CHAPTER 1

INTRODUCTION

A hand is considered as an agent of human brain and is the most intriguing and versatile appendage to the human body. Over the last several years, attempts were made to build a prosthetic/robotic hand to replace a human hand to fully simulate the various natural/human-like operations of moving, grasping, lifting, twisting, and so on. Replicating the human hand in all its various functions is still a challenging task due to the extreme complexity of a human hand, which has 27 bones, controlled by about 38 muscles to provide the hand with 22 degrees of freedom (DOFs), and incorporates about 17,000 tactile units of four different types [1, 2]. Parallels between dextrous robot and human hands were explored by examining sensor motor integration in the design and control of these robots through bringing together experimental psychologists, kinesiologists, computer scientists, and electrical and mechanical engineers.

In this chapter, we present introductory material on relevance to military, overview of control strategies, fusion of hard and soft control strategies, and summary of the remaining chapters.

Fusion of Hard and Soft Control Strategies for the Robotic Hand, By C.-H. Chen and D. S. Naidu

Background

The proposed book is an outgrowth of the interdisciplinary Biomedical Sciences and Engineering (BMSE) research project exemplifying *The Third Revolution: The Convergence of Life Sciences, Physical Sciences, and Engineering*[1] [3–6]. It is to be noted that the book *Fusion of Hard and Soft Control Strategies for the Robotic Hand* basically focuses on the robotic hand applicable to prosthetic/robotic and non-prosthetic applications starting from industrial [7], operation in chemical and nuclear hazardous environments [8, 9], space station building, repair and maintenance [10, 11], explosive and terrorist situations [12] to robotic surgery [13].

1.1 Relevance to Military

During the recent wars in Afghanistan and Iraq, "at least 251,102 people have been killed and 532,715 people have been seriously wounded" [14]. Further, in the United States, the Amputee Coalition of America (ACA) [15] reports that there are approximately 1.9 million people living with limb loss, due to combat operations (such as conflicts and wars), and non-combat operations such as accidents, or birth defects. According to a study of the 1996 National Health Interview Survey (NHIS) published by Vital and Health Statistics [16], it is estimated that one out of every 200 people in the United States has had an amputation. That is, one in every 2,000 new born babies will have limb deficiency and over 3,000 people lose a limb every week in America. By the year 2050, the projected number of Americans living with limb amputation will become 3.6 million [17].

The following documents reveal the intense interest by military in the area of smart prosthetic/robotic hand.

1. First, according to [18], recognizing that "arm amputees rely on old devices" and that the existing technology for arm and hand amputees was not changed significantly in the past six decades, the Defense Department is embarking on a research program to "fund prosthetics research" according to [19] to revolutionalize upper-body prosthetics and to develop artificial arms that will "feel, look and perform" like a real arm guided by the central nervous system.

2. According to [20, 21], Bio-Revolution is one of the eight strategic research thrusts that DARPA is emphasizing in response to emerging trends and national security. In particular, the Human Assisted Neural Devices program under Bio-Revolution will have "immediate benefit to injured veterans, who would be able to control prosthetics..." A related area of interest in Bio-Revolution is Cell and Tissue Engineering.

3. Next, according to Defense Science Office (DFO) of DARPA [22], emerging technologies for combat casualties care with dual usage for both military and

[1] The First Revolution: Molecular and Cellular Biology and The Second Revolution: Genomics

civilian medical care, focus on programs in Revolutionizing Prosthetics, Human Assisted Neural Devices, Biologically Inspired Multi-functional Dynamic Robotics, and so on. In particular, according to [23], "today on of the most devastating battlefield injuries is loss of a limb... at DARPA, the vision of a future is to ... regain full use of that limb again..."

According to an article that appeared in IEEE Spectrum issue of June 2014, "Fifty years out, I think we will have largely eliminated disability" — Eliza Strickland [24]. The robotic hand, in addition to using it for prosthetic applications, is highly useful for performing various operations that a real human hand cannot perform without reaching a fatigue stage and especially for handling of hazardous waste materials and conditions.

Finally, an IEEE video on overview of how engineers are solutionists, poses "What if prosthetics were stronger and more accurate than the human body?" [25]

1.2 Control Strategies

1.2.1 Prosthetic/Robotic Hands

Artificial hands have been around for several years and have been developed by various researchers in the field and some of the prosthetic/robotic devices developed are given below (in chronological order) [2, 26].

1. Russian arm – [27–29]
2. Waseda hand – [30]
3. Boston arm[2] – [31]
4. UNB hand (University of New Brunswick) – [32–34]
5. Hanafusa hand – [35]
6. Crossley hand – [36]
7. Okada hand – [37]
8. Utah/MIT hand (University of Utah/Massachusetts Institute of Technology) – [38–40]
9. JPL/Stanford hand (Jet Propulsion Laboratory/Stanford University) – [41, 42]
10. Minnesota hand – [43]
11. Manus hand – [44, 45]

[2] The "Boston Arm," project involved the Harvard Medical School, Massachusetts General Hospital, the Liberty Mutual Research and Rehabilitation Centers, and MIT

12. Kobayashi hand – [46]
13. Rovetta hand – [47]
14. UT/RAL hand – [48]
15. Dextrous gripper – [49]
16. Belgrade/USC hand (University of Belgrade/University of Southern California) – [50]
17. Southampton hand (University of Southampton, Southampton, UK) – [51]
18. MARCUS hand (Manipulation And Reaction Control under User Supervision) – [52]
19. Kobe hand (Kobe University, Japan) – [53]
20. Robonaut hand (NASA Johnson Space Center) – [54]
21. NTU hand (National Taiwan University) – [55]
22. Hokkaido hand – [56]
23. DLR hand (Deutschen Zentrums für Luft- und Raumfahrt-German Aerospace Center) – [57, 58]
24. TUAT/Karlsruhe hand (Tokyo University of Agriculture and Technology/University of Karlsruhe) – [59]
25. BUAA hand (Beijing University of Aeronautics and Astronautics) – [60]
26. TBM hand (Toronto/Bloorview MacMillan) – [61]
27. ULRG System (University of Louisiana Robotic Gripper) – [62]
28. Oxford hand – [44]
29. IOWA hand (University of Iowa) – [63]
30. MA-I hand – [64]
31. RCH-1 (ROBO CASA hand 1[3]) – [65]
32. UB hand (University of Bologna) – [66]
33. Ottobock SUVA hand – (www.ottobock.co.uk)
34. Northwestern University system – [67]
35. SKKU Hand II (Sungkyunkwan University, Korea) – [68]

[3] The Italy–Japan joint laboratory for Research on Humanoid and Personal Robotics

36. Applied Physics Laboratory (APL) at Johns Hopkins University (JHU) – [23, 69, 70]

and some of the commercial web sites for prosthetic/robotic devices are

1. Sensor Hand^{TM} Speed from Ottobock (www.ottobock.co.uk),
2. VASI (Variety Ability Systems Inc.), a company of the Otto Bock Group (http://www.vasi.on.ca/index.html),
3. Utah Arm from Motion Control (www.utaharm.com),
4. The i-LIMB Hand from Touch Bionics (www.touchbionics.com), and so on.

A very useful comparison table between several hands listed above and human hand, adapted from [2, 26], is updated and shown in Table 1.1.

However, about 35% of the amputees do not use their prosthetic/robotic hand regularly according to [71] due to various reasons such as poor functionality of the presently available prosthetic/robotic hands and psychological problems. To overcome this problem, one has to design and develop an artificial hand which "mimics the human hand as closely as possible" both in functionality and appearance.

There are a number of surveys, and/or state-of-the-art articles that appeared over the years on the subject of myoelectric prosthetic/robotic hand including the work in USSR (Russian) given by [28] and some of them are given by references [2, 72–84].

1.2.2 Chronological Overview

An overview of the literature on *prosthetic/robotic hand technology*, conducted by the authors [85, 86] is briefly summarized in the next Section 1.2.3. This overview, focusing on recent developments and continuously being updated, is intended to supplement the already existing excellent survey articles [2, 79, 81, 87, 88]. Further, this overview is not intended to be an exhaustive survey on this topic, and any omissions of other works are purely unintentional.

Up to 1970

Electromyographic (EMG) signal is a simple and easily obtainable source of information about the various movements to be used for artificial/prosthetic hands. The EMG extraction using surface electrodes is a very attractive method from the point of view of the user compared to implants requiring surgery. Research activity in the field of prosthetic/robotic limbs was initiated by United States National Academy of Sciences in response to the needs of a large number of casualties in World War II [89]. It was first proposed by [90, 91] the concept of EMG signals for the control of a prosthetic/robotic hand for amputees. A proportional (open-loop) control system, in which the amplitude of the hand motor voltage and hence its speed and force measured from strain gauges varies in direct proportion (linearly) to the amplitude of the EMG signal generated by the prosthetic/robotic hand, was first reported by [92, 93]. In addition, the system added force and velocity feedback controls, so the

Table 1.1 Comparison of Human Hand with Artificial Hands: Robotic and Prosthetic/Robotic Hands: *Force* Indicates Power Grasp *Speed* Indicates the Time Required for a Full Closing and Opening; *E*: Stands for *External*; *I*: Stands for *Internal*

	Size (Norm)	No. of Fingers	No. of DOFs	No. of Sensors	No. of Actuators	Weight (gms)	Force (N)	Speed (sec)	Controls
Human hand	1.0	5	22	≈ 17,000	38(I+E)	≈ 400	>300	0.25	E
Russian arm		5		3	1		≈ 147		
Waseda hand									
UNB hand									
Hanafusa hand									
Crossley hand									
Utah/MIT hand	≈ 2.0	4	16	16	32(E)	-	31.8	-	E
JPL/Stanford hand	≈ 1.2	3	9	-	12(E)	1100	45	-	E
Minnesota hand									
Kobayashi hand									
Rovetta hand									
UT/RAL hand									
Dextrous gripper									
Belgrade/USC hand	≈ 1.1	4	4	23+4	4(E)	-	-	-	E
Southampton hand	≈ 1.0	5	6	-	6(E)	400	38	≈ 5	E
MARCUS hand	≈ 1.1	3	2	3	2(I)	-	-	-	I
Kobe hand									
Robonaut hand	≈ 1.5	5	12+2	43+	14(E)	-	-	-	E
NTU hand	≈ 1	5	17	35	17(E)	1570	-	-	E
Hokkaido hand	≈ 1	5	17	35	17(E)	1570	-	-	E
DLR hand II	>1	5	7	-	7(E)	125	-	-	E
TUAT/Karlsruhe hand	≈ 1	5	17	-	17(E)	≈ 120	12	0.1	E
BUAA hand		4			2				
TBM hand									
Oxford hand									
IOWA hand									
MA-I hand									
Robo Casa hand-1	≈ 1	5	16	24	6(E+I)	350	≈ 40	0.25	E
Ottobock SUVA	1	3	1	2	1(E)	600	-	-	I
UB hand									
Hokkaido hand	>1	5	7	-	7(E)	125	-	-	E
Northwestern									
SKKU Hand II	1.1	4	4	-	3	900			
APL-JHU System									

users could feel more natural to utilize this device. An adaptive control scheme was developed by [94] for a Southampton Hand.

1971–1979

The work reported by [32] studied the effect of sensory feedback based on semiconductor strain gauges on either edge of thumb of the prosthetic/robotic hand to adjust the stimulus magnitude to target value and avoid dropping or crushing objects for control of a prosthesis and found this acceptable for patients. When the strain gauges received the stimulus, the system amplified and transferred the signals to comparator, and then the comparator modified the range of amplitude of stimulus to the level that the users needed. However, the device with feedback is two or three times larger than the normal hand. A hierarchical method consisting of analytical control theory such as performance-adaptive self-organizing control algorithm and artificial intelligence using fuzzy automaton was presented by [95] to drive a prosthetic/robotic hand.

1980–1989

In providing a historical perspective, the contribution by [72] presented the status of the closed-loop (feedback) control principles for the application of prosthetic/robotic devices, three concepts relating to supplemental sensory feedback, artificial reflexes, and feedback through control interfaces were discussed and it was concluded that "we have not moved very far in the last 65 years in the clinical application of these concepts." A statistical analysis involving the study of zero crossings, second to fifth moments, and correlation functions and pattern classification of EMG signals was given by [96]. A probabilistic model of the EMG pattern was formulated in the feature space of integral absolute value (IAV) to provide the relation between a command, represented by motion and speed variables, and the location and shape of the pattern for real-time control of a prosthetic/robotic arm as given in [97]. Using kinematic relationships for dynamic model of fingers, multi-variable feedback control strategies using pole assignment in frequency domain were employed by [42] to guarantee local stability for controlling one finger of the JPL/Stanford hand. The work in [42] produced the dynamic models of three fingers (thumb, index, and middle) and three joints first, and then used Laplace transform to work in frequency domain. To get a guaranteed stability of control system, the roots/poles had to be located in the left half plane. Hence, they could get a desired steady movement of fingers by controlling the positions of the roots. The works reported by the group [98, 99] were one of the first groups who investigated various aspects such as kinematics, prehensility, dynamics, and control of multi-fingered hands manipulating objects of arbitrary shape in three dimensions.

1990–1999

Design, implementation, and experimental verification of an improved cybernetic elbow prosthesis was presented in [100, 101] that mimics the natural limb to both internal (voluntary) inputs from the amputee and external inputs from the environment. The work in [102] considered a dextrous hand employing a systematic approach to achieve the object stiffness control by actuator position control, tendon tension control, joint torque control, joint stiffness control, and Cartesian fingertip stiffness control. The work by [75] conducted a survey of 33 patients wearing the proportional myoelectric hand grouped into three categories based on previous experience with a terminal device: digital (on–off) myoelectric hand, body-powered terminal device, and no terminal device. The survey resulted in that the group of patients having experience with digital hand "were most impressed with proportionally controlled hand," because it has the advantages: comfortable, cosmetic acceptance, more natural, superior pinch force (11–25 lb) compared to voluntary opening (7–8 lb), a greater range of function but less energy, sensory feedback, force feedback, and short below-elbow.

The research work in [103] developed three tests for evaluation of input–output properties of patient control of neuroprosthetic hand grasp, which compensates or enriches the function of a damaged peripheral nervous system: first test for static input–output properties of the hand grasp, second one for control of hand grasp outputs while tracking step and ramp functions, and finally to obtain the input–output frequency response of the hand grasp system dynamics to estimate the transfer function using spectral analysis. Each test used visual feedback when the users controlled the grasp force and grasp position tracking of the hand. It was shown in [104] that the myoelectric signal (MES) is not random during the initial phase of muscle contraction thus providing a means of classifying patterns from different contraction types. The means is to establish the 60 records of an isometric contraction of the subjects and then produce some anisometric contraction types, like flexion and extension. This information was useful in designing a new multi-function myoelectric control system using artificial neural networks (ANNs) for classifying myoelectric patterns. Additionally, the hidden layer size, segment length, and EMG electrode positions were studied. See related works in [105–108] on multi-functional myoelectric control systems using pattern recognition methods for MES extraction and classification. The control philosophy of a multi-fingered robotic hands for possible adaptation and use in prosthetics and rehabilitation was discussed by [109–111] with respect to the Belgrade/USC robot hand by [50], called PRESHAPE (Programmable Robotic Experimental System for Hands and Prosthetics Evaluation), which estimates a system that translates task commands to motor commands using pressure sensors, force sensors, and pressure feedback which is very useful to detect small contact forces.

Using the dynamic model of the nonlinear neuromuscular (motor servo) control system of human finger muscles including mechanical properties (such as viscoelasticity) of the muscle and stretch reflex, a surface-based myoelectrically controlled biomimetic prosthetic/robotic hand (called Kobe hand) with three fingers—thumb, index, and middle fingers, was developed at Kobe University, Japan, by [53] with a system consisting of EMG signal processing unit, the dynamic model, positional control unit, and the prosthetic/robotic device. A survey of four important properties of dexterity, equilibrium, stability, and dynamic behavior relating to autonomous multi-fingered robotic hands was presented in [76]. An interesting aspect of this literature survey is a series of tables relating to existing multi-fingered robotic hands, force closure, dexterity in kinematically redundant robotic hands, equilibrium, in robotic grasp, and stability. As reported in [112], an intelligent prosthesis control system, developed by Animated Prosthetics, consists of two parts: the animation control system (ACS) residing in prosthesis and a remote prosthesis configuration unit (PCU) capable of on/off to variable speed/grip. Dynamic control of two arms to manipulate cooperatively an object with rolling contacts was addressed by [113] using a nonlinear feedback control methodology that decouples and linearizes the system.

A sensory control system based on force-sensing resistor (FSR) was developed by [114] at The National Institute for Accidents at Work (INAIL), Bologna, Italy, to control the strength of the grip on objects for a commercial prosthetic/robotic hand having two main functions: the automatic search for contact with the object and the detection of the object possibly slipping the grip by involuntary feedback (force sensors and slipping sensors). Further, automatic tuning of control parameters of prostheses was investigated by [115] using fuzzy logic (FL) expert systems resulting in a software package: microprocessor controlled arm auto tuning. The automatic tuning software works as follows: the client connects the prosthesis hardware, the program needs both sensor signals as client input, the program combines the above qualitative and quantitative information stored in the FL database to calculate the prosthesis parameter values, and the program enables the new parameter values to be down-loaded into the prosthesis control system memory. Dynamic modeling of a robotic hand was proposed in [116] using a hybrid approach with discrete event aspect of grasping and continuous-time part with a variable structure impedance control algorithm. A novel on-line learning method was reported by [56] for prosthetic/robotic hand control based on EMG measurements with a system consisting of three units: analysis unit for generating feature vectors containing useful information for discriminating motions from EMG signals, an adaptation unit for adapting to the amputee's individual variation and for discriminating motions from the feature vector and at the same time generating the necessary control commands to the prosthetic/robotic hand, and a trainer unit for directing the adaptation unit to learn in real time based on the amputee's teaching signal and the feature vector. The work by [114] built a sensory control system based on the FSR for an upper limb prosthesis and an optical sensor for detecting movement. The prostheses produced were of the "all or nothing" (opening or closing) and proportional control type (the relationship between force and EMG signal is linear). For traditional control, it used voluntary (visual) feedback, but the users had to pay good attention. This work developed an involuntary feedback control which uses two kinds of sensors, strength and slipping sensors. If the prosthesis hand is slipping, the control system automatically orders the actuator of the prosthesis to increase the grip strength. On receiving the EMG signal, the hand begins a closing action and goes on closing until the FSRs produce a signal that is greater than or equal to a "contact threshold" value, and then it stops, because the object has been grasped with the required strength of grip. The automatic grip mechanism is very useful in grasping delicate objects.

The investigation by [117] showed that the proposed neuro-fuzzy classifier known as Abe–Lan network, is able to identify correctly all the EMG signals related to different movements of human hand. A highly anthropomorphic human hand, called

Robonaut Hand consisting of five fingers and 14 independent DOFs, was built at NASA Johnson Space Center to interface with extra-vehicular activity (EVA) crew interfaces onboard International Space Station (ISS), as reported by [54].

2000–2007

In [118], estimating muscular contraction levels of flexors and extensors using neural networks (NNs), a new *impedance control* technique [119] was developed to control impedance parameters such as the moment of inertia, joint stiffness, and viscosity of a skeletal muscle model of a prosthetic/robotic hand. An overview of dextrous manipulation was provided by [78] with an interesting time-line chart for the development of robotic dextrous manipulation during the period 1960–2000. An excellent survey appears in [77] summarizing the evolution and state of the art in the robotic hands focusing mainly on functional requirements of manipulative dexterity, grasp robustness, and human operability. Also, the work by [120] exploited the non-holonomic character of a pair of bodies with regular rigid surfaces rolling onto each other, to study the constructive controllability algorithm for planning rolling motions for dextrous robot hands. A control system architectures was proposed in [121, 122] with a feedforward loop based on EMG measurements consisting of a low-pass filter and NN to provide the actual torque signal and a feedback loop based on desired angle consisting of a proportional-derivative (PD) controller to provide the desired torque signal and the error signal between these torques drives the prosthetic/robotic hand to achieve the desired angle while the NN learns based on feedback error.

This work reported by [123] studied finger extension, external control, overhead reach, and forearm pronation. For finger extension, they used two electrodes: one placed between the second and third metacarpals and the other between third and fourth metacarpals. They could provide full extension of the index, long, and ring fingers. For external control, a new form of control was developed by using retained voluntary wrist extension to control grasp opening and closing. Overhead reach is provided by stimulation of the triceps muscle, so elbow position is controlled by voluntary activation of biceps as an antagonist. As for forearm pronation, the main issues are an increased number of stimulus channels to allow stimulation of the finger intrinsic muscles, triceps, and forearm pronator, an implanted control source, bidirectional communication between sensor and body, reduced size, and reduction of all external cables. The work by [2] presents a review of the traditional methods for control of artificial hands using EMG signal, in both clinical and research areas and points out future developments in the control strategy of the prosthetics, in particular advocating neuroprosthesis with biocompatible neural interface for providing sensory feedback to the user leading to electroneurographic (ENG)-based control in place of EMG control. Collaboration between University of Southampton and University of New Brunswick (UNB) by [34] resulted in a hybrid control system using a multilayer perceptron (MLP) ANN as a classifier of time-domain features set (zero crossings, mean absolute value, mean absolute slope and trace length) extracted from MESs and a digital signal processor (DSP) controlling the grip pressure of the prosthetic/robotic hand without visual feedback (voluntary feedback). Design and development of an underactuated (the number of actuators less than the DOF) mechanism applicable to prosthetic/robotic hand was presented in [124] based on dynamic model of fingers leading to adaptive grasp (i.e., being able to conform to the shape of an object held within the hand).

Although an adaptive control scheme was developed by [94] for a Southampton Hand, further developments were made in the research by [79] and [125] producing their IP (Intelligent Prosthesis) according to [51]. The investigation [126] provided an evolution of microprocessor-based control systems for prosthetics with classification into first (based on digital systems), second (with low power), and third generation (based on microprocessors and DSPs). The work in [44] conducted a comparison of Oxford and Manus hand prostheses with respect to

1. hand mechanisms,
2. control electronics: EMG analog amplifiers, A/D converters, DSPs,
3. sensors: force, position and slip sensors based on Hall effect, and
4. manipulation or control schemes: Oxford hand used Southampton Adaptive Manipulation Scheme consisting of three-level hierarchical scheme and Manus used a two-level scheme.

The scheme suggested by [127] consisted of five modules, including an artificial muscoskeletal system, position and force sensors, 3D force sensors, low-level control loop dedicated to control slipping and grasping, and an EMG control unit. Further, the scheme used two semiconductor strain gauges as the force sensor and glues the sensor in SS496B by Honeywell International Inc. as the position sensor, which is the linear slider and small magnets. Moreover, the control system receives three signals: activation (EDG, which is used to identify whether there is a movement), direction (SGN, which decides opening or closing), and amplitude of the movement (AMP, which controls the seed of the movement in a proportional means). As for the control scheme, it uses a simple proportional open-loop control.

A cylindrical grasp of a cylindrical object and a parallel force/position control is studied by [128] to ensure the stability. The work in [129] presented a feedback control system for hand prosthesis with elbow control. Using a concept of extended physiological proprioception (EPP) (i.e., using natural physiological sensors), both the works [129] and the investigation by [130] developed microprocessor-based controllers for upper limb prostheses. A systematic literature review, conducted by [131], is useful for prosthetic/robotic hand, although the survey was done for lower limb prosthesis. This work by [128] developed a procedure to obtain maximum load and contact force distribution for a given grasp task and a parallel force/position control to ensure stability of the grasp. The goal of this control scheme is to specify a set of joint torque inputs so that the desired grasping forces along the constrained directions, and the desired position trajectory along the unconstrained directions are realized.

It was shown by [82, 132, 133] that sensory feedback signals are obtained for a multi-fingered robot hands to perform the function of grasping an object and that dynamic force/torque closure is constructed without knowing object kinematic parameters and location of the mass center. Further, the convergence of motion of the overall fingers-object system was proved using the concepts of "stability and asymptotic stability on a manifold." Mechanical design and manipulation (control) issues were addressed in [45] for a multi-fingered dextrous hand for upper limb prosthetics using the underactuated kinematics enhancing the performance and providing four grasping modes (cylindrical, precision, hook, and lateral) with just two actuators, one for the thumb and one for the remaining fingers. In particular, the hierarchical control architecture consists of a host (or master) controller for EMG management and definition of grasp set points (for position and torque/force) and three local (or slave) controllers for low level implementation of stiffness control of the joints. In [63], design and analysis was presented for a multi-fingered prosthetic/robotic hand consisting of a thumb with three joints and the rest of the four fingers having two joints using Haringx and element stiffness models, which enables the location of actuators far away from the hand to a belt around the waist and further enabling actuation and control with relatively high DOF. Robotic hand MA-I was designed and built by [64] at the Institute of Industrial and Control Engineering (IOC) at the Polytechnic University of Catalonia (UPC) with 16 degrees of freedom and the control system consisting of 16 position control loops, independently controlling each of the 16 DC motors. Visual hand motion capture is a multiple-dimension and multiple-objective searching optimization problem and the work reported in [134] used pose estimation and a motion-tracking scheme with genetic algorithms (GAs) embedded particle filter (PF) to navigate visual hand gesture, such as virtual environment and control of a robot arm.

The fabrication of a complaint, under-actuated prosthetic/robotic hand (both palm and fingers) moulded as a soft polymeric single part for providing *adaptive* grasp was reported by [135, 136]. Since the analysis and synthesis are "so complex and only experimental analysis of the solution adapted validate our works." It was shown by [137] that an object with parallel surfaces in a horizontal plane could be controlled by a pair of robotic fingers to achieve stable grasping, angle, and position control without the need for the object parameters or object sensors such as tactile, force, or visual sensors. At Northwester University Prosthetics Laboratory (NUPL), the researchers [138, 139] developed multi-function prosthetic/robotic hand/arm controller system receiving signals from as many as 16 implantable myoelectric sensors (IMES) and a heuristic FL approach to EMG signal pattern recognition by [140, 141]. In particular, FL was explored for discriminating between multiple surface EMG control signals and classify them to user intention. The multi-functional hand mechanism consisted of three motor hands (one motor for driving the thumb, one motor drives index finger, and the third motor drives middle, ring, and little finger) and two motor wrists (one motor for wrist extension/flexion and the other motor for wrist rotation). Further, the research by [67] demonstrated that in implementing the EPP control for a powered prosthesis, the backlash is determined by the stiffness of the control cable as well as mass located at the distal end of the forearm and that reduction of static friction and backlash in the system could prevent the limit cycle.

It was demonstrated by [142] that by implanting electrodes within individual fascicles of peripheral nerve stumps, appropriate, distally referred sensory feedback about joint position and grip force from an artificial arm could be provided to an amputee through stimulation of the severed peripheral nerves which also provide appropriate signals. It is interesting to note the work of [143] on the mechanism, design, and control system of a humanoid-type hand with human-like manipulation capabilities as a part of development of service robots and the comparison (shown by [144, 145]) of natural and prosthetic/robotic hands. In [146], the EMG motion pattern classifier was developed using on parametric autoregressive (AR) model and Levenberg–Marquardt (LM)-based NNs to identify three types of motion of thumb, index, and middle fingers to control a five-fingered underactuated prosthetic/robotic hand.

The work in [147] focussed on the "optimal" delay as the maximum amount of time, which is from command to hand movement, for a prosthesis controller with a delay of 200–400 ms as the range which is accepted by users. A bypass prosthesis called Prosthetic Hand for Able-Bodied Subjects (PHABS) was developed to allow able-bodied subjects to operate a prosthetic/robotic terminal device. The controller is a commercially available Myo-pulse control, which combines pulse width modulation (PWM) and pulse period modulation (PPM) because it provides a linear relation between motor speed and the pulse width and timing of a digital control signal. In addition, it also used a mechanical low-pass filter to smooth the pulse train and movement. If the EMG reaches the threshold, the motor will be turned "on"; otherwise, it will be turned "off." Furthermore, the experimental controller was created in Simulink of MATLAB and executed using Simulink Real Time and XPC Target Toolboxes. Finally, this work summarized seven time-delay sources, including

1. the time from the intent of movement to the development of EMG,
2. the time constant of the analog filters contained in the EMG pre-amplifiers,
3. the analog-to-digital sampling period,
4. the time required to collect the EMG signal for feature extraction,
5. the time required to perform the EMG signal for feature extraction,
6. the time required to execute th pattern recognition on the extracted features, and
7. the time required to actuate the component.

In [81], a review of the traditional methods of control as well as the current state of new control techniques was provided. A newly developed intelligent flexible hand system with 3 fingers, 10 joints, fitted with a small harmonic drive gear and a high power mini actuator, providing 12 DOFs applied to a catching task was developed by [148]. The authors [149] developed an EMG-based (using electrodes, torque, and angle sensors) prosthetic/robotic hand control system composed of a human operator, a five-fingered under-actuated prosthetic/robotic hand system, the prosthetic/robotic hand controller (with analog-to-digital converters and DSP board and stepper motors), and visual feedback. In particular, the EMG signals undergo feature extraction and feature classification using NNs with parametric autoregressive (AR) model and wavelet transforms. In an under-actuated system, there is less number of actuators compared to the number of DOF of the system. Further in [150], a hierarchical control system was proposed with a high-level supervisory controller for implementing the EMG signal acquisition and pattern recognition and also providing a set of commands (for operations such as close, open, position, etc.) to a low-level controller. A sensor-based hybrid control strategy (using normal feedback control based on EMG signals from sensors and feedback to the user) was presented by [151] where a digital controller operating from prosthetic signals converts the user grasping intention (EMG signal) into an order for the control of prosthesis.

The investigation by [68] developed a robot hand with tactile sensors (slip sensor and force sensor), called SKKU Hand II, having two functional units: a PolyVinyliDene Fluoride (PVDF)-based slip sensor designed to detect slippage and a thin flexible force sensor that read the contact force of and geometrical information on the object using a pressure variable resistor ink. A biomechatronic approach to the design and control of an anthropomorphic artificial hand was studied by [152] for closing the hand finger while grasping an object using a reference trajectory and using two different versions (joint space and slider space) of PD control system. In particular, the artificial hand consists of three under-actuated fingers (index, middle, and thumb) which are actuated by three cable-driven DC motors placed in the lower part of the arm. The work by [153] studied large controller delays created by multi-functional prosthesis controllers. A device called PHABS was utilized to test the performance of 20 able-bodied subjects to the Box and Block Test. To estimate and compare the performance of prosthetic/robotic hands, a functionality index is proposed by [147]. An underwater flexible robot manipulation (called HEU Hand II) that utilized Position-Based Neural Network Impedance Control (PBNNIC) for the force tracking control was studied by [154].

This work from [154] developed dextrous underwater robot hand, called as HEU Hand II. The sensor system mainly includes 12 strain gauges at different locations. When the robot hand is under water, the control system is more complicated because the complete dynamic model is not known exactly. Hence, the control system considers the uncertainty of the robot dynamic model. The controller of the hand force tracking is designed by PBNNIC scheme. Using biologically inspired principles for design and control of a bionic robot arm by [155], several control approaches were presented such as trajectory planning and optimization based on robot dynamics.

An alternate learning control strategy was proposed by [156] based on the working assumptions that both human motor commands and sensory information are passed on in a discrete, episodic manner, quantized in time with a learning algorithm called S-learning based on *sequences* arguing against the traditional control approaches due to highly nonlinear robot's dynamics and large number of DOF.

In the works by [157], the first prototype of a five-fingered prosthetic/robotic hand fitted with only three motors and achieving 20 DOFs was described using a new "strings and springs" mechanism and a continuous wavelet transform (CWT) for extraction of EMG inputs for a feed-forward, back-propagation NN to recognize the type of grip.

The work in [158] focuses on the control system of the hand and on the optimization of the hand design. It proposes the control action as proportional to the superficial EMG signals extracted by surface electrodes applied to a couple of antagonistic user's residual muscles. This work first explains designs of the hand prototype, such as biomechatronic design approach, under-actuated artificial hand, 3D CAD model (by ProEngineer), and dynamic analysis (by ANSYS). Secondly, it builds the model of control system, including the kinetics and dynamics of hand in PD control in the joint space and slider space with elastic compensation. Thirdly, it validates and optimizes the hand design in multiple objective problems (four goals). The first two goals are related the closed-loop control performance and the remaining two goals are part of joint trajectories. Besides, it develops the simulation in MATLAB/Simulink. Finally, it compares the experimental results with the simulation.

The dynamic system of a nonlinear flexible robot arm with a tip mass was introduced by [159] and the proposed intelligent optimal controller, in which the fuzzy neural network controller and robust controller were respectively designed to learn a nonlinear function and compensate the approximation errors, could control the coupling of bending vibration and torsional vibration for the periodic motion. To overcome the traditional FL difficulties, such as large rule bases and long training times, [160] proposed a self-learning dynamic fuzzy network (DFN) with dynamic equality constraints to speed up the trajectory calculations for intelligent nonlinear optimal control. For a five-finger under-actuated prosthetic/robotic hand with tendon transmission, [161] presented a robust controller implemented two subsequent and different phases, including the pre-shaping of the hand and the involved fingers rapidly closing around the object.

1.2.3 Overview of Main Control Techniques Since 2007

Hard Computing strategies:

1. **PD Controller**: Rong et al. [162] presented one kind of PD controller with feed-forward control based on adaptive theory for two DOFs direct driven robot with uncertain parameters.

2. **Adaptive Controller**: Cai et al. [163] developed an observer back-stepping adaptive control scheme for two-link manipulator under unmeasured velocity and uncertain environment and the adaptive velocity observer was designed independently from the state-feedback controller in order to compensate the estimation errors. Seo and Akella [164] derived the novel adaptive control solution involving a new filter design for the regressor matrix for n-DOF robot manipulator systems. By developing the Fourier series expansion from input reference signals of every joint, Liuzzo and Tomei [165] designed a global, output error feedback, adaptive learning control for two-DOF planar robot with uncertain dynamics. To achieve the tracking control objective, Chen et al. [166] proposed an adaptive sliding-mode dynamic controller for wheeled mobile robots with

system uncertainties and disturbances to make the real velocity of the wheeled mobile robot reach the desired velocity command.

3. **Robust Controller**: Because of the visco-elastic properties of manipulator links, Torabi and Jahed [167] utilized the loop-shaping method which decreases the order of the robust control model of a single-link manipulator examined in time and frequency domains. To enhance control of powered prosthetic/robotic hands, Engeberg and Meek [168–171] proposed robust sliding mode, back-stepping, and hybrid sliding mode-back-stepping (HSMBS) parallel force–velocity controllers which enabled the humans to more easily control a fine object by 10 able-bodied test subjects. Ziaei et al. [172] developed the modeling, system identification adopting generalized orthonormal basis functions (GOBFs), and robust position and force controllers for a single flexible link (SFL) manipulators required to operate the contact motion. Jiang and Ge [173] transformed the nonlinear kinematic models of three-DOF mobile robot with uncertain disturbance into linear control systems through an approximate linearization algorithm and then designed a partial feedback H_∞ robust controller through linear matrix inequality (LMI).

4. **Optimal Controller**: Vitiello et al. [174] synthesized the position controller and the Kalman filter to perform the planar movements, such as reaching and catching, of the NEURARM hydraulic piston actuation with nonlinear springs connected on the cable. Vrabie et al. [175] designed an online method via a biological inspired Actor/Critic structure to solve the adaptive optimal continuous-time control problem by the solution of the algebraic Riccati equation without using knowledge of the system internal dynamics. To minimize the positioning time (traveling between two specific points) of an under-actuated two-DOF robot manipulator restricted to the input constraint and the structural parameter constraint, Cruz-Villar et al. [176] developed a concurrent structure-control redesign method which combined the structural parameters and a bang–bang control law. Duchaine et al. [177] derived the position tracking and velocity control, the dynamic model of the robot, the prediction and control horizons, and the constraints by a general predictive control law and also derived an analytical solution for the optimal control by a computationally efficient model-based predictive control scheme for a six-DOF cable-driven parallel manipulator.

5. **Hierarchical Controller**: Fainekos et al. [178] proposed a hierarchical control law addressing the temporal logic motion planning problem for mobile robots modeled by second-order dynamics to track a simpler kinematic model with a globally bounded error and then the new robust temporal logic path planning problem for the kinematic model using automata theory and simple local vector fields were solved.

Soft Computing strategies:

1. **Fuzzy Logic**: According to human anatomy, Arslan et al. [179] developed the biomechanical model with a tendon configuration of the three-DOF index finger

of the human hand and the fuzzy sliding mode controller in which a FL unit tuned the slope of the sliding surface was introduced to generate the required tendon forces during closing and opening motion.

2. **Artificial Neural Networks**: Onozato and Maeda [180] utilized two NNs learning inverse kinematic and inverse dynamic to control the positions of two-DOF SCARA robot. Aggarwal et al. [181] obtained the neural recordings from rhesus monkeys with three different movements, the flexion/extension of each finger, the rotation of wrist and dextrous grasps and designed the separate decoding filters for each movement by using multilayer feed-forward ANN in order to be implemented in real-time MATLAB/Simulink. An online decentralized NN control design without deriving the dynamic model for a class of large-scale uncertain robot manipulator systems was proposed by Tan et al. [182]. Kato et al. [183] expressed the reaction of brains to the adaptable prosthetic/robotic system for a 13-DOF EMG signal controlled prosthetic/robotic hand with an EMG pattern recognition learning by ANNs. In addition, functional magnetic resonance imaging (f-MRI) was used to analyze the reciprocal adaptation between the human brain and the prosthetic/robotic hand by the plasticity of the motor and sensory cortex area in brains based on the variations in the phantom upper limb.

3. **Genetic Algorithm**: Marcos et al. [184] proposed the closed-loop pseudo-inverse method with genetic algorithms (CLGA) to minimize the largest joint displacement between two adjacent configurations, the total level of joint velocities, the joint accelerations, the total joint torque, and the total joint power consumption for the trajectory planning of three-DOF redundant robots. Kamikawa and Maeno [185] used GA to optimize locations of pivots and grasping force and designed one ultrasonic motor to move 15 compliant joints for an under-actuated five-finger prosthetic/robotic hand.

4. **Particle Swarm Optimization**: Khushaba et al. [186] developed a PSO-based method for myoelectrically controlled prosthetic/robotic devices. However, the artificial hands had limitation on precision grasping, such as grasping a screw or needle. To overcome the limitation, the accuracy and effectiveness of fingertip trajectory and control systems need to be optimized.

Fusion of Soft and Hard Computing strategies:

1. **PID Controller and Robust Controller**: Dieulot and Colas [187] presented a case study of the design of robust parametric methods for flexible axes and an heuristic initial tuning of the proportional-integral-derivative (PID) controller from additional pole placement constraints on the rigid mode.

2. **Adaptive Controller and Robust Controller**: To implement the trajectory tracking mission under the influence of unknown friction and uncertainty, Chen et al. [188] utilized a composite tracking scheme, including the adaptive friction

estimation to determine Coulomb friction, viscous friction, and the Stribeck effect and a robust controller to enhance the overall stability and robustness, for a two-DOF planar robot manipulator.

3. **Robust Controller and Optimal Controller**: Huang et al. [189] designed the robust control systems with some uncertainties, including the unknown payload and unknown modeling of objects and the unknown dynamic parameters, as the performance index that was optimized by the optimal control method for the space robot to capture unknown objects.

4. **Robust Controller and Fuzzy Logic**: Tootoonchi et al. [190] combined a robust quantitative feedback theory (QFT) designed to follow the desired trajectory tracking with the fuzzy logic controller (FLC) designed to reduce the complexities of the system dynamics for two-DOF arm manipulator. The control gain of the sliding mode controller tuned according to error states of the system by a fuzzy controller and a moving sliding surface whose the slope is dynamically changed by a FL algorithm for a three-DOF spatial robot were presented by Yagiz and Hacioglu [191].

5. **Robust Controller and Artificial Neural Networks**: Siqueira and Terra [192] developed a neural-network-based H_∞ controller which approximated the uncertain factors of an actual under-actuated cooperative manipulator and robustly controlled the position and squeeze force errors between the manipulator end-effectors and the object, although one joint was not actuated.

6. **Sliding Mode Controller and Genetic Algorithm**: Chen and Chang [193] utilized the multiple crossover GA to estimate the unknown system parameters and the sliding mode control method to overcome the uncertainty for a two-link robot control, respectively.

7. **Sliding Mode Controller and Particle Swarm Optimization**: Salehi et al. [194] used an online particle swarm optimization (PSO) to tune the parameters of sliding mode control at the contact moments of end-effector and unknown environments for the two-DOF planar manipulator.

8. **Fuzzy Logic and Artificial Neural Networks**: Subudhi and Morris [195] proposed a hybrid fuzzy neural control (HFNC) scheme containing a FLC and a NN controller to balance the coupling effects for the multi-link flexible manipulator with both rigid and flexible motions.

9. **Artificial Neural Networks and PSO**: Wen et al. [196] addressed the hybrid particle swarm optimization neural network (HPSONN) to compute the pseudo-inverse Jacobian of two-DOF planar manipulator inverse kinematic control.

1.2.4 Revolutionary Prosthesis

In 2009 (see the press releases [23, 69], the Applied Physics Laboratory (APL) of Johns Hopkins University (JHU), in Baltimore, MD received funding for the Rev-

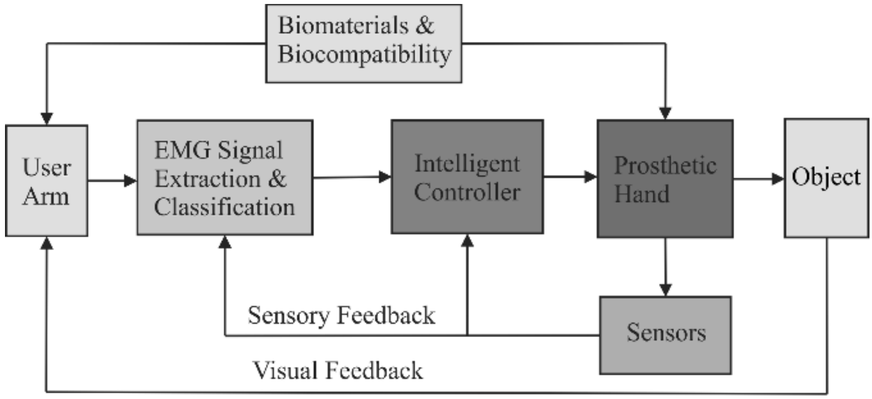

Figure 1.1 Schematic Diagram of Prosthetic/Robotic Hand Technology

olutionary Prosthesis 2009 program from DARPA (Defense Advanced Research Projects Agency), the U.S. Department of Defense, to "develop a next-generation mechanical arm that mimics the properties and sensory perception of the real thing." The APL leads an international team of about 30 organizations from Austria, Canada, Germany, Italy, Sweden, and USA. The APL team delivered first DARPA Limb Proto 1 (see [70], which "is a complete limb system that also includes a virtual environment used for patient training, clinical configuration, and to record limb movements and control signals during clinical investigations."

1.3 Fusion of Intelligent Control Strategies

Here we present the recent research activities on fusion control strategies for a smart prosthetic/robotic hand. The schematic diagram of the work is shown in Figure 1.1 (see the works of [34, 149, 151]). The overall system, in brief, consists of EMG signal acquisition from user arm for surface or implanted electrodes (in the implanted case we focus on biocompatibility based on nano-materials research). The EMG signal is then processed for feature extraction and classification or identification of EMG signal to correspond to different motions of the prosthetic/robotic hand. The classified signal is then used to control the prosthetic/robotic hand using actuators and driving mechanisms. It is to be noted that the EMG signal extraction and identification and the control algorithm are investigated using the fusion of soft computing (SC) and hard computing/control (HC) strategies.

1.3.1 Fusion of Hard and Soft Computing/Control Strategies

HC strategies are used at lower-level control for accuracy, precision, stability, and robustness and comprise PD control [197], PID control [198, 199], optimal control [199–202], adaptive control [203–206], etc. with specific applications to robotic hand devices. The authors conducted an overview of control strategies for robotic and prosthetic/robotic hands [85, 86]. However, our previous works [197–199, 207] for a robotic hand showed that PID controller resulted in undesirable feature of overshooting and oscillation, which were also demonstrated by Subudhi and Morris [195] in a two-link flexible robot manipulator and Liu and Chen [208] in a 6-DOF underwater robot (autonomous underwater vehicle).

The term SC or computational intelligence (CI) has been already used by L. A. Zadeh in 1994 and he defined SC as "a collection of methodologies that aim to exploit the tolerance for imprecision, uncertainty, partial truth, and approximation to achieve tractability, robustness, low solution cost and better rapport with reality" [209]. The fundamental concepts of SC have been influenced by Zadeh's earlier publications [210–212]. Since 1994, many researchers and engineers have worked on different methods using SC.

Unlike HC, SC strategies are meant to adapt to an environment under imprecision, uncertainty, partial truth, and approximation [209]. The review paper of L. Magdalena has analyzed, compared, and discussed some definitions of SC found in the literature [213]. Unlike the lower-level control of HC, SC is used at high-level control of the overall mission where human involvement and decision making is of primary importance. SC is an emerging field based on synergy and seamless integration of NN, FL, and optimization methods, such as GA and PSO [197, 209, 213–220]. The previous works on robotic/prosthetic hand used NN by [33, 34, 221], FL by [140, 141, 222], GA by [223], etc. mostly for EMG signal classification for various movements or functions of the robotic hand.

The brain analogy corresponds to the fusion of HC and SC strategies. We therefore propose hybrid intelligent control strategies with the integrated structure by blending [215, 216] the upper-level control of SC strategies and lower-level control of conventional HC strategies. Fusion of SC and HC methodologies can solve problems that cannot be solved satisfactorily by using either HC or SC methodology alone and can lead to high performance, robust, autonomous, and cost-effective missions, such as accuracy and effectiveness of fingertip trajectory and control systems [215, 216]. The hybrid intelligent control strategies for a robotic hand can be also applied to robotics for hazardous environments, surgery, etc. and clinical prosthetic/robotic hands [224–226].

The integration of SC and HC strategies shown in Figure 1.2 has the following attractive features [215, 216]:

1. The methodology based on SC is used, in particular with FL, at upper levels of the overall mission where human involvement and decision making is of primary importance, whereas the HC is used at lower levels for accuracy, precision, stability, and robustness.

2. In another situation using hybrid scheme, a NN of the SC is used to supplement the control provided by a linear, fixed gain controller for a missile autopilot.

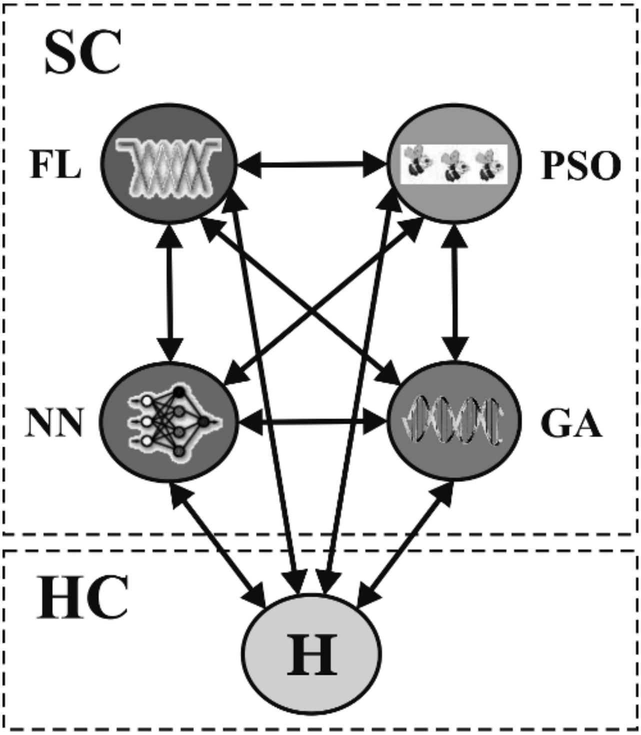

Figure 1.2 Fusion of Soft Computing and Hard Control Strategies

3. Further, the SC-based GA is used to tune the parameters of the PID controller and to achieve good performance and robustness for a wide range of operating conditions.
4. The SC and HC are potentially complementary methodologies.
5. The fusion could solve problems that cannot be solved satisfactorily by using either methodology alone.
6. Novel synergetic combinations of SC and HC lead to high performance, robust, autonomous, and cost-effective missions.

Our research focuses on developing intelligent autonomous strategies for EMG signal, extraction, analysis, and control of prosthetics by fusion of SC strategies comprising NN, FL, and GA (see [216, 227]) and HC strategies. The proposal takes advantage of our in-house research experience with problems in prosthetics as shown in [228, 229], in particular, and with problems in biomedical engineering as reported in [230, 231], in general.

An overview of nine papers using the strategies in industrial and engineering applications was presented by [232]. For the fusion strategies, the work by [233] described a multidimensional categorization scheme in five aspects: the degree of interconnection of soft and hard computing components (fusion grade), the topology of fusion skills (fusion structure), the time when fusion happens (fusion time), the layer of a system architecture (fusion level), and the motivation for the application (fusion incentive). Further, [234] classified the fusion strategies to 12 main categories and 6 supplementary categories.

1.4 Overview of Our Research

A chronological overview of our research is provided below.

A short review by Lai et al. [235] notes the importance of the biological interfaces that robotic implants and other prosthetic/robotic devices and notes an interdisciplinary team of biomedical and tissue engineers, and biomaterial and biomedical scientists is needed to work together holistically and synergistically.

In addressing the PSO technique, a set of operators for a PSO-based optimization algorithm is investigated for the purpose of finding optimal values for some of the classical benchmark problems. Particle swarm algorithms are implemented as mathematical operators inspired by the social behaviors of bird flocks and fish schools. In addition, particle swarm algorithms utilize a small number of relatively less complicated rules in response to complex behaviors, such that they are computationally inexpensive in terms of memory requirements and processing time. In particle swarm algorithms, particles in a continuous variable space are linked with neighbors, therefore the updated velocity of particles influences the simulation results. The work presents a statistical investigation on the velocity update rule for continuous variable PS algorithm. In particular, the probability density function influencing the particle velocity update is investigated along with the components used to construct the updated velocity vector of each particle within a flock. The simulation results of several numerical benchmark examples indicate that small amount of negative velocity is necessary to obtain good optimal values near global optimality [219].

A chronological overview of the applications of control theory to prosthetic/robotic hand is presented focusing on HC strategies such as multi-variable feedback, optimal, nonlinear, adaptive, and robust and SC strategies such as artificial intelligence, NN, FL, GA, PSO, and on the fusion of hard and soft control strategies [85]. The work [197] presents the PSO algorithm for identifying the rupture force for leukocyte adhesion molecules and the problem of finding the correct control parameters of a robotic hand. Another work by the group at ISU presents the fusion of SC technique of GA and HC technique of PID control with application to prosthetic/robotic hand. In particular, an adaptive neuro-fuzzy inference system (ANFIS) is used for inverse kinematics of the three-link index finger, and feedback linearization is used for the dynamics of the hand and the GA is used to find the optimal parameters of the PID controller [198]. An adaptive PSO (APSO) approach based on altering the maximum velocity at each iteration for two 30-dimensional benchmark problems is used [220].

A hybrid of a SC technique of ANFIS and a HC technique of adaptive control for a two-dimensional movement of a prosthetic/robotic hand with a thumb and index finger is investigated [205]. The dynamics of the prosthetic/robotic hand is derived and feedback linearization technique is used to obtain *linear* tracking error dynamics. Then the adaptive controller was designed to minimize the tracking error. The results of this hybrid controller show enhanced performance when compared with the PID controller. The adaptive control strategy is extended for the 14-DOF, five-fingered smart prosthetic/robotic hand with unknown mass and inertia of all the fingers [206]. The simulation results show that the five-fingered prosthetic/robotic hand with the proposed adaptive controller can grasp an object without overshooting and oscillation [236].

A novel condensed hybrid optimization (CHO) algorithm using enhanced continuous tabu search (ECTS) and the PSO was examined [207]. The proposed CHO algorithm combines the respective strengths of ECTS and the PSO. In particular, the ECTS is utilized to define smaller search spaces, which are used in a second stage by the basic PSO to find the respective local optimum. The ECTS covers the global search space by using a TS concept called diversification and then selects the most promising areas in the search space. Once the promising regions in the search space are defined, the proposed CHO algorithm employs another TS concept called intensification in order to search the promising area thoroughly. The proposed CHO algorithm is tested with the multi-dimensional hyperbolic and Rosenbrock problems. Compared to the other four algorithms, the results indicate that the accuracy and effectiveness of the proposed CHO algorithm was enhanced. Another hybrid of a SC technique using the ANFIS and a HC technique using finite-time linear quadratic optimal control for a two-fingered (thumb and index) prosthetic/robotic hand was investigated [201, 237, 238]. In particular, the ANFIS is used for inverse kinematics, and the optimal control is used to minimize tracking error utilizing feedback linearized dynamics. The simulations of this hybrid controller, when compared with the PID controller showed enhanced performance. This work was extended to a five-fingered, three-dimensional prosthetic/robotic hand [199]. To make the optimal controller fast acting and improve the accuracy, the performance index J is modified by including an exponential term [202, 239]. Simulations show that the proposed technique provides fast action with high accuracy and 30-fold faster than ANFIS- or GA-based trajectory planning [201, 239, 240].

1.5 Developments in Neuroprosthetics

It is worth noting some of the developments in neuroprosthesis reported in [241–244].

An interesting study was made by [245] on implanted neuroprostheses employing functional electric simulation (FES) to provide grasp and release to individuals with tetraplegia and comparing three control methods for shoulder position, wrist position, and myoelectric wrist extensors. To improve the control of grasp strength, forearm pronation, and elbow extension to the people with spinal cord injury at C5 and C6, the investigation by [123] developed an advanced neuroprosthesis that includes implanted components, including 10-channel stimulator, leads and electrodes, and a joint angle transducer, and external components, such as a control unit and transmitter–receiver coil.

In particular, it was reported in [246–248] that Jesse Sullivan, who lost both arms in an electric accident, could move his bionic arm with his brain—basically rewiring the severed live nerves that control arm and hand movements by redirecting the nerves to pectoral muscles in his chest. Electrodes attached to the chest muscles produce an electrical signal which controls the robotic arm depending upon the nature of muscle movement which in itself is characterized by “thinking” in the brain what is to be done with arms. However, the demonstrated bionic arm is only a “prototype and for research only.”

Another interesting news appeared in [249, 250] regarding implantation of an electronic chip into the brain of a quadripledge man to use a computer to operate a robotic arm.

An article that appeared in IEEE Spectrum issue of September 2014 [251], describes about “an epilepsy patient ... controlling the mechanical limb with her brain waves.”

1.6 Chapter Summary

This book is composed of seven chapters. Chapter 2 presents kinematics and trajectory planning and Chapter 3 presents dynamics for the robotic hand. The SC strategies such as FL, NN, ANFIS, GA, and PSO are addressed in Chapter 4. Chapters 5 and 6 present the fusion of soft and hard control strategies for each finger of the robotic hand and all the five fingers. Finally, conclusions and some thoughts on future work are given in Chapter 7.

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