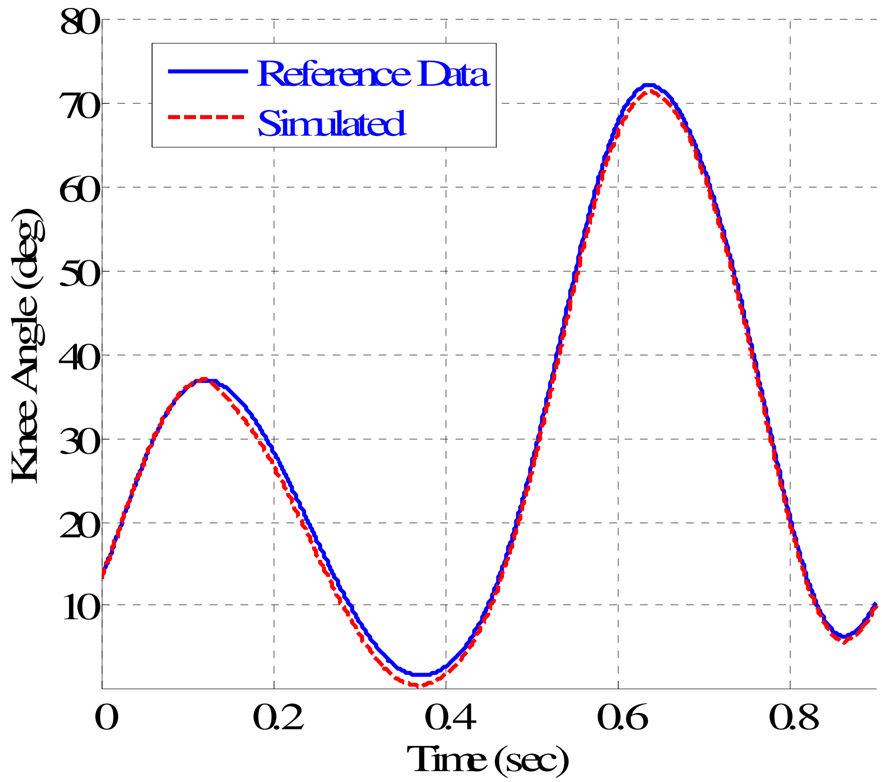

Figure 6: The simulated knee angle (dashed red line) compared to the reference knee angle (solid blue line). The averaged difference between the two trajectories over one stride is 5.15 degrees.

To improve the amount of energy that the capacitor regenerates during braking actions, BBO can be used differently. The desirability of each individual can be biased so that more emphasis is placed on the ability to regenerate energy than the ability to track. Initial tests of this idea have shown that sacrificing a small amount of knee angle tracking for a large change in the increase of energy that is regenerated is possible.

5. Conclusion and Future Work

A prosthesis was modeled with mathematical equations and simulated with the MATLAB and Simulink software. This simulation includes equations that model the mechanical sections of a prosthesis, the electric circuit that connects the motor and supercapacitor, and the control system that allows the circuit to properly operate the prosthesis. Biogeography-based optimization was successfully able to provide knee angle tracking and some energy regeneration. Preliminary tests showed the ability to regenerate a larger amount of energy at a small sacrifice of knee angle tracking.

The prosthesis could be optimized further with BBO by running more generations of the algorithm while placing more emphasis on energy regeneration than knee angle tracking, within certain boundaries. Once the prosthesis simulation is thoroughly tested and continually provides desirable operation, a prototype could be built that can be tested with a hip robot [8].

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