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# A PLC Based Gait Phase Identification for Bilateral above Knee Leg Prosthesis Solution

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## Abstract

The focus of this work is to offer a gait phase identification mechanism for prosthesis development for amputees with both legs imputed above knees and with a reasonable size of stump to fit the artificial leg. This paper can be used as starting step and the algorithm can be used for controlling actuators fitted on above knee prostheses. Ladder diagram approach to design has been used and a PLC was successfully simulated and programmed as per ladder. The mechatronic based prosthesis solutions have made life better for single leg amputees, but stability aspect still remains a concern for double leg prosthesis designers. The leg in stance phase has to be locked and the one in swing phase has to have a swing controller. The timing of such an actuator in real time requires accurate gait phase identification and further control. The algorithm being proposed in this paper gives a technique on the basis of which a bilateral above knee prosthesis solution can be developed.

**Key words -** Gait, AK Prosthesis, Mechatronics, PLC Programming.

## Introduction

This work demonstrates use of PLC control for a wearable machine / prosthesis for bilateral leg amputee without knees. The prosthesis solution required for such amputees need machines like those being used in biped robots, except for need to balance centre of gravity and hip control. As compared to single leg above knee amputees, where only a simple swing control knee can be used, here both swing as well as stance control will be required in preferably hydraulically controlled prosthesis or MR based knee joints. The leg in stance phase needs to be locked and the other has to have a controlled swing. Not much work has been done to cater to amputees with both legs cut above knees. This work gives a gait identification technique which can be employed for developing a control system for such prosthesis. Many more aspects will be involved for developing an acceptable solution for such amputees and this will be work for further study. In our paper, It has been proposed that there should be two artificial knees with sensors fitted in each for knee angle identification and special feet or shoes with sensors to identify heel and toe strike. Ankle control will also be required, but has not been dealt in this paper. For feedback based systems, micro-controllers can also be used and will be more economical but PLC (program logic controller) is more reliable and hence this study has been done on PLC.

A PLC can be interfaced with sensors and programmed to control the actuators, dampers and stance controllers. This paper demonstrates an algorithm for gait identification for plane surface walking. A ladder program has been designed on Bytronics (England) make Ladsim software and further mnemonic coding was done on Vinytics (India) make PLC interfaced to a LED (light amplification diode) simulator. Two optical encoders interfaced to an ATMEL S52 micro-controller were designed to sense knee angles, as shown in figure1c. A set of specially designed shoe were also made in house with sensors to identify toe and heel strike to check feasibility for developing such a system. For successful implementation in any project it is important to know the psychology and constraints involved. Geertzen *et al.*, (2001) did a literature review of One hundred and four (104) articles and selected 24 articles to summarize on quality of life, functional outcome and predictive factors on lower limb amputees. They found that about 80% of patients with a lower limb amputation are older than 60 years. They concluded that good motivation of the patient and rehabilitation team, and good communication, will also increase the chance for a successful rehabilitation.

People with both legs cut above knees need a solution similar to biped robots but similar application for developing a prosthetic solution for double leg amputees has not yet been made. This work is a starting step in this direction. A basic problem with such people is of stability. Datta *et al.*, (1992) performed a study to evaluate the outcome in 41 bilateral lower-limb amputees admitted to an inpatient unit for prosthetic rehabilitation. It was found that majority of the above-knee amputees had abandoned their prostheses by the time of review. Bilateral below-knee amputees, however, continued to do well regarding their prosthetic mobility, and prosthesis users were more independent in their activities of daily living.

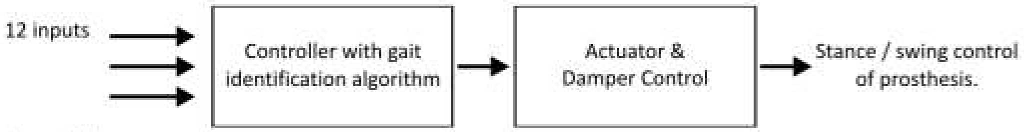

Figure (1a)

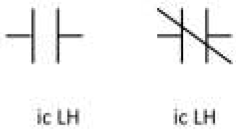

Figure (1b)

Figure (1c)

**Figure1**: (1a) Shows block diagram for the prosthesis solution. (1b) Represents the symbol of normally open and normally closed contact used in the program. (1c) Shows pictures of specially developed shoes with sensors & prosthetic knee with angle sensor.

Stability criteria have been dealt with in biped robots as well. Sardain *et al.*, (2004) gave a theoretical study to deal with difficulties, particularly about the implementation of fast and dynamic walking gaits, in other words anthropomorphic gaits, especially on uneven terrain. In this perspective, both concepts of center of pressure (CoP) and zero moment point (ZMP) were emphasized. Shuuji *et al.*, (2001) introduced a new biped robot with telescopic legs. For 3D walking control of the robot, they analyzed the dynamics of a three dimensional inverted pendulum in which motion is constrained to move along an arbitrarily defined plane. Ambarish *et al.*, (1998) did a systematic study of the passive gait of a compass-like, planar, biped robot on inclined slopes. The robot was considered kinematically equivalent to a double pendulum, possessing two knee-less legs with point masses and a third point mass at the "hip" joint. The gait was described on the basis of three parameters, namely- the ground-slope angle and the normalized mass and length of the robot describe its gait. Chevallereau *et al*., (2001) performed study to obtain optimal cyclic gaits for a biped robot without actuated ankles for walking and running conditions.

The stability problem can be solved by developing mechatronic based prosthesis systems and this requires sensors and actuators similar to a biped robot. Kajitae *et al*., (1997) investigated real time control of dynamic biped locomotion using ultrasonic range sensor mounted on the robot to measure the distance from the robot to the ground surface. During the walking control, the sensor data was converted into a simple representation of the ground profile in real time. Kazuo *et al*., (1998) presented the mechanism, system configuration and basic control algorithm and integrated functions of the Honda humanoid robot. The sensors used in the robot were – inclination sensor, which consisted of three accelerometers and three angular rate sensors (optical fiber gyros). This was also used a navigational sensor. Each foot and wrist was equipped with a 6 axis force sensor (a 3 dimensional force and a 3 dimension moment sensor). In the head of the robot there were four video cameras, two were used for vision processing and could pan and tilt independently. The other cameras were used for the tele-operation. Endo *et al*., (2006) seek to understand how leg muscles and tendons work mechanically during walking in order to motivate the design of efficient robotic legs. They hypothesized that a robotic leg comprising only knee and ankle passive and quasi-passive elements, including springs, clutches and variable-damping components, can capture the dominant mechanical behaviour of the human knee and ankle during level-ground walking at self-selected speeds.

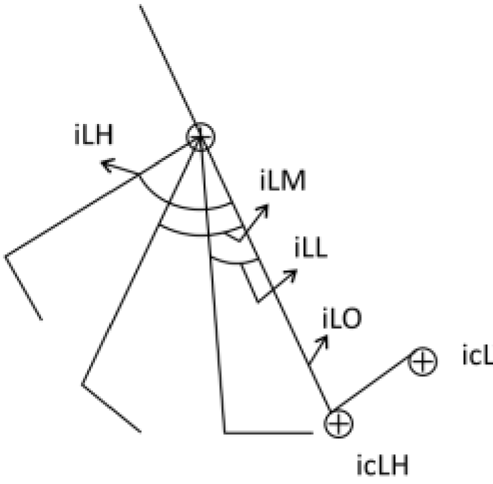

**Figure 2**: The sketch shows various sensor inputs from left artificial leg.

Using the leg model they evaluated the hypothesis that a robotic leg comprising knee and ankle passive and quasi-passive elements can capture the dominant mechanical behavior of the human knee and ankle during level-ground ambulation at self-selected speeds. By modeling spring stiffness, damping levels and actuator contributions, they found good agreement between biological and simulated gait data for most regions of the walking cycle.

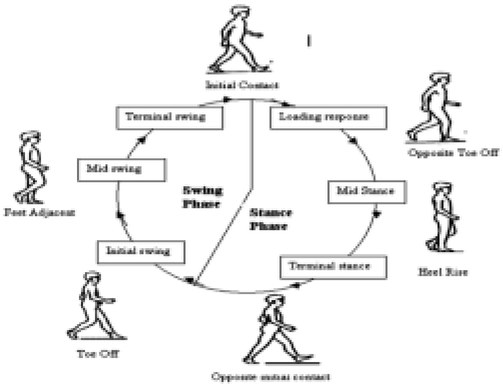

**Figure 3**: Various phases in gait of a normal person walking on level ground are shown with terminology

Hof *et al*., (2007) stated that the human body is never in balance. Most of the time the trunk is supported by one leg and the centre of mass (CoM) 'falls' to the contra-lateral side. In dynamical situations the velocity of the CoM should be acknowledged as well in the 'extrapolated centre of mass' (XcoM). They recorded centre of pressure (CoP) position by a treadmill with built-in force transducers and concluded that a simple mechanical model, the inverted pendulum model, can explain that a less precise foot placement (greater CoP–XcoM margin) results in a wider stride They suggested that not in all cases symmetric gait should be an aim of rehabilitation. Active prosthesis is an option which can solve stability problem and open acceptance of prosthesis by bilateral above knee amputees. Sup *et al*., (2008) described the design and control of a trans-femoral prosthesis with powered knee and ankle joints. The control was implemented on the prosthesis prototype and experimental results demonstrated the promise of the active prosthesis and control approach in restoring fully powered level walking to the user. Using MR fluids is another option which can be investigated for developing such prosthesis. Kim *et al*., (2001) presented a semi active type prosthesis. They proposed to use the rotary Magneto-reological fluid (MR fluid) as a damper. The torque dissipation in the knee joint could be controlled by the magnetic field induced by solenoid. The 3 DOF leg simulators were also developed to generate various hip motions and analyse the results of walking motions. The damper was attached into knee of leg simulator and experimental tracking control of above knee angle was carried out. Hafner *et al*., (2007) worked to evaluate differences in function, performance, and preference between mechanical and microprocessor prosthetic knee control technologies. The study population showed improved performance when negotiating stairs and hills, reduced frequency of stumbling and falling, and a preference for the microprocessor control C-Leg as compared with the mechanical control prosthetic knee. An active prosthesis with inbuilt sensor and control system will be most appropriate solution for the problem. Gait identification is first step for development of acceptable prosthesis for bilateral above knee amputees and this has been done using ladder logic simulation technique.

A prototype of AK prosthesis was made and optical encoder as a knee angle sensor and foot sensors were used as shown in fig. 1c. and a PLC was programmed to validate.

## Methods

It is proposed that two circular optical -encoders be installed, one on each prosthetic knee as shown in figure 1c. The optical encoder senses knee angle at a particular instant of time. Fig. 2 shows the various angles being sensed by the optical encoder. Here 'i' stands for input, 'L' stands for left. Here, iL0 represents, knee angle is zero, iLL – knee angle is low, iLM- knee angle is medium and iLH- knee angle is high. Inputs coming from foot are also shown in figure and 'c' stands for contact. Here, icLH and icLT are inputs coming from two touch switch sensors installed on each foot, these may be contact sensors, strain gauges, or Hall Effect sensors to identify if there is a toe strike or a heel strike or both. For model development, special shoes were made with inbuilt touch sensors as shown in fig 1c.

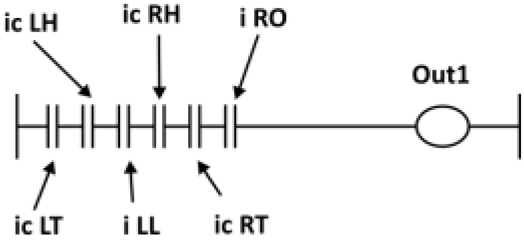

**Figure 4**: Initial Contact state is identified by activation of relay - named out 1.

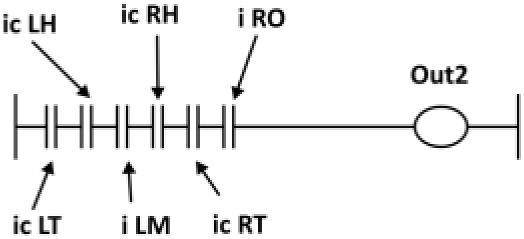

**Figure 5:** Opposite toe off state is identified by activation of relay-named out 2.

The inputs which will be received from right leg have been represented with 'R'. Thus there are inputs represented as i R0, i RL, i RM, i RH, ic RT, ic RH for right leg. Where, the inputs coming to the controller may be normally open inputs or normally closed inputs. If the sensors are normally open, then when they will close, the controller will come to know that there is an input and similarly a normally closed input will stop giving signal when the contact sensor is pressed. By this way the controller has a combination of inputs coming to it at a particular point of time. All these 12 inputs are connected to the controller (PLC) and controller gets signal from both the normally open as well as normally closed connections, symbols used for these connections is shown in figure 1b. The symbol of – ic LH contact sensor without a cutting line represents a normally open connection and one with a diagonal line cutting the vertical parallel lines represents, that a normally closed point of the sensor has been connected in the circuit.

### *Gait State Identification*

Each gait state will have separate set of inputs. The fig. 4-9, represent the combination of inputs which will identify the particular gait state. The logic has been made referring to figure 3. In each of these figures an output is achieved. This output may be an auxiliary relay in a PLC or a normal output which is being activated by the particular combination of inputs.

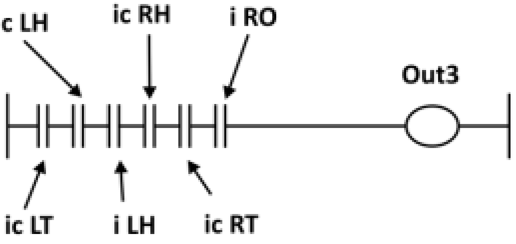

**Figure 6:** Heel Rise state is identified by activation of relay - named out 3.

Fig. 4 gives the combination of inputs which identify Initial contact. This state is identified by normally closed contacts - ic LH and ic RT, and normally open contacts - ic LT, i LL, ic RH, i R0. Fig. 5 gives the combination of inputs which identify Opposite Toe off. This state is identified by normally closed - ic LT and ic LH, and normally open - i LM, ic RH, ic RT, i R0.

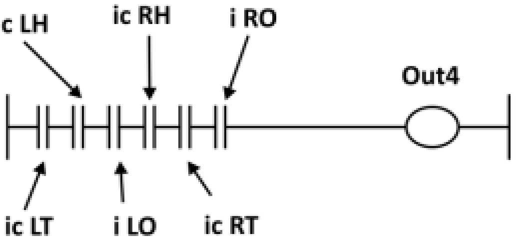

**Figure 7:** Opposite Initial Contact state is identified by activation of relay - named out 4.

Fig 6 gives the combination of inputs which identify Heel Rise. This state is identified by normally closed - ic LT and ic LH, and normally open - i LH, ic RH, ic RT, i R0. Fig. 7 gives the combination of inputs which identify Opposite Initial Contact. This state is identified by normally closed - ic LT and ic LH, and normally open - i L0, ic RH, ic RT, i R0. Fig. 8 gives the combination of inputs which identify Toe Off. This state is identified by normally closed - ic RH and ic RT, and normally open - ic LT, ic LH, i L0, i RM. Fig. 9 gives the combination of inputs which identify Feet Adjacent. This state is identified by normally closed - ic RH and ic RT, and normally open - ic LT, ic LH, i L0, i RH. A programmable logic controller on simulation can show about the validity of our control algorithm. On the basis of inputs a ladder program was developed, simulated on a ladder simulation software and further Vinytics make PLC was programmed. The program fed to Vinytics makes PLC fitted with LEDs for validation is written as under:

### *Validation and PLC Program*

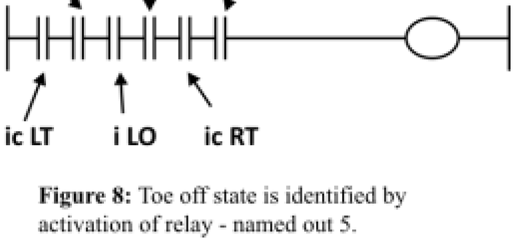

**Figure 8:** Toe off state is identified by activation of relay - named out 5.

Vinytics make PLC was successfully programmed as per mnemonics mentioned under: Cpu plc; Org 2000h; Ld 11h; ani 10h; and 05h; and 07h; ani 12h, and 00h, Out 20h; Ldi 11h; ani 10h; and 06h; and 12h; and 07h; and 00h; Out 21h; Ldi 11h; and 13h; ani10h; and 00h; and 07h; and 12h; Out 22h; Ld 04h; ani 10h; ani 11h; and 12h; ani 07h; and 00h; Out 23h; Ld 10h; and 11h; and 04h; ani 12h; ani 07h;

and 02h, out 24h; ld 11h; and 10h; and 04h; ani 12h; ani 07h; and 03h; Out 25h; Stop; End.

## Results

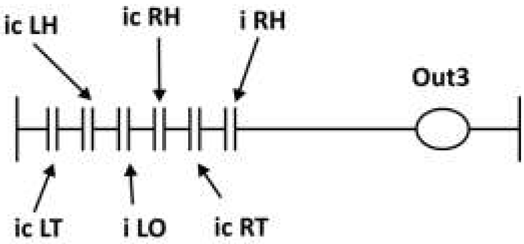

**Figure 9:** Feet Adjacent state is identified by activation of relay - named out 6.

Ladder simulation of the logic proposed gave successful results on Ladsim software without any error. The Vinytics PLC that was programmed also gave correct results and no mismatch was observed. All the 12 inputs in combinations proposed in this work represented the gait condition. Out 20h in mnemonic program referred to initial contact of the gait phase; Out21 to Opposite toe off; Out22 to Heel Rise, Out 23 to Opposite Initial Contact, Out 24 to Toe off and Out25 to Feet Adjacent. Photographs of the Vinytics LED simulator are shown in figure 10. The inputs are represented by upper row of LED's and the output is represented by lower row of LED's. There are total of 16 inputs and are number from 00H – 07H and 10H – 17H. The Outputs are numbered as 20H – 27H and 30H – 37H

## Discussion and Conclusion

Gait phase identification is being done in laboratory with a number of cameras observing the movements of the subject. This method is not possible for designing a controller to actuate an artificial limb in real time. A controller fitted to an intelligent prosthesis needs a feedback mechanism, which is possible through inbuilt sensors in the prosthesis along with a micro-controller or a PLC to work as brain. Developing the logic for this prosthesis will be a massive project and our paper gives a starter to design the controller for this application. Still the problem is acceptability by the patients. They feel instability after wearing this prosthesis. Moore *et al*., (1989) evaluated 57 patients following major lower extremity amputation to determine functional prosthetic ambulation. Of all above-knee amputees, 46% became functional prosthetic ambulators. Only 19% of bilateral lower extremity amputees became functional prosthetic ambulators. To make the prosthesis still more acceptable latest techniques of Fuzzy and neural can also be incorporated. Zhou *et al*., (2003) presented a fuzzy reinforced learning (FRL) method for biped dynamic balance control. The proposed FRL agent was constructed and verified using the simulation model of a physical biped robot. The development in biped robotics has not reached the need for such a technology for amputees.

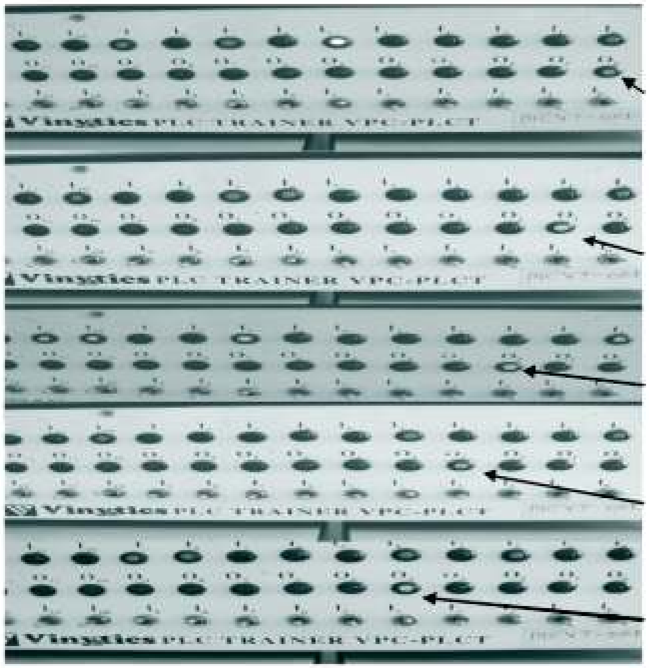

**Figure 10**: Gray-scaled photographs of Vinytics make PLC simulator, programmed to validate the proposed model. Arrows are pointing to the Output LED glowing for the combination of inputs.

We finally conclude that work should be carried out in this direction, using the developments in biped robots and our paper can be used as starting step to identify gait in dynamic walking conditions and can be incorporated for development of a prosthesis solution for bilateral above knee legs amputee.

**List of abbreviations**

i L0 – Input left knee angle zero;

i LL – Input left knee angle low;

i LM – Input left knee angle medium;

i LM – Input left knee angle high;

ic LH – Input Contact Left Heel;

ic LT – Input Contact Left Toe;

i R0 – Input right knee angle zero;

i RL – Input right knee angle low;

i RM – Input right knee angle medium;

i RM – Input right knee angle high;

ic RH – Input Contact right Heel;

ic RT – Input Contact right Toe;

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