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Active Prosthetic Knee Fuzzy Logic - PID Motion Control, Sensors and Test Platform Design

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Abstract— The purpose of this paper is to describe and evaluate the design and testing of a control system and test platform for an Active Prosthetic Knee (APK). The research scope includes mechanical design, sensing system, and motor (motion) controller of the Active Prosthetic Knee. The main objective is to produce an affordable yet rugged active prosthetic for above-the-knee amputees in developing countries. The main advantage of an active prosthetic is its ability to more accurately mimic the motion of a healthy limb without producing strain on the patient's muscles. The APK needs to be able to decide when to move by analysing the motion of the healthy leg without the use of expensive sensory system.

Index Terms— Active Prosthetic, Controller Design, Fuzzy Logic, Gait Cycle, PID Control, Platform Design

1 INTRODUCTION

The field of prosthetics has been in development for thousands of years. Historical records show that research into prosthetics was undertaken during the time of the ancient Romans, Egyptians, and Greeks. Modern day prosthetics can be divided into active and passive devices. Passive prosthetics require the patient to move the prosthetic device with their own effort. Often times this can be difficult since passive prosthetics cannot fully mimic the motion of a healthy, functioning limb. Active prosthetics aim to solve this problem by using their own power source and sensors placed on the patient to move with the patient [1].

1.1 Background

Current active prosthetic knee joints such as the Ottobock C-Leg offer the most advanced treatment for above-the-knee amputees. However, this technology comes at a high price and is far too expensive for amputees in countries such as Afghanistan where the average salary is only $300/yr [2]. The only type of above-the-knee prosthetics available in such countries are passive devices which are cumbersome and do not fully restore a person's previous degree of mobility and freedom.

1.2 Needs Assessment

Currently there are between 300,000 and 400,000 people around the world living with landmine related injuries. Most of these injuries involve leg amputations. Current active prosthetics cost between $30,000 and $45,000, placing them out of reach of most of the people that are affected by landmines [3]. In addition, current active prosthetics need to be calibrated to suit each individual patient and it is impractical for them to be mass manufactured and deployed around the world. Therefore there is a clear need for an affordable, reliable, and practical active prosthetic knee device.

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1.3 Problem Formulation

The goal of this project is to develop an active prosthetic knee that uses the position of the healthy leg to determine the position of the prosthetic knee. The position of the healthy leg is tracked using sensors mounted on the healthy tibia and femur. This data is sent to a controller that modulates the amount of torque applied to the prosthetic knee. The purpose of this project is to continue the work started by three previous masters' level collegues who finished the fabrication of the APK prototype. This work includes: designing a sensor system to track the motion of the healthy leg, programming a controller to manipulate the prosthetic knee, and designing a test platform to evaluate the performance of the completed system. Specific design constraints for each of the project's components are discussed in the next section.

1.4 Design Criteria and Design

The sensing system and the controller should work together to accurately mimic the human gait cycle [4]. Specifically, the sensor and control system should meet the following constraints:

1. Mimic a human gait at a steady walking speed of 1.5 m/s.
2. Control the knee over a range of motion of between 0° and 30°.
3. The sensors should require little to no calibration.
4. The sensors should be easy to wear and should not inhibit the motion of the healthy leg.
5. The wireless sensors should accurately measure the angle of the femur and tibia and wirelessly transmit the data to the controller.

The test platform is being designed to evaluate the performance of the APK over a steady walking cycle for a 50^{th} percentile male [5]. The APK will be mounted to an artificial femur that will replicate the motion of an amputated femur. Specifically, the test platform should meet the following requirements:

1. Replicate the femur's range of motion of -20° to 30°.
2. The system should match a walking speed of 1.5 m/s.
3. The swing speed and acceleration should be 5.08 rad/s and 230 rad/s^2, respectively.

Overall, the entire APK should cost under $3000, be compatible with a broad range of physiques with minimal calibration, and generally have an aesthetic appearance.

2 Patent Search

A search of the Canadian Intellectual Property Office and US Patent databases shows five different approaches towards the design and control of an active prosthetic knee. Although all five patents discuss new and novel methods for controlling an active prosthetic, none of the patents use the control approach outlined in this paper or utilise the same pulley-ball screw mechanism as the APK. Therefore the project described in this paper is patentable. The patents are discussed in detail in the following paragraphs.

Fig. 1. Operation: The knee joint (18) is connected to the tibia (10) via a hydraulic fluid control unit (20). The hydraulic piston lengthens and shortens to simulate the movement of a knee.

Key Differences: Use of hydraulics to actuate the knee joint. No mention of how the speed of the piston is controlled.

Fig. 2. Operation: The amputated femur (104) sits in a housing (102). A variable-torque damping system (130) is controlled by (120) to simulate movement of the knee. A knee-angle sensor measures the angle of the prosthetic knee, and compares this value with a pre-programmed gait cycle to determine the next movement.

Key Differences: Angle sensor is mounted on the prosthetic knee. Use of MR fluid to provide knee actuation.

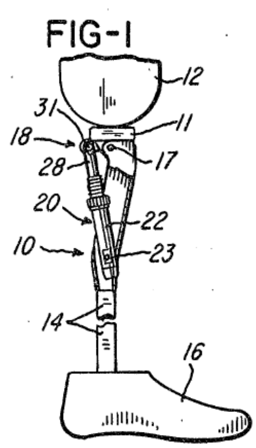

Fig. 1. Hydraulic Control Unit for Prosthetic Leg: CIPO #02056134

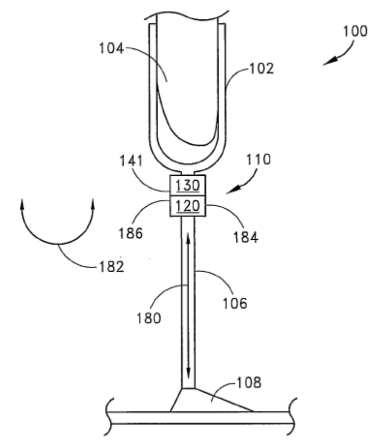

Fig. 2. Speed-Adaptive and Patient-Adaptive Prosthetic Knee: CIPO #02405356

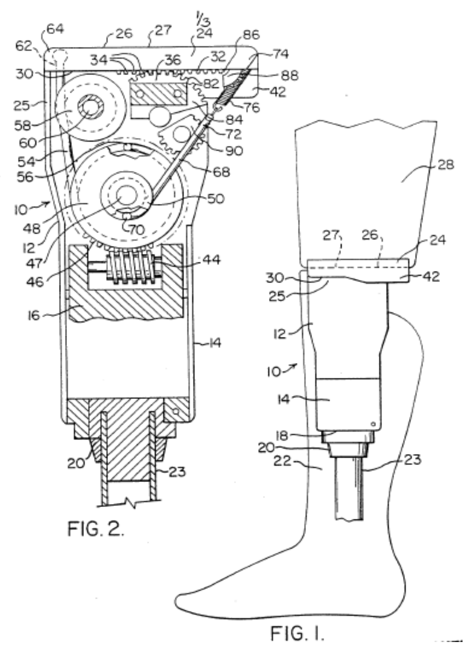

Fig. 3. Prosthetic Knee Joint: CIPO #02108378

Fig. 3. Operation: The amputated femur sits in a housing (28) which is connected to the knee mounting plate (24). A motor (16) in the tibia section drives a worm gear (44). The worm gear turns the main drive gear (46) which uses cables to turn a gear segment (36). The gear segment simulates the knee joint by rocking back and forth along the rack gear (32).

Key Differences: Use of cables and pulleys to actuate knee joint. Proposes the use of myoelectric (EMG) sensors for control.

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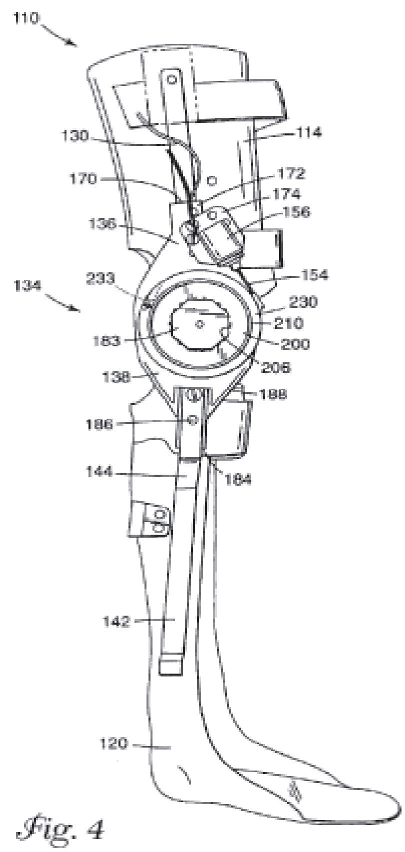

Fig. 4. Electromechanical Joint Control Device: US Patent #6834752

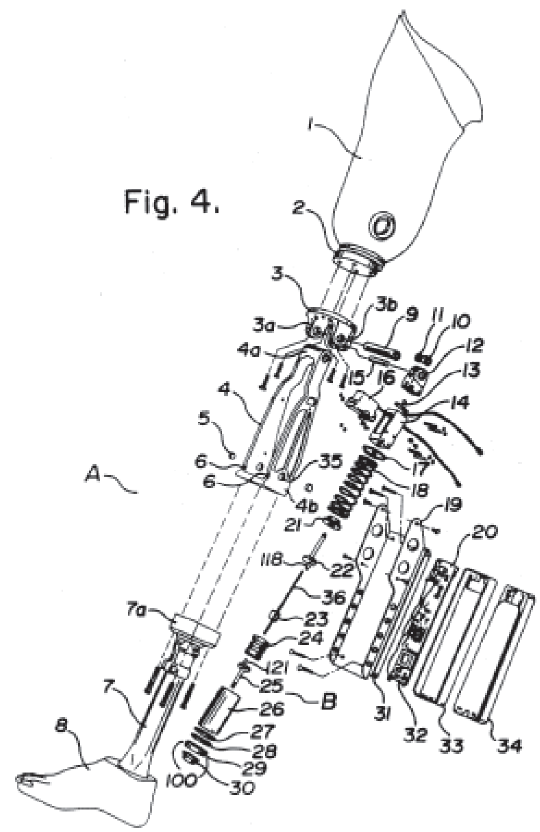

Fig. 5. System for Controlling Artificial Knee: US Patent #5571205

Fig. 4. Operation: A controller operates a linear solenoid (156) which extends or retracts to turn the knee joint (183). Two force sensors mounted on the sole of the foot send varying electrical signals based on what part of the gait cycle the foot is operating in. An angle sensor mounted on the knee provides feedback.

Key Differences: Use of force sensors on prosthetic foot. Use of solenoid to actuate the knee joint.

Fig. 5. Operation: A hydraulic damper (26) actuates the knee joint (30). The gait cycle is programmed into the microcontroller. Four strain gauges mounted on the prosthesis monitor the bending moment strain on the frame. Each part of the gait cycle is associated with a certain bending moment. A Hall-effect sensor monitors the angle of the knee for feedback.

Key Differences: Use of strain gauges to determine phase of gait cycle. Use of hydraulic damper to actuate knee joint.

3 Abstraction

The mechanical prototype of the APK has already been fabricated by previous collegues who worked on this project. Therefore, this section will focus on the different alternatives considered for the design and implementation of the sensor system, wireless angle measurement, fuzzy logic controller, and APK test platform.

3.1 Sensing System

The input sensors are required to determine the position of the leg with respect to the human gait cycle shown in Fig. 6. The sensors are part of a feedback control system where the system has the ability to know the exact state the user is in and the capability to forecast later states based on previously encountered information [6].

The two sensors considered are electromyography (EMG) sensors and accelerometers. The sensors will be installed on the healthy leg to determine which phase the prosthetic knee should be in.

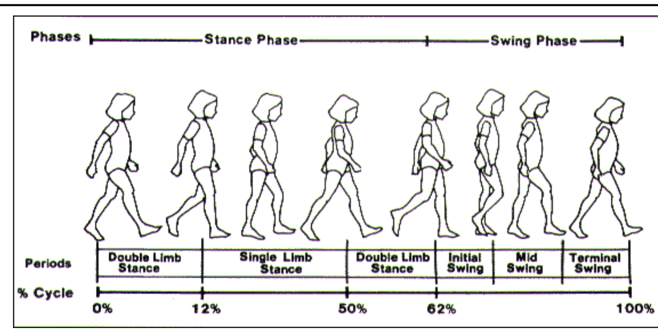

Fig. 6. Phases of the Human Gait Cycle

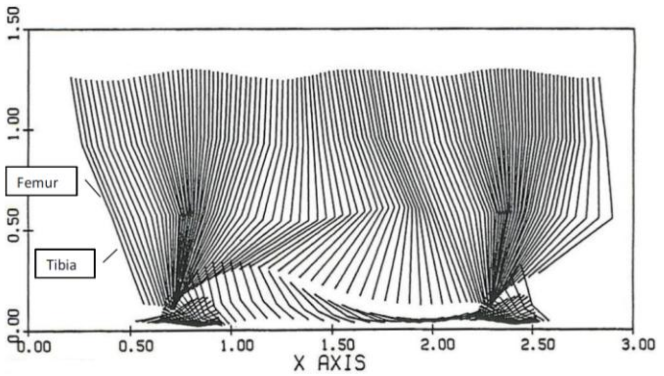

Fig. 7. Stick Diagram of Gait Cycle

Electromyography (EMG) is a technique for evaluating and recording the physiological properties of muscles at rest and during contraction. An EMG sensor detects the electrical potential generated by muscle cells when these cells contract, and also when the cells are at rest. The accelerometers are used to calculate the angle of the healthy femur and tibia during the course of the gait cycle. The angle of the healthy femur and tibia is used to pin point the user's movement during the gait cycle and provide the information required to predict the timing for future phases [7].

3.2 Wireless Sensor System

A wired or wireless approach can be taken for communication between the sensors and the microprocessor. The wired solution has the advantage of transmitting information at relatively high speeds in a dedicated channel for communication that is not as susceptible to interference as a wireless solution. The limitation of the wired solution is the length of the cable connecting the sensors to the microprocessor. In order to increase the practical applications of the APK the wireless solution has been given focus to improve the device after successfully proving the working system with a wired solution. Standardized communication protocols such as Wifi, Bluetooth, and Zigbee are considered within the various wireless solutions available. Solutions that do not have standardized communication protocols consist mainly of hardware operating at specific frequencies, for which the method of handshaking that occurs between the transceivers needs to be determined as part of the project specifications [8].

3.3 Controller Design

As mentioned in section 1.3 – Problem Formulation, the goal of this project is to develop an active prosthetic knee which uses the position of the healthy leg to control the motion of the active prosthetic knee. The challenge associated with gait analysis and control is the uncertainty in tracking the human locomotion within a gait cycle. In addition, the changing dynamics of the system such as the variable ground reaction forces require a system that is either highly adaptive or modular. This idea motivates the research of implementing an artificial neural network or fuzzy logic based controller. Each approach has different characteristics which are outlined in the following points.

- Neural networks systems are excellent interpolators whereas fuzzy logic systems are highly modular and can handle uncertainty.
- A fuzzy logic system does not require training whereas a neural network does require training.
- Continuous online-training of the neural network makes it computationally expensive.
- A neural network has to be retrained if disturbances are introduced to the system whereas fuzzy logic can make intelligent decisions even with imprecise input data.
- Fuzzy logic implementation allows for use of inexpensive sensors which reduces overall cost.

Both implementations are valid solutions for developing the intelligent control system. However, both cost and efficiency need to be considered when selecting one design over another.

3.4 Test Platform Design

The purpose of the test platform is to simulate the human gait cycle during a steady walking motion. In other words, the test platform must allow the APK to match the position of the tibia shown in Fig. 7. As Fig. 7 shows, the entire leg has motion in the vertical, horizontal, and angular directions. Therefore, 3 DOF are required to accurately simulate the motion of the human gait cycle.

The three designs considered for the test platform are described in the following paragraphs.

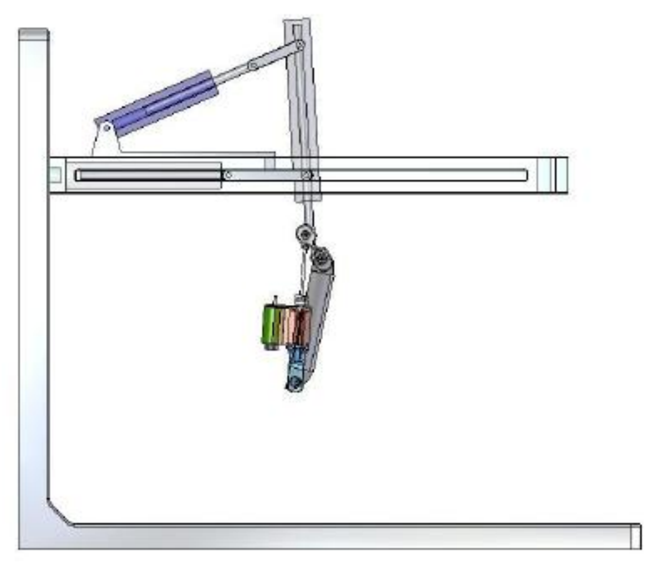

Fig. 8. Angled Piston Design

Angled Piston Design: The first design uses three pistons to provide the 3 DOF. As seen in Fig. 8 each pneumatic piston provides one DOF. The horizontally mounted piston slides along in a machined groove, while the vertically oriented piston replicates the movement of the hip. The blue piston

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changes the angle of the femur by pivoting the vertical piston about the joint connecting the horizontal and vertical pistons. The vertical piston represents the femur.

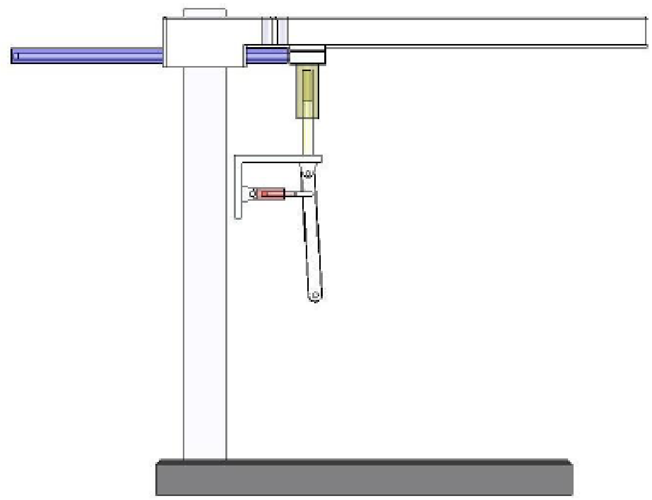

Fig. 9. Cartesian Piston Design

Cartesian Piston Design: A simpler version of the previous design can be seen in Fig. 9. In this design the 3 pistons still provide 3 DOF but are installed in a more conventional arrangement. The blue piston provides horizontal movement, the beige piston provides vertical movement, and the red piston changes the angle of the femur (shown in white).

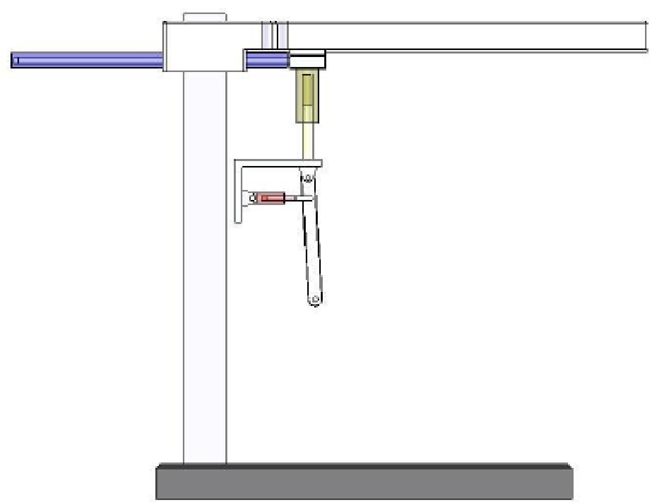

Fig. 10. Single Piston Design

Single Piston Design: This design uses a single position to simulate the angular movement of the femur, and a set of springs to simulate the limited vertical movement of the hip. Horizontal movement is not simulated directly as in the other two designs. Instead, the APK will be made to walk along a treadmill mounted in the base of the platform. As the APK walks along the treadmill it will move in the vertical direction along 4 rods. This design is shown in Fig. 10.

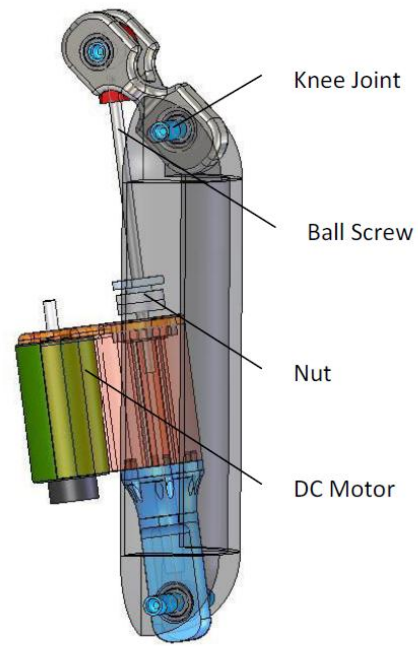

Fig. 11. APK Mechanical Design

4 PROPOSED SOLUTION

The APK is a microcontroller-operated knee prosthetic device with a single degree of freedom (DOF) at the knee joint. A DC motor is connected to a pulley system that drives a nut. The nut moves a ball screw up and down to create a pivoting action about the knee joint. The prototype and its main components are shown in Fig 11.

The entire structure is fabricated from an aluminium 6061 alloy for enhanced weight-strength characteristics. The prototype is designed to handle a maximum dynamic load of 2000 N to replicate the mass of a 70 kg subject, with a safety factor of three. The motor is a high-speed, high-torque DC brushed motor with a peak operating speed of 7468 RPM. Since the focus of this project is on the design of the sensors, control system, and test platform, the following sections will provide more detail into the proposed solutions for these components instead of the design of the APK.

4.1 Sensing System Proposed Solution

The two approaches considered for the sensing system have a number of differences. The main difference involves the electronic aspect of the control system. The EMG signal must be amplified and filtered to produce a usable data set for the microprocessor. The angular model requires additional inputs in the form of foot contacts to further complete the various gate cycle phases. Table 1 compares the two alternatives using five key criteria. Each alternative is assigned a grade between 0 and 5, with 5 being the highest grade.

TABLE 1
EMG SENSOR VS. ACCELEROMETERS

Design Criteria	EMG Sensors	Accelerometers
Number of Sensors	5	4
Calibration Required	2	4
Reliability	3	5
User Comfort	2	4
Ease of Implementation	2	4
Total	**14**	**21**

Based on the evaluation criteria the accelerometers are the favoured solution for the sensing system.

4.2 Wireless Sensor System

The chosen solution uses the Bluetooth protocol within the Nintendo Wiimote as the main transceiver. The advantage of this solution is that the accelerometers can be used to measure angle of the human femur and tibia bones, which are also the inputs for the control system. To narrow down the list of design alternatives only wireless solutions with a set of standardized communication protocols are considered since the development of such protocols is not part of the project scope. In addition, the technical specifications of the protocols are examined to determine which method does not meet the project specifications. Lastly, protocols with specifications which best meet the operating conditions of the project are evaluated. Based on these criteria Bluetooth is the only viable wireless protocol. To ease the implementation off-the-shelf units such as the Nintendo Wiimote and the Sony Playstation SIXAXIS controllers are considered since both use Bluetooth for communication and have built-in accelerometers built. A comparison of the two controllers is shown in Table 2. Each alternative is assigned a grade between 0 and 5, with 5 being the highest grade.

TABLE 2
WIIMOTE VS. SIXAXIS

Design Criteria	Nintendo Wiimote	Sony SIXAXIS
Functionality	4	4
Hardware Community Support	5	3
Cost	4	3
Total	13	10

The Nintendo Wiimote is chosen based on its superior support and lower cost. In terms of hardware community support and the number of functions that meet the project specifications, the Nintendo Wiimote has a hardware community that is much larger and can give much needed support during the project development and also provide adequate functionality.

4.3 Control System Proposed Solution

The uncertainty involved in tracking the walking patterns of the human gait necessitates the use of a fuzzy logic or artificial neural network based controller. However, as mentioned previously, using a neural networks approach requires online supervised-training of the system due to the varying dynamics of the system. The issue with online training is it requires more processing time which may slowdown the system response and reduce the performance of the controller. Although this can be overcome by using a faster and more powerful processor one of the main objectives is to develop a cost-effective solution. A morphological table comparing the use of neural networks to fuzzy logic for the controller implementation is shown in Table 3. Each criterion is assigned a grade between 0 and 5 where 5 represents the highest score and 0 is the lowest score.

TABLE 3
NEURAL NETWORK VS. FUZZY LOGIC

Design Criteria	Neural Networks	Fuzzy Logic
Speed of Computation	2	4
Minimal Level of Training	2	4
Ability to Handle Uncertain Data	3	5
Reduced Sensor Cost	3	4
Ease of Implementation	2	4
Total	**12**	**21**

The approach of using a fuzzy logic based controller enables the system to integrate human intelligence into the control system while benefiting from reduced processing associated with online training. The initial fuzzy logic-based controller is shown in Fig. 12.

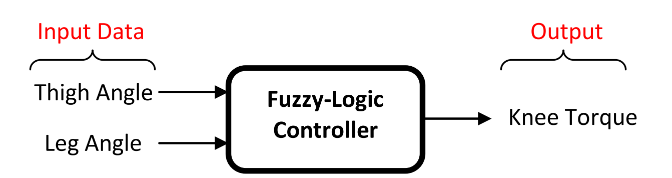

Fig. 12. Feed Forward Fuzzy Logic Control Architecture

4.4 Test Platform Proposed Solution

As mentioned earlier, the purpose of the test platform is to provide a platform that can be used to evaluate the performance of the APK under a steady walking gait cycle. Therefore the chosen design must satisfy the performance constraints associated with the steady walking gait, and meet the proposed budget of $1000. The three designs are evaluated in the morphological Table 4. Each design is evaluated according to four criteria and is assigned a grade between 0 and 5, with 5 being the highest grade.

TABLE 4
TEST PLATFORM DESIGN EVALUATION

Design Criteria	Angled Piston Design	Cartesian Piston Design	Single Piston Design
Manufacturing Simplicity	2	3	5
Simulated DOF	5	5	4
Gait Cycle Accuracy	3	5	4
Overall Cost	1	2	4
Total	**11**	**15**	**17**

Design 3 is the clear victor in this comparison since it has the simplest design, can simulate vertical and angular movement, can replicate the gait cycle, and has the lowest projected cost.

5 DESIGN

Each section requires a detailed design to meet the required criteria and constraints. This section builds on the proposed solution outlined in the previous section by describing the design of the sensing system, controller, and test platform.

5.1 Sensing System Design

Accelerometer Setup: The sensing system is designed using two three-axis accelerometers mounted on each axis of the human leg. In other words two accelerometers are mounted on the healthy femur and two more are mounted on the tibia. Although one accelerometer can be used to record a static angle, it is difficult to record a dynamic angle using just one accelerometer. The difficulty in cancelling out the motion of the leg can be overcome by using two accelerometers with a one-axis methodology.

This algorithm utilizes two accelerometers separated by a distance D to determine the angular acceleration and velocity. Using this, the result can be integrated to find the angle travelled. The downside to this algorithm is that the leg will require occasional calibration. The theory involves two accelerometers mounted a distance D (r2-r1) apart as in Fig. 13.

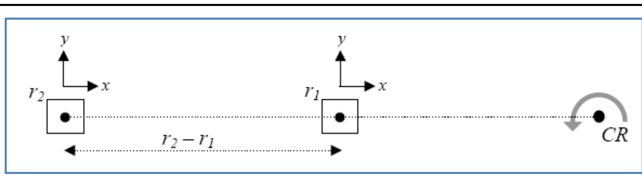

Fig. 13. Accelerometer Placement

The radial acceleration measured by each accelerometer in the x direction is:

$$a_{x1} = \omega^2 r_1 \quad (1)$$

Where ω is the angular velocity. The radial acceleration measured by accelerometer 2 is:

$$a_{x2} = \omega^2 r_2 \quad (2)$$

The difference of the two accelerometers yields the result below:

$$a_{x2} - a_{x1} = \omega^2 (r_2 - r_1) = \omega^2 D \quad (3)$$

$$\omega = \sqrt{\frac{a_{x2} - a_{x1}}{D}} \quad (4)$$

Also, the tangential acceleration (y-direction) can be measured by the equation:

$$a_{y1} = \alpha r_1 \quad (5)$$

Where α is the angular acceleration. The tangential acceleration measured at accelerometer 2 is:

$$a_{y2} = \alpha r_2 \quad (6)$$

Again, taking the difference:

$$a_{y2} - a_{y1} = \alpha (r_2 - r_1) = \alpha D \quad (7)$$

$$\alpha = \frac{a_{y2} - a_{y1}}{D} \quad (8)$$

It is important to note that the center of rotation does not matter; only the distance between the two accelerometers, D. The readings are taken by the microcontroller at a certain frequency and this Δt can be used to find the angle travelled. The angle and the sign of the movement can be determined using the velocity and acceleration. The measurements in this study can verify that two linear accelerometers can be used to determine angular rotation rates.

This method works best when the rotational motions are quick, and have large angular accelerations to avoid any divide-by-zero errors. Drift is not a problem since integration only takes place for a short time. Angular accelerations need to be lower than the accelerometer sensing range. This method does not work as well when angular accelerations (α_y and α_z) are very small since the algorithm relies on knowing the sign (+/-) confidently. There is some sensitivity to offset and sensitivity differences between the two sensors. Therefore, some method is needed to compensate for sensor mismatch, such as a calibration on start-up. Selection of the ω threshold (ω_t) is dependent on sensor performance and the expected motions in the application.

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Circuit Design: The circuit is designed to take the output of the two accelerometers, compare them ($a_{x2} - a_{x1}$ and $a_{y2} - a_{y1}$), and output the resultant voltage to the microcontroller. The op-amp circuit shown in Fig. 14 performs the subtraction of $a_{x2} - a_{x1}$ and $a_{y2} - a_{y1}$ and also increases the gain of the system.

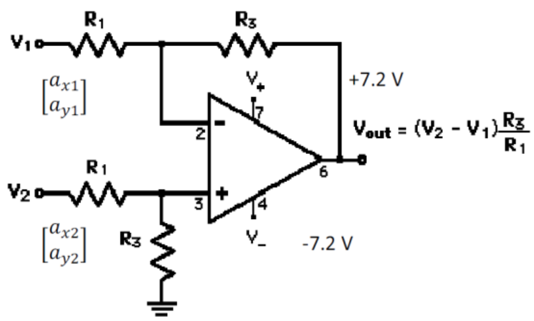

Fig. 14. Accelerometer Circuit

It is important to note the supply of 7.2 V from the DC to DC converter. This is the voltage of the battery; however for the purposes of the circuit the supply voltage has to be regulated to 5 V and inverted to -7.2 V.

The voltage is regulated to 5 V for the accelerometer supply using a standard 7805 voltage regulator and a DC-DC converter shown in the circuit in Fig. 15. Since the capacitors in this circuit are used to “smooth” out or remove noise from the circuit their value can be varied depending on the desired characteristics. For this project the capacitors are not needed to obtain a high quality accelerometer rating and are removed altogether.

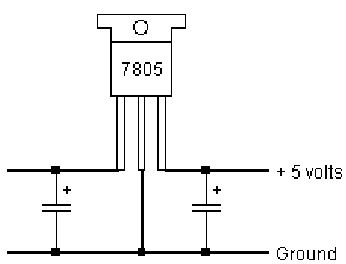

Fig. 15. Voltage Regulator

The inverting circuit is used to invert the voltage from a + 7.2 V value to a -7.2 V value. This is done using a DC-DC converter shown in Fig. 16. Providing a supply voltage to pin 8 will result in a negative voltage of the same magnitude from pin 5. This chip is very useful since prior to this a negative power supply was used alongside of a positive to provide the negative value.

The schematic of the overall circuit is shown in Fig. 17.

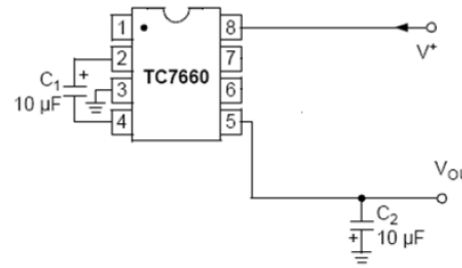

Fig. 16. DC-DC Converter

5.2 Wireless Sensor System Design

software development of the wireless communications is divided into three phases which helps systematically work from the flexible programming language of C++ to the highly specialized C code for the specific microprocessor used for this project.

Phase 1 involves the development of a utility in C++ that can connect with the Wiimote through the USB Bluetooth dongle and access the accelerometer measurements from both the Wiimote and the Nunchuck controller.

Phase 2 involves porting the C++ code into C code before it is modified to operate on the microprocessor in the third phase. Design of the wireless communication involves the Nintendo Wiimote which initially communicates with the computer via a USB Bluetooth module in the first two phases of the software development stage.

Phase 3 of the software development includes the Wiimote connecting to a Bluetooth module on the microprocessor side instead of a computer. The Bluetooth module connected to the microprocessor communicates through the serial port and acts as a transceiver between the Wiimote and the microprocessor.

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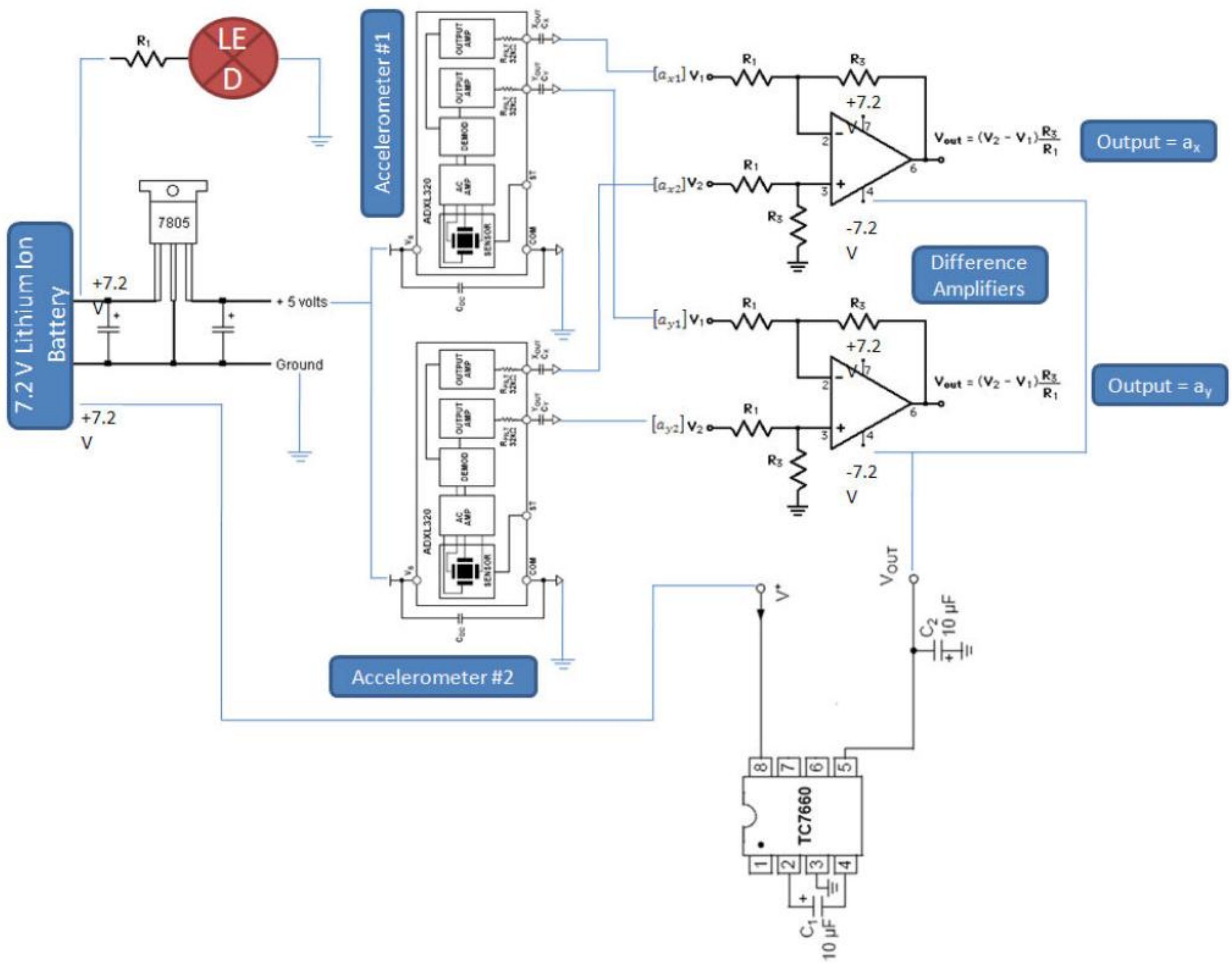

Fig. 17. Overall Sensor Circuit

5.3 Control System Design

The fuzzy logic-based controller consists of a feed forward architecture designed from nominal empirical data. Consequently, a feed forward architecture is only sufficient under nominal conditions and will fail if excessive disturbance is introduced into the system. Therefore, the initial controller architecture is modified to include a feedback loop containing a proportional-integral (PID) controller which tracks the actual position of the APK. The error signal is calculated by comparing the actual APK position to the desired APK position and is fed into the PID controller which outputs a control signal (torque command) that supplements the output of the fuzzy logic controller. Hence the feed forward fuzzy control predicates which phase of the gait cycle the APK is in and outputs a nominal output torque corresponding to the determined phase. Meanwhile the PID control compensates for excessive ground reaction forces (disturbances) by supplying additional torque to drive the APK to its desired position. The final control architecture consists of a fuzzy-PID controller which is shown in Fig. 18.

Fuzzy Logic Design: As mentioned previously, angular data from the healthy leg is fed into the fuzzy logic controller which determines the current phase of the APK and outputs an associated torque command to the motor. The fuzzy inferencing system (FIS) consists of two components: a set of input membership functions that map angular data to a set of phases within the gait cycle and a set of if-then rules which describe the human-like reasoning mechanism of the FIS. Each of the seven phases in the gait cycle has an associating membership function corresponding to the angle of the healthy femur and tibia. The membership function for both angular inputs is shown in Fig. 19.

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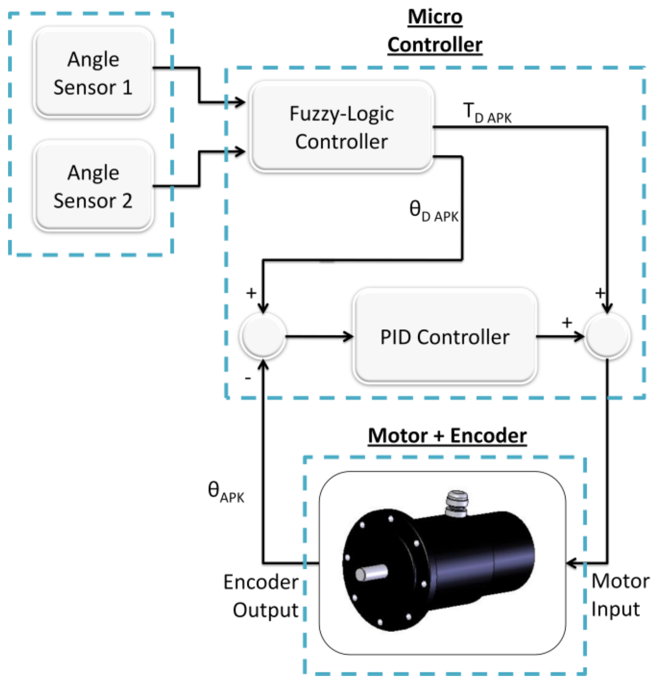

Fig. 18. Fuzzy-PID Control Architecture

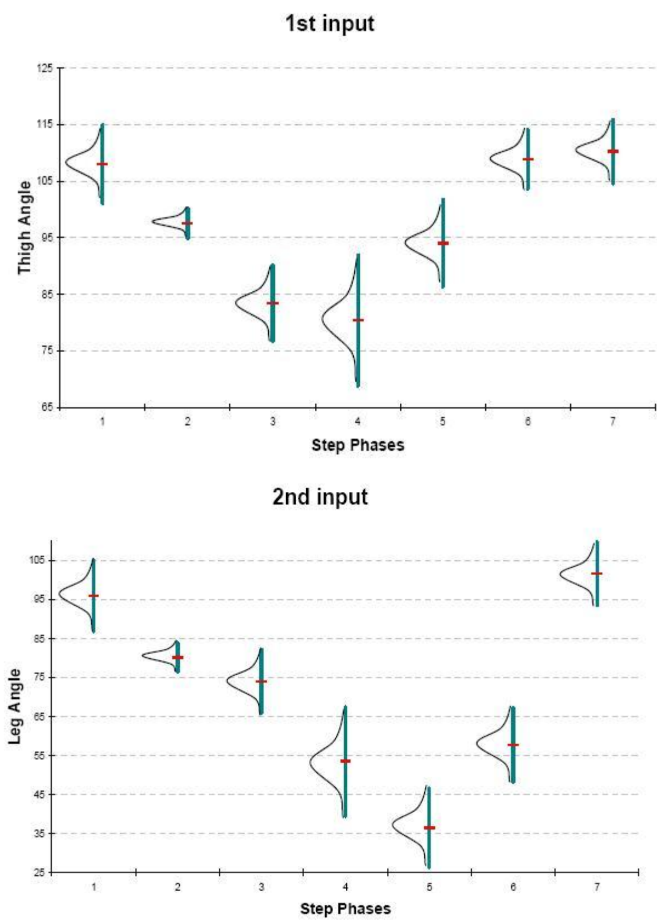

Fig. 19. Input Membership Functions

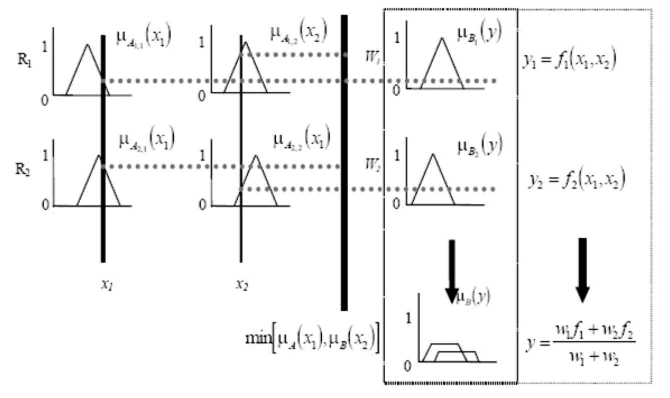

Fig. 20. Fuzzy Inferencing Mechanism (Simplified)

A set of output membership functions for each rule is triggered based on the firing strength of its antecedents, similar to mapping angular data using a set of input membership functions. The implication (or fuzzified output) is aggregated to produce an overall fuzzy output which is then defuzzified using a centre of heights method. A simplified diagram showing the entire FIS mechanism is shown in Fig. 20.

Fuzzy Rule Base: The following points show the basic rules used to design the knowledge base of the fuzzy inferencing system, where X1 and X2 are the angular inputs from the femur and tibia respectively. The seven phases LR, MST, TST, PSW, ISW, MSW, and TSW correspond to the loading response, mid stance, terminal stance, pre-swing, initial swing, mid swing, and terminal swing, respectively.

IF X1 is LR	**AND**	X2 is LR	**Then** Y is LR
IF X1 is MST	**AND**	X2 is MST	**Then** Y is MST
IF X1 is TST	**AND**	X2 is TST	**Then** Y is TST
IF X1 is PSW	**AND**	X2 is PSW	**Then** Y is PSW
IF X1 is ISW	**AND**	X2 is ISW	**Then** Y is ISW
IF X1 is MSW	**AND**	X2 is MSW	**Then** Y is MSW
IF X1 is TSW	**AND**	X2 is TSW	**Then** Y is TSW

As with all control systems a method of tuning the system to optimize performance is an important aspect of the controller design. In the case of the fuzzy logic controller the parameters associated with the input and output membership functions (Gaussian distribution) such as the mean and standard deviation need to be tuned. The method used to tune the fuzzy parameters is known as "adaptive network-based fuzzy inference system" (ANFIS). Similar to training an artificial neural network, training data is fed into the ANFIS which then outputs a set of optimized fuzzy parameters to be used in the actual fuzzy logic controller.

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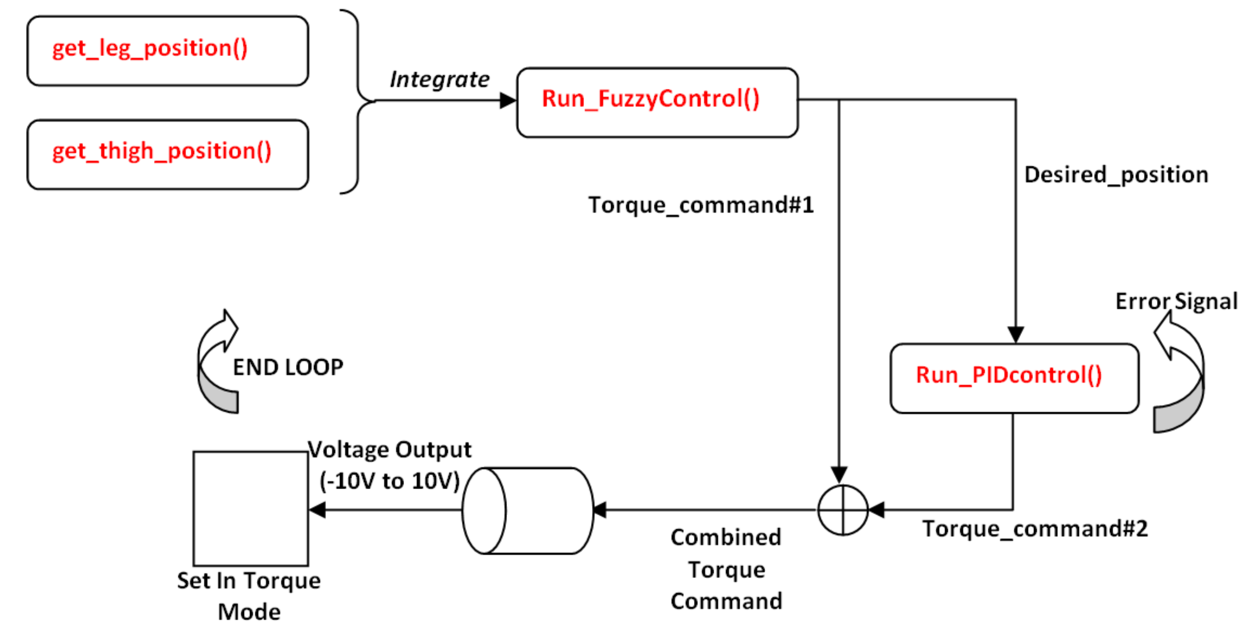

Fig. 21. Software Main Loop

Embedded Design: The fuzzy-PID controller is developed on a 16-bit PICMicro microcontroller (MCU) operating at 32MHz obtained through an 8MHz internal clock with a 4x-phase-locked-loop (PLL) [9]. The 80-pin MCU is chosen since it satisfies all the necessary I/O and serial communication requirements, sufficient built-in flash memory capacity, and external memory expandability at a low cost. The embedded system interfaces with all external peripherals such as the motor driver, angular sensors, and a Bluetooth module. The embedded software for the overall controller is interrupt driven for the following purposes:

- Capturing encoder pulses used for acquiring speed and position data
- Ensuring all incoming serial data is properly received and stored in a buffer for processing
- Timer interrupts used in functions requiring integration (i.e., integral control of the PID)

Aside from the interrupts used in the software the main program consists of sampling the ADC channels for accelerometer data from the femur and tibia where a total of 4 ADC channels are used (2 for each segment of the healthy leg). The ADC data is converted to an angular velocity and using known initial conditions (initial position of the leg) the angular velocity is integrated to get the angular position. The angular position of the leg is then passed into the *run_fuzzyControl* function which returns the output torque command and desired knee position of the APK. The *run_PIDControl* function takes in the desired knee position data and uses it to calculate the proportional, integral, and derivative terms of the PID control signal which is then converted to a secondary output torque command and sent to the motor driver via the Digital-to-analog Converter (DAC). Fig. 21 shows the execution path of the main loop of the software.

5.4 Test Platform Design

Based on anthropometric measurements the length of the femur is equal to the length of the tibia. Since the APK prototype has a tibial length of 0.36 m, the length of the artificial femur is also 0.36 m. The femur is actuated by a pneumatic piston acting at the femur's midpoint. Based on the required range of motion of -20° to 30° the required piston length is calculated to be 152mm using the geometry shown in Fig. 22.

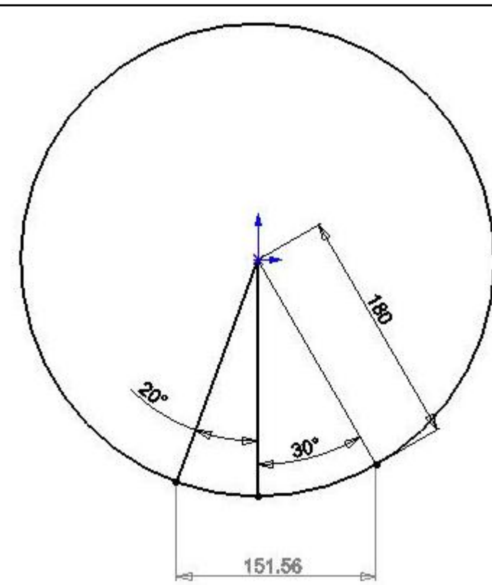

Fig. 22. Piston Stroke Calculation

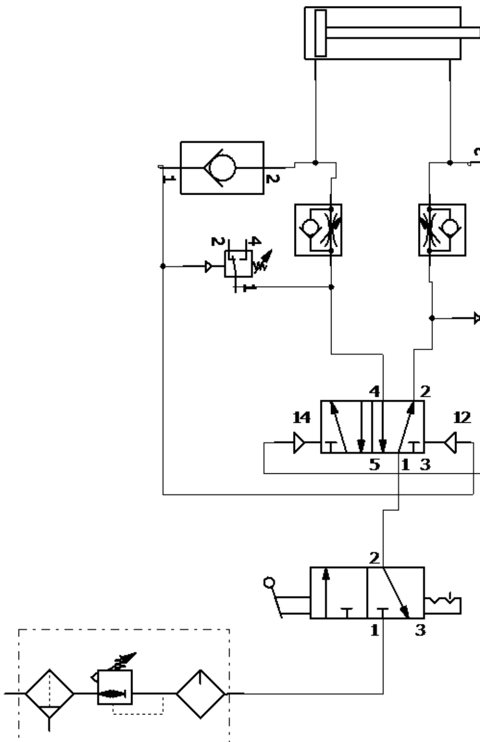

Fig. 23. Initial Pneumatic Reciprocating Circuit Design

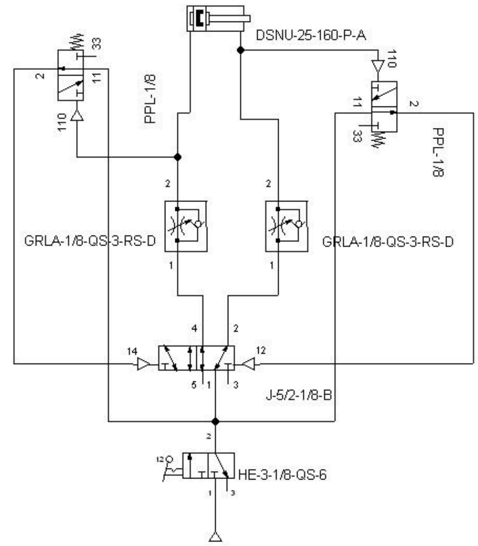

Fig. 24. Revised Pneumatic Reciprocating Circuit Design

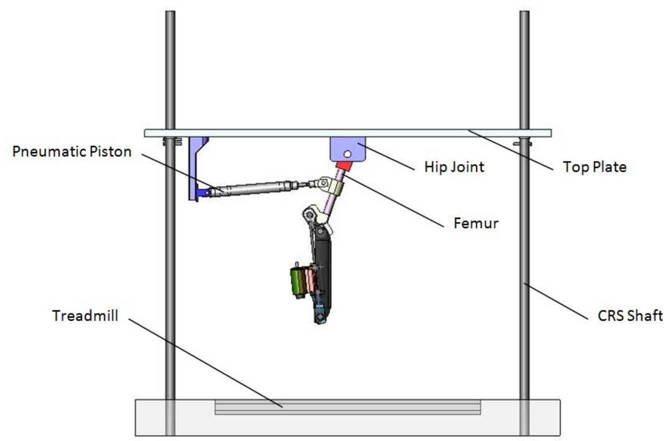

Fig. 25. Detailed Test Platform Design

The pneumatic system will reciprocate at a user-defined speed to replicate the motion of the femur. The speed of the piston is variable to allow the APK to be tested at higher speeds in the future. The bore of the piston is determined using the maximum acceleration of the femur. Based on a mass of 6 kg for the entire leg assembly and an acceleration of 230 m/s^2 the required bore diameter is 0.020m (see Appendix A for calculations). A 0.025 m bore diameter piston is used for a small factor of safety. Based on a required swing speed of 5.08 rad/s, the piston should have an extension speed of 0.9144m/s and a flow rate of 0.449 l/s based on a 0.025 m bore. Therefore the pneumatic system will require a double-acting piston with a 0.025 m bore and a flow rate of 0.449 l/s. The preliminary design of the reciprocating circuit is shown in Fig. 23.

The final cost of this design is $798.62. Since the budget for the test platform is only $1000, a simpler circuit needs to be designed. The new circuit is shown in Fig. 24. The total cost for this revised design is only $326.72.

The hip joint and pneumatic piston are supported by a top plate that moves up and down a set of 1″ diameter CRS shafts to simulate the vertical movement of the hip. The APK will walk along a small treadmill mounted in the base of the platform. The top plate also provides a platform on which to mount weights to simulate the mass of a person. A labelled diagram of the test platform is shown in Fig. 25. The foot attachment is not shown in Fig. 25.

6.0 Design Analysis

Based on the design outlined in the previous section this section will describe whether the proposed design meets the required specifications.

6.1 Sensing System Design Analysis

Consider the two three-axis accelerometers separated by distance D with X-axes aligned as shown in Fig. 26. The radial and tangential accelerations should be able to determine the angular velocity around the Y-axis (ω_y, roll rate) and the Z-axis (ω_z, yaw rate).

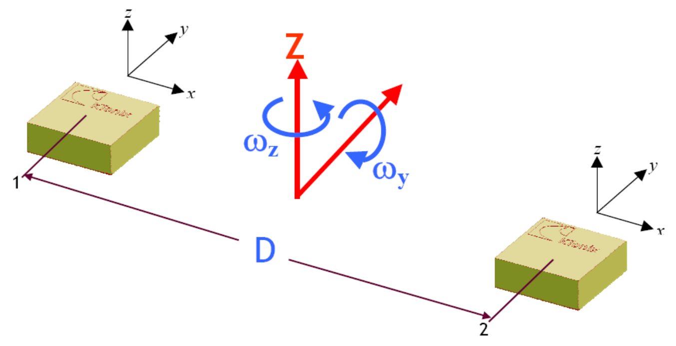

Fig. 26. Two Three-Axis Accelerometers On a Rotating Rigid Body

The X, Y, and Z-axis accelerations of both accelerometer #1 and accelerometer #2 are sampled to calculate the rotational rates. Keeping a running average (around 5 samples at 60 Hz) of the accelerations will reduce noise. The total rotation rate magnitude (ω) is calculated directly from radial acceleration as shown in Eqn. 9. Any ω that is below a threshold (ω_t) is set to 0 [10].

$$\omega = \frac{\sqrt{|a_{x2} - a_{x1}|}}{D} \tag{9}$$

When $\omega \geq \omega_t$

$\omega = 0$ when $\omega < \omega_t$. The magnitude of the total rotation rate magnitude calculated using equation 9 is shown in Fig. 27.

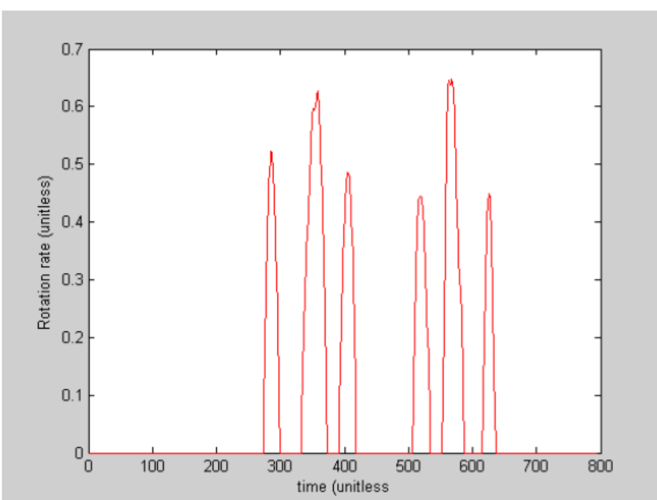

Fig. 27. Total Rotation Rate Magnitude

The total rotation rate is now known but the direction (sign) and the rotation rate about the Y-axis (roll) and the Z-axis (yaw) are still unknown. The angular accelerations about the z-axis and y-axis are calculated from the Y-axis and Z-axis accelerations using equation 8:

$$\alpha_z = \frac{a_{y2} - a_{y1}}{D} \tag{10}$$

$$\alpha_y = \frac{a_{z2} - a_{z1}}{D} \tag{11}$$

When ω is nonzero ω_y and ω_z can be determined by integrating α_y and α_z. Thus the relative magnitude and direction of rotation are calculated from the integrals of the tangential accelerations.

$$\omega_z = \int_0^t \alpha_z \, dt \tag{12}$$

$$\omega_y = \int_0^t \alpha_y \, dt \tag{13}$$

Since the angular accelerations, α_y and α_z, rise before ω, it is necessary to add the integral of α_y and α_z from several time steps before ω crosses the ω_t threshold. This timing is shown in Fig. 28.

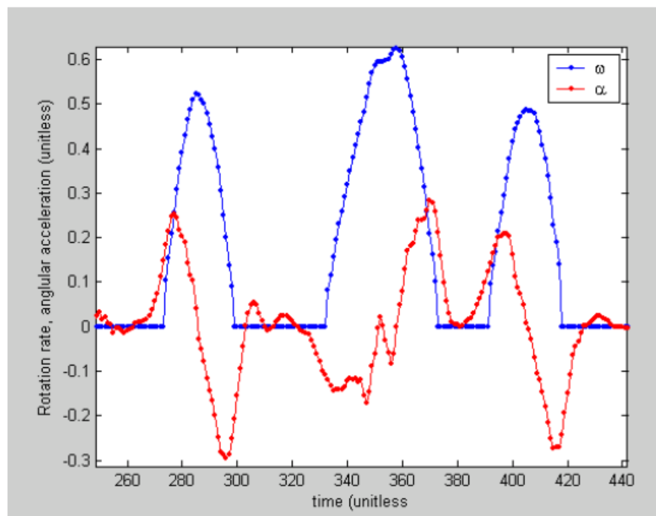

Fig. 28. Timing of α and ω

vector sum of ω_y and ω_z from Eqns. 12 and 13 is equal to the magnitude of the total angular rotation rate, ω_{total}.

$$\omega_{total} = \sqrt{\omega_y - \omega_z} \tag{14}$$

Using the total rotation rate magnitude calculated in Eqn. 9 and the relative magnitude and direction of rotation obtained from Eqn. 12, we can determine the yaw and the roll.

$$yaw = \omega * \left(\frac{\omega_z}{\omega_{total}}\right) \tag{15}$$

$$roll = \omega * \left(\frac{\omega_y}{\omega_{total}}\right) \tag{16}$$

An example of the calculated yaw and roll rates is shown in Fig. 29.

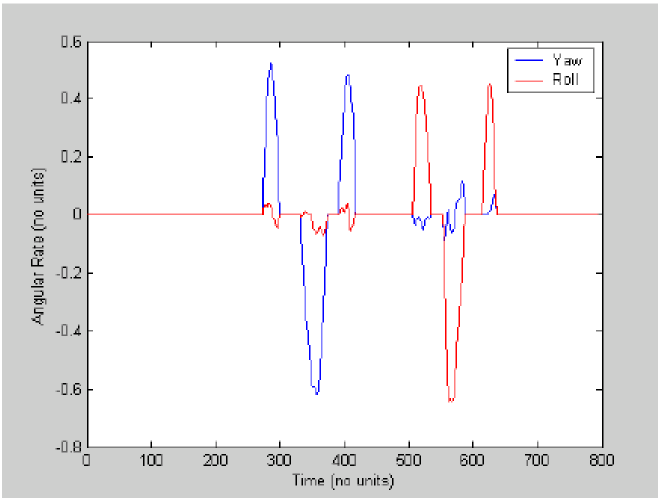

Fig. 29. Examples of Yaw and Roll Rates

6.2 Wireless Sensor Design Analysis

The basic requirement of this aspect of the project is to further improve the system by using a wireless communication method. The use of the Bluetooth modules in the first and second phase of communication development meets this basic requirement. Use of Bluetooth also meets the requirements of improving the comfort of the device and also meets the small power requirements. The Wiimote accelerometers also meet the requirement of filtering the sensor signals and implementing a method for using the sensors to determine the phase of the gait cycle of the healthy leg.

6.3 Control System Design Analysis

To show that the design of the fuzzy logic system meets expectations, a database of simulated input data (training data) is inputted into the controller. The graph in Fig. 30 represents the normalized knee torque vs. % stride where the vertical lines on the graph shows the torque deviation. As shown in Fig. 31, the ANFIS output resulting from the training data set follows the desired knee torque trend of Fig. 30. This theoretical analysis in Matlab proves the fuzzy logic controller produces highly accurate results under nominal conditions.

6.4 Testing Platform Design Analysis

The test platform has been designed to simulate a range of motion between -20° and 30° [11]. This range of motion is met in the design and is shown in Fig. 32.

The extension and retraction speed of the reciprocating pneumatic has also been verified to be correct.

7.0 Manufacturing, Testing, and Commissioning

This section will discuss the results of the finished prototype and whether it met the specified design requirements. Overall the system met the specified design requirements.

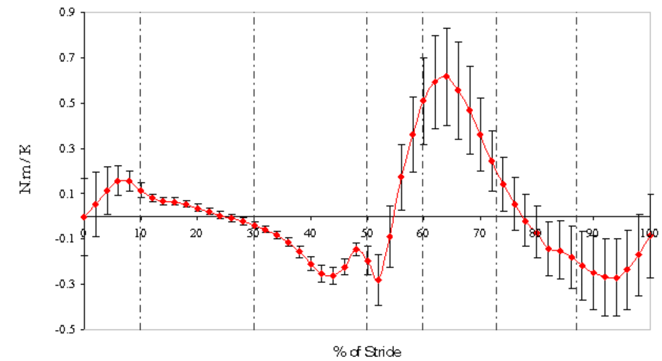

Fig. 30. Normalized Knee Torque Vs % Stride

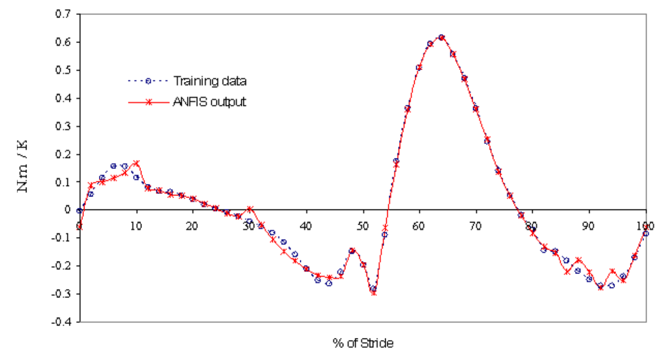

Fig. 31. ANFIS Output Result from Training Data

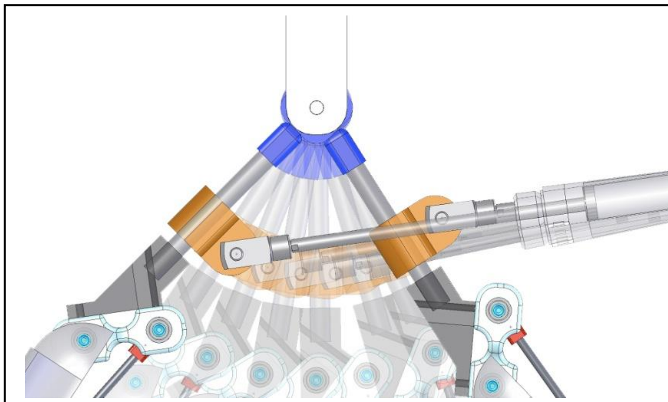

Fig. 32. Test Platform Range of Motion

7.1 Sensing System

The algorithm can be tested by mounting two accelerometers on a rigid body separated by a distance of 9.2cm. A gyro is also mounted on the rigid body to compare the angular rate determined by the two accelerometers to the angular rate output of the gyro. Fig. 33 and Fig. 34 show the results of the testing.

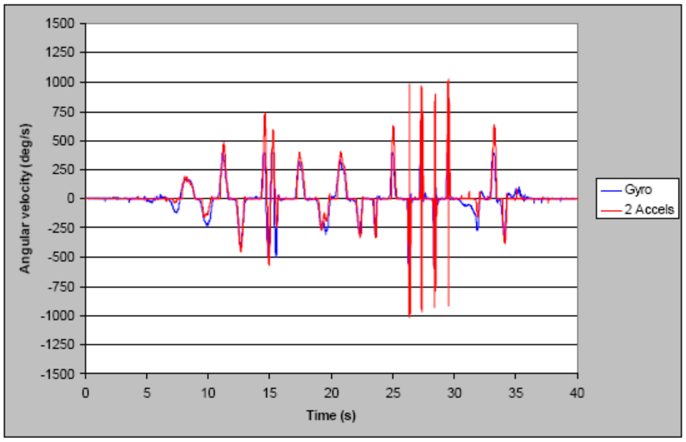

Fig. 33. Angular Velocity Measurement Test: Trial 1

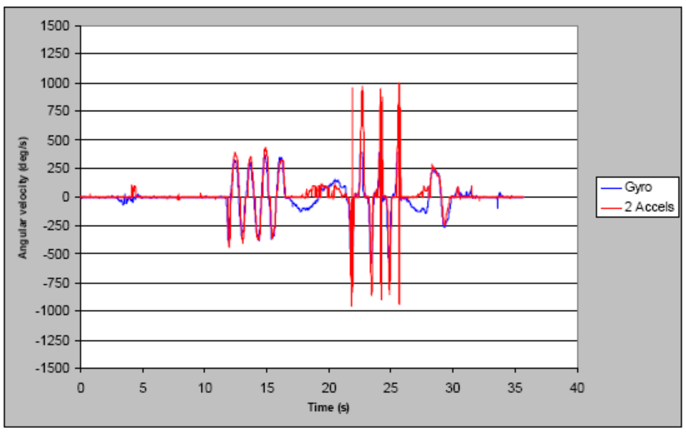

Fig. 34. Angular Velocity Measurement Test: Trial 2

As seen in the measurements this method works very well for short motions (<2seconds) of medium magnitude (140 °/sec to 1200 °/sec). Low magnitude (<140 °/sec) motions are not sensed because they are below the system resolution. During long motions (>2 seconds) the integration error becomes large. Very large magnitude (>1200 °/sec) motions will cause error because the accelerometer outputs saturate. The finished accelerometer circuit is shown in Fig. 35.

7.2 Wireless Sensor System

Testing of the Wiimote and Nunchuck in the first and second phases of the software development involved successfully acquiring the measured accelerometer of each controller. Initial tests confirmed that there were slight differences in the measurement of the two controllers even when they were oriented in the same position. A calibration process was then introduced to the program to allow for an initial calibration which would attempt to eliminate any offset that is present between the Wiimote and the Nunchuck.

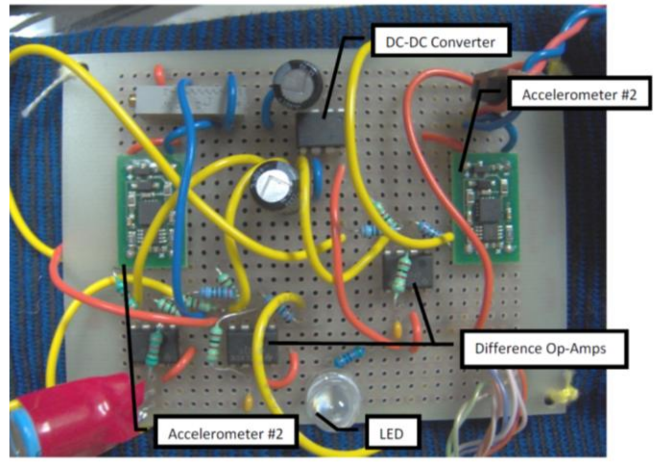

Fig. 35. Completed Sensor Circuit

In the modified third phases of the software development where the first phase with the addition of the serial code became the replacement for the Bluetooth module to be connected to the microprocessor, initial testing involved sending specific strings of data to the microprocessor to determine if the serial communication had been properly set up. On both sides, a null modem was connected to first determine if both the computer and the microprocessor were indeed sending and receiving properly. Once the bugs for that stage were fixed, a serial link between the computer and microprocessor was established. After testing of the static string used in data transmission between the two components was successful, the actual accelerometer measurements were sent to the microprocessor from the computer. Additional code was added to the computer for converting the accelerometer readings into angle readings with the assumption that vertical and horizontal acceleration is not significant (for testing of working concept).

7.3 Controller

As mentioned in the previous section the final design of the control system differed from the initial design due to the lack of simulating a ground reaction force. As a result, position control is used in place of torque control. Therefore the feed forward fuzzy control portion is modified to contain only one output - the desired knee position of the APK. The feedback portion consisting of the PID controller is modified to a proportional-integral (PI) controller since adding a derivative term resulted in an over-aggressive compensation for overshoot. This overly aggressive overshoot compensation is a highly undesirable as it reduced the smoothness of the motion while adding some additional unwanted jerk. The resulting control system architecture is shown in Fig. 36.

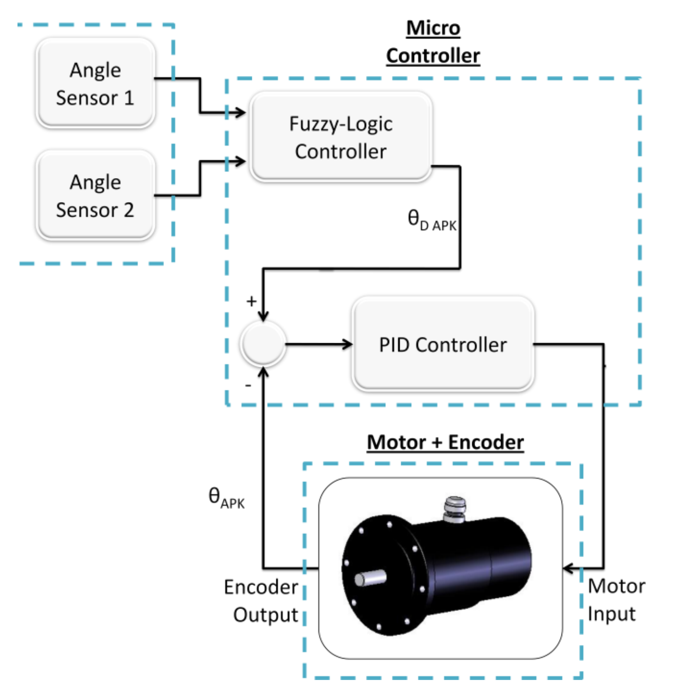

Fig. 36. Final Fuzzy-PID Control Architecture

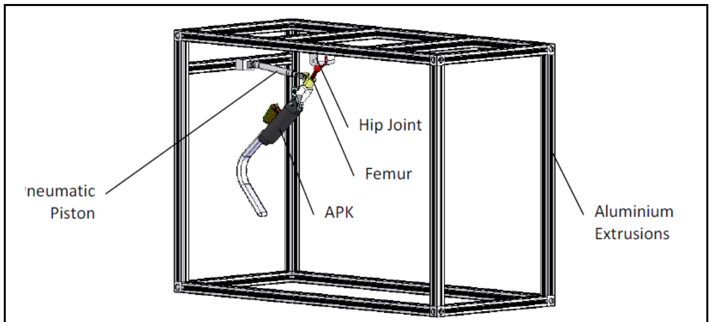

Fig. 37. Test Platform Final Design

7.4 Test Platform

The final design of the test platform for the APK is shown in Fig. 37.

The finished test platform assembled from aluminium extrusions and provides 2 DOF. One DOF is provided by the pneumatic piston whereas the second DOF is provided by a set of springs in the hip joint that allow the joint to move in the vertical direction.

8 Recommendations

Based on the analysis in this paper the following initiatives are recommended.

First, the existing DC motor should be replaced with a lighter unit to reduce the weight of the device. The current APK has a mass of approximately 6 kg, most of which can be attributed to the motor.

Second, as a safety measure, limit switches should be integrated into the APK design to prevent the knee joint from exceeding the allowable range of motion

Third, the Sony Playstation SIXAXIS controller should also be tested to determine whether the gyroscopes in the SIXAXIS controller provide a better measurement for controlling the APK. The current use of the Wiimote and Nunchuck requires two sets of such controllers to effectively cancel out the effects of the horizontal and vertical accelerations associated with walking. Using gyroscopes over accelerometers may reduce the number of sensors required to properly determine the phase of the gait cycle.

Further work on the implementation of four three-axis accelerometers should be investigated to verify that vertical and horizontal acceleration can be cancelled resulting in a purely angular input for the control system. The current simplified system uses only two sets of three-axis accelerometers as inputs to the control system. Errors in control can occur when a significant vertical and horizontal acceleration is measured. To fully test out the control system the extra vertical and horizontal accelerations need to be removed from the input to the control system.

Appendix A

Pneumatic Sizing Equations

$$\text{force/area relation } A = \frac{F}{P} = \frac{ma}{P} = \frac{m(\alpha r)}{P}$$

$$\text{area/diameter relation } A = \frac{\pi d^2}{4}$$

$$\text{bore diameter } d = \sqrt{\frac{4m(\alpha r)}{\pi P}} = \sqrt{\frac{4(6\text{ kg})\left(230\frac{\text{rad}}{\text{s}^2}\right)(0.105\text{ m})}{\pi(500\,000\text{ Pa})}} = \mathbf{0.020\ m}$$

$$\omega = 5.08$$

$$v = wr = 5.08 * 0.18 = \frac{0.9144m}{s}$$

$$Q = VA = 0.9144 * 4.9087 * 10^{-4} = 0.44885\ l/s$$

9 Summary

There is a large and growing need for affordable and rugged active prosthetics around the world. The aim of this project is to develop an active prosthetic knee that will use the position of the healthy leg to determine the torque required to actuate the prosthetic knee. The purpose of this paper is to describe the development of the control system and the test platform for the active prosthetic knee (APK).

The goal of this project is to develop a cost-effective, rugged, and easy to calibrate prosthetic knee for above-the-knee amputees. The scope of this paper includes the design and implementation of: a sensor system to measure the position of the healthy leg, a Wiimote to measure the position of

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the healthy leg, a fuzzy logic control system to control the DC motor, and a test platform to evaluate the performance of the finished prototype. Since a prototype of the APK has already been designed and fabricated by previous collegues this paper will not discuss in detail the mechanics of the prosthetic knee. Instead this paper focuses on the development of the control system and test platform.

Different methods are considered for the design of the sensing and control system. One of the main findings is the superiority of accelerometers over EMG sensors to determine the position of the healthy leg since accelerometers are more comfortable to wear and require less calibration. A fuzzy logic controller is used over a neural-network approach since a fuzzy logic approach is more capable at handling uncertainty in data and is based on empirical methods whereas a neural network requires training.

The completed prototype is capable of replicating a steady walking gait and can receive angular measurements via the accelerometers or the Wiimote. The test platform can fully mimic the gait cycle of a 50^{th} percentile male and is currently being used to test the performance of the prototype.

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