# Development of a control system for artificially rehabilitated limbs: a review

**M. S. H. Bhuiyan · I. A. Choudhury · M. Dahari**

**Abstract** Development of an advanced control system for prostheses (artificial limbs) is necessary to provide functionality, effectiveness, and preferably the feeling of a sound living limb. The development of the control system has introduced varieties of control strategies depending on the application. This paper reviews some control systems used for prosthetics, orthotics, and exoskeletons. The advantages and limitations of different control systems for particular applications have been discussed and presented in a comparative manner to help in deciding the appropriate method for pertinent application.

**Keywords** Prosthesis · Control system · Non-linear control strategy · Control system element

## 1 Introduction

Amputation or a limb defect creates the need for getting help from different supporting devices. Amputees have been aided by a walking stick/cane, walking frame, crutch, wheelchair, motor wheelchair, stroller, motor stroller, and more recently by artificial prosthetics (Gao et al. 2010). The amputee with a transfemoral and knee level amputation generally uses a wheelchair, whereas an amputee with lower-level amputations (transtibial and foot amputation) primarily uses a prosthesis (Karmarkar et al. 2009). A prosthesis is a device that replaces a missing extremity, such as an arm or leg. The extent of an amputation or loss and location of the missing extremity largely determine the type of prosthesis to be used. Recently, the design of prosthetics has been significantly improved by incorporating some extra features as well as introducing new controlling methods.

In newer and more improved designs of prosthetics, more control is given to the users by employing different control systems, muscle of carbon fiber, mechanical linkages, motors, computer microprocessors, and innovative combinations of these technologies (Wen-Wei Hsu et al. 1999). More importantly, essential factors such as weight-force ratio, strength, durability, adaptability, wearability, degree of freedom, resistance to environment, and functional capabilities are being addressed seriously to develop a more efficient prosthesis. The operating power consumed by the prosthesis is another essential factor to be considered, which varies depending on the prosthesis type. According to Johnson et al. (1997), a transfemoral amputee must use approximately 80 % more energy to walk than a normal person (with two whole legs). Currently, new plastics and other materials, such as carbon fiber, have allowed prosthetics to be stronger and lighter, limiting the amount of extra energy necessary to operate the limb (Sawers and Hahn 2011; Esposito et al. 1997). Because of the exceptional strength-to-weight characteristics and quality of superior biocompatibility, a majority of today's upper-limb and lower-limb prostheses have now been made from composites with underlying polymer matrix (Scholz et al. 2011). More advanced control systems and more compatible choice of material will ensure more efficient functionality of prostheses. An automated control system could provide more realistic movement to the prosthetic's components and to itself. For instance, a myoelectric control system, which controls the limbs by converting muscle movements

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to electrical signals may allow the amputees to control the prosthesis more directly (Jawhar et al. 2011).

The latest research has focused on the development of an artificial prosthetic limb, which would be capable of imitating the behavior of a biological limb. The desired movement of the prosthesis is obtained with the help of different types of joints, sensors, controllers, and actuators (Martins et al. 2012). Application of artificial intelligence has made the control system more spontaneous with the ability of decision making.

This article presents a brief discussion on the importance of prosthesis construction followed by a thorough study on control system development, and the different components of the system. A comprehensive review has been carried out on available control systems for prosthesis operation, and thus their suitability for particular application has been weighed and illustrated meticulously to help the future user in choosing an appropriate control system for a pertinent problem. A systematic approach has been followed to highlight advantages and limitations of various control systems for specific applications.

## 2 Importance of prosthesis reconstruction

The necessity of prosthesis reconstruction arises because of the increasing rate of limb loss due to accidents, war, diseases, or congenital defects. In recent years, there has been an increased rate of diseases causing paraplegia due to spinal cord injury or from different types of stroke incidences. Functional electrical stimulation (FES) has been applied as a tool to improve trunk stability in paraplegic subjects during activities of daily living (ADL) (Kukke and Triolo 2004; Newham and Donaldson Nde 2007; Vanoncini et al. 2012). However, the major drawbacks of FES are that it causes early damage of cells, sagging of muscles, and in the long run it loses the ability to stimulate the muscle (Matjačić et al. 2003; Vanoncini et al. 2012). In this case, use of orthotics is preferred over FES by the patients with paraplegia. Orthoses are used to support the patient with limb problems using different types of passive or active attachments without stimulating the muscle externally.

Damage to limbs is another commonly seen defect among the disabled due to diseases, congenital defects, accidents, or war, which most often results in amputation (Sagawa et al. 2011). Industrial, vehicular, and war-related accidents are the leading causes of amputations in developing countries, such as those in large portions of Africa (Burger et al. 2004). In more developed countries like those in North America and Europe, disease is the primary cause of amputations (Rosenfeld et al. 2000). Cancer, infection, and circulatory disease are the leading diseases that result amputation (Albertini et al. 2000). Trauma is another prevailing cause of amputation (Gallagher and MacLachlan 2004). In addition to trauma, dysvascular disease is a predominant cause of lower limb amputation (60 % case) (Resnik et al. 2012; Bryant and Pandian 2001). However, upper limb amputation due to disease is found to be relatively rare (3 % case) (Resnik et al. 2012). A study carried out by Esquenazi and Meier Iii (1996) reported that the estimated ratio of arm to leg amputations was 1:3. Similar results have been obtained from a recent study conducted by Watve et al. (2011). They have also added that the most common level of amputation is below the knee. According to Sagawa et al. (2011), approximately 1.7 million people experienced limb loss in the United States in 2007, and more than 185,000 new amputations are performed each year in that country. Ziegler-Graham et al. (2008) stated in a survey report that the number of amputees in the USA in 2005 was 1.6 million, which is expected to more than double to 3.6 million by 2050. These people will need to have limbs replaced using the correct prosthesis arrangement to ensure a high-quality, active life.

A study (Couture et al. 2011) on patients with limb diseases, defective limbs, or seriously injured limbs showed that amputation helps patients to have greater functional independence and greater body image satisfaction than those patients without amputations with limb defects. On the other hand, amputation alters the biomechanics of the amputee's body movement.

According to Gailey et al. (2008), the intact limb of lower-limb amputees is often stressed or favored more during their everyday activities. This primarily causes osteoarthritis of the knee and/or hip joints of the intact limb, which in the long run causes osteoporosis that limits sufficient loading of the lower limb through the long bones. A poor prosthetic fit and alignment, postural changes, leg-length discrepancy, amputation level, and general deconditioning commonly cause back pain to the lower-limb amputee. The right selection of prosthesis with appropriate physics would be helpful in this case, which is usually defined by the amputee's body construction and his/her activity. The correct choice of a control system complements the other part of prosthesis development, which is usually performed by some external device such as electrical, mechanical, and artificial intelligence. All of the difficulties associated with amputation necessitate that the amputee obtain a tailor-made prosthesis with an appropriate control system, which should be capable of balancing their body dynamics and providing desired movement to its user.

## 3 Development of a control system for prostheses

The prosthesis consists of some mechanical elements replacing the missing extremity and some electrical components that support desired movement in the prosthesis arrangement. The electrical and mechanical components independently or combined with artificial intelligence form a system that gives control of the prosthesis to its user and it is regarded as the control system for the prosthesis.

## 3.1 Background

Prior to developing a control system for a prosthesis, one has to study thoroughly the body dynamics and functionality of the subject's impaired limb. Some intervention and assessment tools are available to identify the major factors that contribute to the risk of falling (Maki et al. 2011). The relationships among static ground friction, hip torque, and the trajectory of the prosthetic foot has been investigated with a two-dimensional model proposed by van Keeken et al. (2012). The static and dynamic balancing of perturbation of an amputee has been assessed by measuring the weight distribution force below the prosthetic foot (Nederhand et al. 2012). In another investigation, the center of pressure (COP) and center of mass (COM) were indicated as the major parameters to be controlled to balance an amputee's body dynamics (Mergner 2010). The gait phase mechanism (stance and swing) under different walking conditions was identified to be useful in determining the intended limb motion (Jiménez-Fabián and Verlinden 2012). On the other hand, Nagano et al. (2005) studied muscle force, work, and power output of major lower limb muscles during jumping. Hemami and Dariush (2012) modeled and simulated lower-limb movement as a system of connected rigid bodies. They studied the behavior of the central nervous system (CNS) when producing the desired trajectories of motion and the force of contact prior to the control of the prosthesis. The projection of force in the sensory cortex was implemented with a standard integral unit controller in the spinal cord and a well-defined neural population unit. It was extended to the case for direction of motion with two other neural units of visual input and spindle efference.

An effective control system is required to recreate a similar force-length-velocity mechanism, and thus to imitate the biological limb control faculty to produce the required movement to the prosthesis. The effectiveness of the prosthesis depends on its ability to simulate the functionality of a real, healthy biological limb. Therefore, an efficient prosthesis should have all the same faculties as a natural limb. A natural limb has the degree of freedom to produce different directional movement, ability to receive commands from the possessor and perform accordingly, e.g. for lower limb: standing, walking, running, jumping, and for upper limb: holding, lifting, and carrying, (Previdi 2002; Previdi et al. 2004). All movements of a biological limb are reportedly nonlinear due to gravity and muscle contraction dynamics (Previdi 2002; Previdi et al. 2004). The moment generated at the joint during a non-isometric muscle contraction depends very strongly on muscle length and velocity. These variables are functions of a set of joint angles and their derivatives, which are nonlinear. In addition, gravity and elastic passive moment cause a nonlinear term to be present in the equation of limb movement. In a prosthesis control system, similar nonlinear movements are reproduced by representing the various nonlinear movements into different nonlinear equations (Schauer and Hunt 2000). Development of a control system for a nonlinear system like a prosthesis is much more challenging than controlling a linear system (Tan 2009). Different types of closed-loop, nonlinear control strategies have been used to control different movements of prosthetics (Pujana-Arrese et al. 2010; Yap et al. 2007).

Depending on the aim, the prosthesis controllers are equipped with different task controllers that can be formed in several ways based on application. The control action of a prosthesis is usually accomplished by controlling the position and force/torque parameters. Based on the physical parameters, the prosthesis control system can be classified by position, torque/force, and force interaction controllers. The position control scheme is mostly implemented as a low-level controller, which is commonly used to ensure that the limb joints turn in a desired angle (Timmermans et al. 2009). Force interaction controllers are generally used either in the form of impedance or admittance controllers. The impedance or admittance controllers are reported to work only if they are followed by either the force or the position controller, respectively. The combination of the impedance or admittance controller is considered a high-level controller, while the force or position controller is known to be the low-level controller. The torque/force controller is mostly used for a physical parameter-based control system (Nef et al. 2009). The high level controller, on the other hand, is the impedance controller that controls the interaction force between the human and the prosthesis by receiving position as input and producing force as output. The output force of the impedance model becomes the reference force to the force/torque controller. Besides the impedance control, the admittance control is used to control the interaction force between the amputee and prosthesis. The admittance model receives forces and produces positions, rather than receiving positions and producing forces. A position controller based on the position references of the admittance model output is used to control the angle of the prosthesis joints (Carignan et al. 2009). The impedance and admittance controller produce desired movement in the prosthesis by controlling the interaction force between the amputee and prosthesis (Anam and Al-Jumaily 2012). The control system for the prosthesis, on the other hand, has been gradually transformed from mechanical to electrical and now to a bioelectrical control system (Le et al. 2010; Zhang et al. 2012; del-Ama et al. 2012; Resnik et al. 2012).

Some essential components such as sensors, controller/microprocessors, actuators, and interfacing units were shown

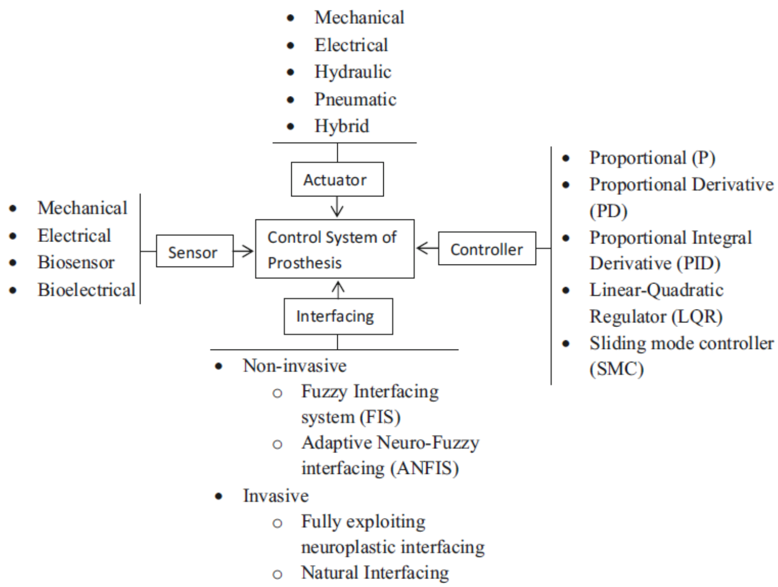


**Fig. 1** Components of a typical control system used for prosthetics

by Klute et al. (2009) to be required for developing a control system for prosthetics. A more effective combination of the different elements mentioned would provide better control of the prosthesis. Figure 1 depicts the essential components of a typical control system applied in controlling a prosthesis.

In the control system of a prosthesis, mainly four types of sensors, five types of controllers, five types of actuators, and two types of interfacing units are used. The components listed in Fig. 1 are discussed in the following subsections.

### 3.2 Sensors

Sensors in a prosthesis control system are used to sense force, torque, position, angle, proximity, power, speed, velocity, strength, etc., enabling the process to develop an efficient prosthesis. Through stages of improvement, the sensors presently have reached at a considerable advanced state that could competently capture the nerve signal. The gait feature signals are now obtainable using an inertial miniature accelerometer sensor (Alaqtash et al. 2011). The sensors' data captured from the limb movement are then input into a rule-based relational matrix of a fuzzy logic controller for modulation based on the fuzzy data set (Magdalena 1997).

The sensor can be mechanical, electrical, biological, or many more types. Zhang and Yin (2012) have developed and deployed a mechanical sensor based on a shape memory alloy (SMA) to sense and thus control movement of artificial skeletal muscle. Dutta et al. (2011) used Ag/AgCl (silver metal and silver chloride) electrodes with 2 cm interelectrode distance following the Surface ElectroMyoGraphy for the Non-Invasive Assessment of Muscles (SENIAM) method to collect surface EMG signals. Akagi et al. (2012) employed a displacement sensor consisting of two photo reflector electrodes to assess muscle movement of the prosthesis. A tri-axial accelerometer with a dynamic time warping (DTW) method was applied on the inner forearm of some volunteers to recognize limb movement (Muscillo et al. 2011). Tormene et al. (2009) used 29 strain sensors distributed on the upper limb of a patient under rehabilitation to observe their limb movement. Jae-Myung and Yong-Myung (2006) have employed flex sensors attached to biceps brachii muscles and triceps brachii muscles of alternate arms to identify the arm's movement. Inertial sensor technology, accelerometers, and gyroscopes were employed to assess a Paralympics amputee runner with prosthesis before changing to a new prosthetic (Lee et al. 2012).

From a thorough study carried out by Schultz and Kuiken (2011), it has been found that the main challenge in controlling the prosthesis is to read the intention of the user to perform a movement or action, which creates a need to capture the signal from the nervous system of the remaining limb or from the amputee's brain. This is commonly divided into two types: invasive and non-invasive. Some sensor examples are implantable electrodes, pattern recognition of myoelectric signals, targeted re-innervation. Sensors that intercept nerve signals include extraneural electrodes and intraneural electrodes. Some information can be obtained directly from the brain, such as cortical spike activity (action potential and field potential), local field potential, intracortical stimulation for sensory feedback, electrocorticogram recordings, or electroencephalogram recordings. Even if there is sufficient motor command information available for multifunction prosthesis control, adequate control would still require some degree of sensory feedback. Both tactile and proprioceptive feedback play important roles in volitional movement (Le et al. 2010). Tactile feedback allows for modulation of grip forces and hand postures for grasping and object manipulation (Crevecoeur et al. 2011). Proprioceptive feedback is essential for accurate motor control and joint coordination (Vaugoyeau et al. 2011).

A large number of articles on sensing techniques available for clinical application have been revisited by Tiwana et al. (2012). From their study, the use of tactile sensors in the rehabilitation of amputees became very obvious, particularly to investigate the severity of the stump–socket interaction. To acquire information about the force or torque applied to a prosthesis during object manipulation or during walking is done using visual, auditory, electrical, tactile, and vibrotactile stimulation. The latest addition to sensing techniques is a specially designed chemical sensor comprising a biological recognition element and a physicochemical transducer known as a biosensor. The functionality of biosensors and actuators are typically based on the concept of the bio-microelectromechanical systems (MEMSs) (Ponmozhi et al. 2012). A barrier to obtaining implantable biosensors is biocompatibility. To eliminate this difficulty, subcutaneously implantable needle-type electrodes were developed (Wang 2001). Because of unique physical and chemical properties of carbon nanotubes (CNTs), such as their high aspect ratio, ultra-lightweight, high mechanical strength, high electrical conductivity, and high thermal conductivity, the CNT has been applied in the biomedical field (Sinha and Yeow 2005). A large variety of potentiometric biosensors were developed using biocatalytics and bioaffinity-based biosensing schemes. However, only a few of them are considered to be applicable to biomedical analysis (Wise 2007). The functionality, quality, and longevity of total knee arthroplasty and other kinds of implants can be enhanced by the improved design of sensors (Ponmozhi et al. 2012).

### 3.3 Controllers

The controller is another essential element of a control system, which uses the captured signal as input and produces corresponding output to help facilitate the movement of the prosthesis to the desired position. The use of some fundamental control units such as proportional (P), proportional derivative (PD), proportional integral (PI), proportional integral derivative (PID), and linear quadratic regulator (LQR) have been observed extensively in different types of control systems (Weir 2008). Chang et al. (2011) have proposed a novel T–S fuzzy model-based controller applied to a one-dimensional manipulator actuated by a pneumatic artificial muscle (PAM). The T–S fuzzy model-based controller can decompose a nonlinear system into a set of linear subsystems. Thus, the simple linear control techniques can successfully reproduce complicated nonlinear systems. Timmermans et al. (2009) have used proportional (P), and proportional derivative (PD) controllers to control the arm position of an exoskeleton robot, ARMIN III. A PID controller has been applied by Aliff et al. (2012) to control expanding and contracting of a prosthesis. Kaluza and Cioacă (2012) modeled an artificial neural network-based controller inspired by biological central pattern generators for a toy robot. Their proposed neural network-based controller has achieved a great level of success in controlling the body dynamics of the toy, and thus effective control of its movement.

### 3.4 Actuators

The actuator is the next important unit of the prosthesis control system to execute the instruction from the controller, and thus to trigger the end effector. The conventional DC motors and micromotors, some exotic shape-memory alloys, ultrasonic motors, and pneumatic artificial muscles have been used as actuators during the past decade. Wide ranges of actuator such as mechanical, electrical, hydraulic, pneumatic, and hybrid have been used to actuate different systems depending on the nature of the end effector and its application (Varol et al. 2009). The large variety of applications has resulted in a diversity of actuation methods. Micro-ultrasonic, ultrasonic, and piezoelectric motors are identified to be the most promising when compared with hydraulic actuators, shape-memory alloys, and contractile polymer gels with regards to size, weight, applicability, precision, hysteresis and non-repeatability, energy consumption, operating frequency, efficiency, power density, anthropomorphism, and cost (Cura et al. 2003). Recent advancements in shape-memory alloys have produced actuators with increased strains of up to 32 % using a braided coil design; however, response speed, durability, actuation stress, energy consumption, and hysteresis persist as obstacles to their implementation (Biddiss and Chau 2008). Recently, the application of bio-inspired actuators with built-in sensors or control strategies has made the position controlling more accurate (Nguyen et al. 2012). Although polymer-based dielectric elastomer actuators provide advantages in terms of very high functioning frequency and remarkably large force delivered, they need quite high applied voltage (over 100 V) (Torop et al. 2012). Recently, much attention has been focused on soft materials that can directly transform electrical energy into mechanical work for a wide range of applications including robotics, tactile

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