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Bipedal Humanoid Robot

Iman, ZAYER[a*], Aris, I. B.[b], Marhaban, M. H., [c] and Ishak, A. J.[d]

[a,b,c,d]Department of Electrical and Electronic Engineering, Faculty of Engineering, University Putra Malaysia, 43400 Serdang, Selangor.

[a]Department of Mechatronics Engineering, Al Khwarizmi College of Engineering, University of Baghdad,

[*]eng.iman79@yahoo.com; ishak_ar@upm.edu.my

Abstract – The new millennium witnessed increasing attention to the field of robotics, especially the development of humanoid bipedal robot. Attention is noticed from the increasing number of publications as a result of a multitude of humanoid projects for commercial and academic goals. This paper briefly visits the recent activities in this field, highlighting the importance and motivation behind adopting bipedal humanoid projects, particularly underlining biologically inspired design concept, bipedal locomotion and communication. Ultimately, emphasising on power-efficient design. The problem of endurance and effective duty cycle were presented. Finally, potential future application for the humanoid robot was briefly listed.

Keywords: Bipedal robot, Humanoid, Locomotion, Communication, Power.

Introduction

More than five decades ago, researchers started to design and build a machine that resembles a human being, walk, talk, precept, and behave like humans with the intention of creating a complementary layer to human. Planning to reinforce human capabilities through the integration of these machines with the human environment (R. A. Brooks, 1996). Up to date, such goals are not reached. However, significantly remarkable advances were achieved in various related fields and areas pertinent to robotics. Starting from the first functional bipedal robot which was developed during the 70s (Kato, 1972), to ASIMO of Honda-Japan (Hirose & Ogawa, 2007), a humanoid robot, nowadays, are more sophisticated and advanced with greater autonomy level. However, they still suffer from plentiful shortcomings in which constraint their ability to be completely integrals with human, function freely and safely within structured or natural environment (Blar, Azni Jafar, Idris, & Mat Ali, 2015). In addition to that, their power limit and endurance add further constraints on their performance, particularly when performing tasks that require dynamic decision making (Luo, Yuan, Xue, Yang, & Zhang, 2015). Humanoid integration with the human environment has been tackled through categorisation of possible solutions to this paradigm; (1) dual ecology concept, (2) incorporating autonomy into teleoperation and (3) integration in designing functional systems (Walker & Orin, 1982). Within the context of dual ecology, which is a concept developed based on a humanoid interaction both with an operator and other humans, including patients, clients and bystanders (Goodrich, Crandall, & Barakova, 2013; Kuzuoka et al., 2004). Academic researcher's vision for humanoid robot development stresses the cultivation of key human skills, human system efficiencies, and design optimality, in addition to the task-oriented limitations, shortcomings, and incapability in certain situations and cases (Adams, Breazeal, Brooks, & Scassellati, 2000). Integrating robotic systems in mission design may contribute to optimise human efficiency and alleviate constraints echelons in human performance through managing workload requirement, minimising operation costs, limitation-based error and fatigue-based risk (Adams et al., 2000). Special attention must be paid to multilevel based human-robot interaction to ensure smooth and efficient integration of robotic systems within the human-engineered environment and potential/planned environment required to be explored. Many giant industrial companies, academic institutions, and specialised laboratories invested heavily in the development of interactable consumer robots to be used by humans in home and workplace (Chen, Billinghurst, Green, & Chase, 2008). Complete coverage of humanoid robotic is far from reach in this paper, especially when tackling a rapidly expanding field. Nevertheless, integrated view to the problem may partially compensate this expected limitations. The article reviews bipedal humanoid robot design approaches which cover energy efficiency, autonomy, endurance and applications and focus on energy management strategies employed to consolidate this discipline. It also pinpoints future research auspicious ambit concentrating on how integrated design concept can naturally promote synergy and thus enhance humanoid robot efficiency and consolidate endurance.

The Link: Human Schema and Imitation, Humanoid

One of the early and interesting research studies conducted to address the anatomy issue of a humanoid robot by mapping humanoid versus human. Thus, defining key requirements for a humanoid based on quantified engineering terms of the principal properties and capabilities of the human body (Seward, Bradshaw, & Margrave, 1996). Figure 1 shows mass distribution and coordinates of a target human chosen to be an adult male of 1.8 m height and 75 kg mass. Table 1 presents a comparison of some basic mechanical properties between human bones and a possible robot frame constructed from two types of composite materials.

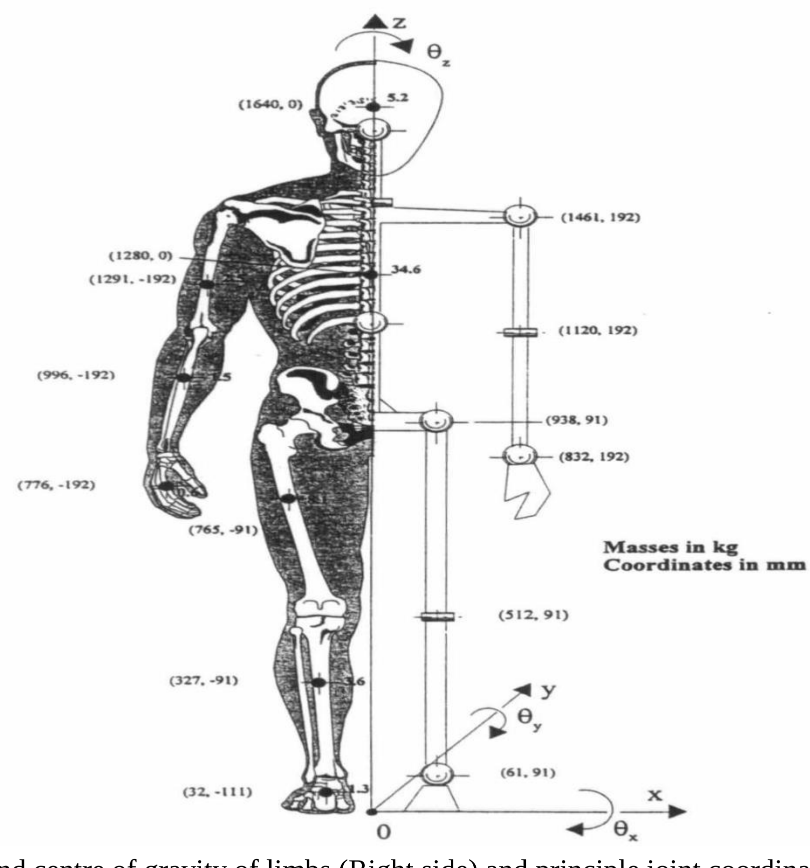

Figure 1: Mass and centre of gravity of limbs (Right side) and principle joint coordinates (left side) (Seward et al., 1996)

Table 1: Comparison of some basic mechanical properties between human bones and a possible robot frame constructed from two types of composite materials (Seward et al., 1996)

Mechanical Property	Human (Bones)		Robot Frame (Composites)	
			Glass fibres and polyester polymer	Carbon fibres and epoxy polymer
	unit	value	value	value
Tensile strength, *a*	N/mm^2	100	250	1400
Modulus of elasticity , *E*	N/mm^2	10 000	130000	130000
Density	Mg/m^3	2	1.8	1.6
The second moment of area, I	mm3	4 300	--	--
Elastic modulus, Z	mm3	4 300	--	--
Max. allowable bending moment, o-Z [thigh bone] OD = 36 mm	kNm	0.43	0.43 Tube Thickness = 1mm OD = 50 mm	--
Max. allowable bending moment, o-Z [upper arm bone] OD = 24 mm	kNm	0.13	0.13 Tube Thickness = 1mm OD = 30 mm	--

The biological interaction between the nervous system and the human body dictate the base of a particular motion and stability control of the human being. Figure 2 illustrates this interaction where the nervous system, the cognitive sensors and the human body interact. To draw a logical analogy between a humanoid robot and human being, the nervous system might be compared to a controller interpreting the cognitive signals acquired from the environment by the sensors in order to realise or generate as a humanoid robot a stable dynamic walking motion (Breazeal et al., 2004).

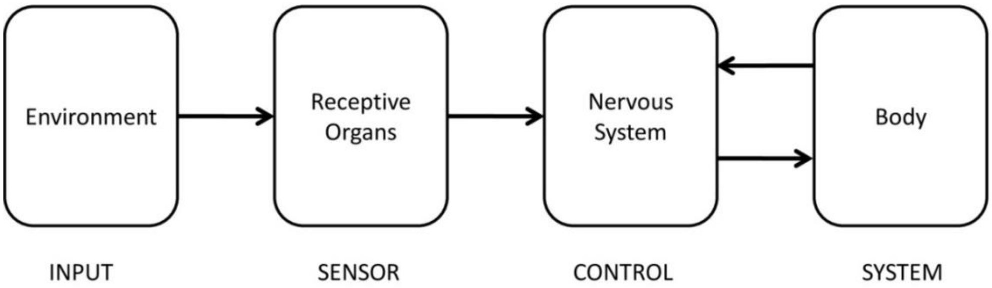

Figure 2: Biological microorganism interaction with the environment

Bipedal locomotion

The human gait cycle is divided into two phases; single support phase where only one foot touches the ground and double support phase where both feet touch the ground (Q. Huang, Yokoi, et al., 2001). The major constraints on the walking pattern of biped humanoid are; stability, actuator's limited torques and robot's joint velocities, minimisation of energy consumption, environment condition such as uneven terrain pose another set of constraints for gait generation and must be taken into consideration (Usherwood & Bertram, 2016).

Zero Moment Point (ZMP) is the first important concepts pertinent to dynamic and kinematics. ZMP originally introduced in 1969 by Vukobratovic (Miomir Vukobratović & Borovac, 2004). ZMP is defined as, "*The point on the surface where the moment of the resultant inertia forces becomes zero, where, the resultant inertia forces is the combination of inertia and gravity forces*.".

The second concept is the static and dynamic walking. Where, static walking is defined as a motion where the projected Centre of Mass (CoM) is always inside the contact polygon, which is the area that encompasses the contact between the ground and the feet. While, in the case of dynamic walking, CoM is not always above the stable region. Therefore, instability may results for short intervals. Now, the planning of walking pattern for biped robots, in general, can be categorised into; first, low energy reference trajectory approach and second a ZMP based walking pattern syntheses approach (M Vukobratović & Rodić, 2004).

The balance of the human and humanoid robot
An assortment of measures utilised by a human to sustain balance status when encountering disturbance. Depending on the degree or level of disturbance. Here recapping briefly three common solutions identified to counteract disturbances as illustrated in Figure 3, through sustaining posture balance in human and inspiringly in humanoid:

a) Ankle torque that is used with robots when the disturbance is small or the robot is in a natural environment. In this particular case, the system model for the balance controller can be selected as a single inverted pendulum (Pratt, Carff, Drakunov, & Goswami, 2006; Miomir Vukobratović & Borovac, 2004; Zhang, Meng, Davies, Zhang, & Xie, 2015).
b) A reactive momentum will be used when the disturbance is too large, and it is impossible for the robot to maintain stability with only the ankle torque control. For this second case, the reactive momentum generated by the movement of humanoid torso or arm is utilised to maintain the ZMP within the supporting polygon (Yi, Zhang, Hong, & Lee, 2012; Yun & Goswami, 2011).
c) When the disturbance becomes higher to the extent that even the reactive momentum will not be enough to keep a balance, a very intuitive method termed a foot placement control is used, changing a landing position of the foot. It mimics a human when stretching out his leg to the falling direction to keep a balance when there is a big disturbance (Kuo, 1999; Tajima, Honda, & Suga, 2009; Urata et al., 2011), Mergner, & Lippi, (2018).

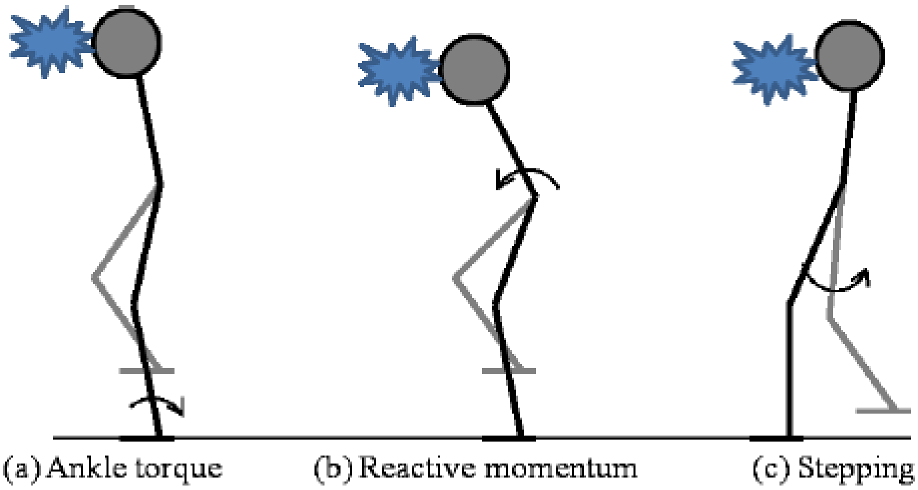

Figure 3: General balancing strategy of a human-being (Cho, Kim, & Oh, 2013).

Equations of Motion
Controlling biped walking humanoid requires difficult control strategy to attain accurate and robust performance. As a rule of practice, the researcher uses a simple two-dimensional model with 5 DOF. A five-link bipedal walking robot represents a simple model among several more complicated ones Figure 4, with motion constrained in the sagittal plane (Cheng & Lin, 1997; Furusho & Masubuchi, 1986; Pettersson, Sandholt, & Wahde, 2001).

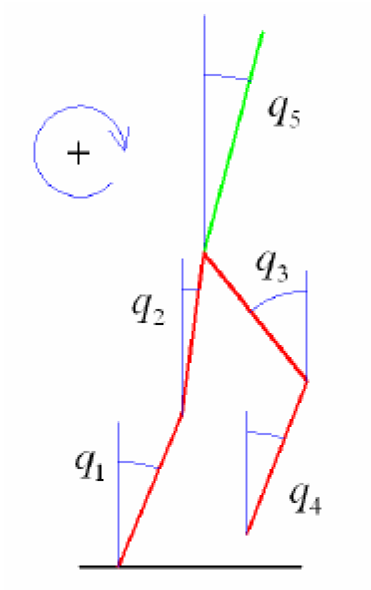

Figure 4: Configuration of a five-link bipedal walking robot(Zonfrilli, Oriolo, & Nardi, 2002)

The biped humanoid robot can be modelled either be using the Lagrangian or the Newton-Euler formulation. The latter formulation is a force-balance approach to dynamics, whereas the first formulation might be considered as an energy-based approach. However, both methods will yield the same equations of motion (Featherstone & Orin, 2000; Walker & Orin, 1982).

Denavit-Hartenberg convention (Tatsch et al. 2018; Klug et al. 2018) is a method of assigning coordinate frames to joints and expressing the joint's rotation and position with a 4x4 matrix (Flanders & Kavanagh, 2015). This notation then forms the building block for later algorithms such as forward kinematics and Jacobian calculation. Attaching frames to the links of a robotic structure and the Jacobian Matrix used for transformations between Work and Configuration Space (Rocha, Tonetto, & Dias, 2011). The human proportion data for diferent parts of the body and the corresponding proportion, as illustrated in Figure 5, are given in Table 2. Moreover, Table 3 presents a comparison of joint distribution in humans and a humanoid robot.

A well-motivated approach for gait generation is the use of genetic algorithms GA when the system's dynamic model under study is either too complex to be implemented or not available (Wolff & Nordin, 2001). Also, in optimisation process GA allow a large degree of flexibility (Paul & Bongard, 2001).

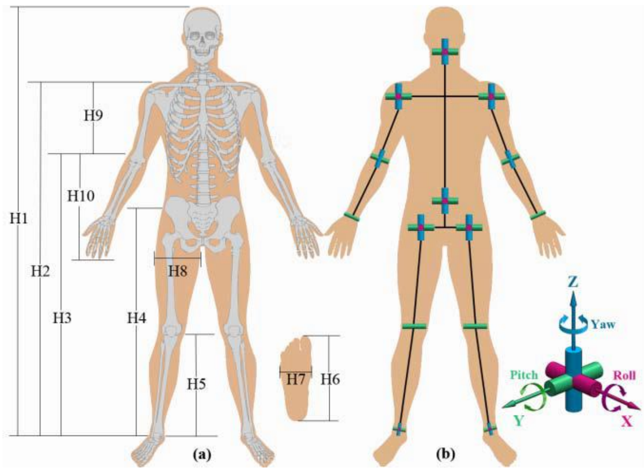

Figure 5: (a) Human dimensions, (b) kinematics diagram representing the DOF in human proportions (D., P., & M., 2012)

Recent advancement in optimised gate generation is to adopt modified differential evolution (MDE) optimisation technique to optimally identify the adaptive evolutionary neural model (AENM) to generate gait for biped humanoid dynamically, Huan et al. (2018). The proposed technique is implemented and tested on a small-sized prototype humanoid robot. Then, the MDE method is compared with genetic algorithm (GA) and particle swarm optimisation (PSO) approaches. The results of comparison shows that the newly proposed neural AENM model proves an effective approach for a robust and accurate biped gait generation.

Table 2: Robot proportion data based on the human (D. et al., 2012)

Dimension	Value for human		Value for robot	
Stature	H1	1740	R1	430
Shoulder height	H2	1425	R2	352
Elbow height	H3	1090	R3	270
Hip height	H4	920	R4	250
Knee height	H5	545	R5	136
Foot length	H6	265	R6	97
Foot-breadth	H7	95	R7	61
Thigh thickness	H8	160	R8	46
Shoulder to elbow	H9	365	R9	84
Elbow to finger tip	H10	475	R10	115

Table 3: Comparison of joint distribution in humans and humanoid robots BONTEN-MARU II (Yussof, Yamano, Nasu, & Ohka, 2006), BIOLOID(D. et al., 2012)

Joint	The quantity of DOF right/left (rotation axis)		
	Human	Humanoid robot	
		Bonten-Maru II	Bioloid Premium
Neck	3 (yaw, pitch, roll)	2 (yaw, pitch)	--
Right/left shoulder	3/3 (Yaw, pitch, roll)	2/2 (pitch, roll)	2/2 (pitch, roll)
Right/left elbow	1/1 (roll)	1/1 (roll)	1/1 (pitch)
Right/left wrist	3/3 (Yaw, pitch, roll)	0/0	--
Waist	3 (Yaw, pitch, roll)	1 (yaw)	--
Right/left hip	3/3 (Yaw, pitch, roll)	3/3 (Yaw, pitch, roll)	1/1 (pitch)
Right/left knee	1/1 (pitch)	1/1 (pitch)	1/1 (pitch)
Right/left ankle	3/3 (Yaw, pitch, roll)	2/2 (pitch/roll)	2/2 (pitch, roll)

Advanced locomotion

Gait generation can be achieved off-line and then later implemented in the object target, the robot (Hirai, Hirose, Haikawa, & Takenaka, 1998; Q. Huang, Nakamura, & Inamura, 2001). Alternatively, an on-line controller can be used following control law to generate the required appropriate torques (Fujimoto, Obata, & Kawamura, 1998). Most of the research focuses on generating stable bipedal gaits handling flat ground surface. However, some research addresses advanced locomotion problems, like; inclined ground, stair climbing as in Honda's humanoid, ASIMO (Kato, 1972), somersault motion which all requires more complex motions and larger range for joint movements (Furuta, Okumura, Tawara, & Kitano, 2001). The family of biped humanoid robots designed and constructed by Boston Dynamics with sophisticated dexterity and state-of-the-art mobility features based on the first robot, PETMAN. Later evolved into different versions of Atlas Humanoid and have been configured through programming to mimic human speeds, walk through rough terrain like rock fields, climb stairs, capability for inclination, and cope with outdoor environment terrain wise, Nelson et al. (2019).

Walking pattern

The walking pattern that is generated by the brain is updated in real time from the feedback provided by the sensory organs due to the possible changes in the terrain and the environment. The updating is necessary to handle sudden changes in the environment. Biologically inspired humanoid designers attempt to mimic this process (D. et al., 2012; Heo & Oh, 2015). Figure 6 illustrates the basic process of a pattern generator in human and humanoid.

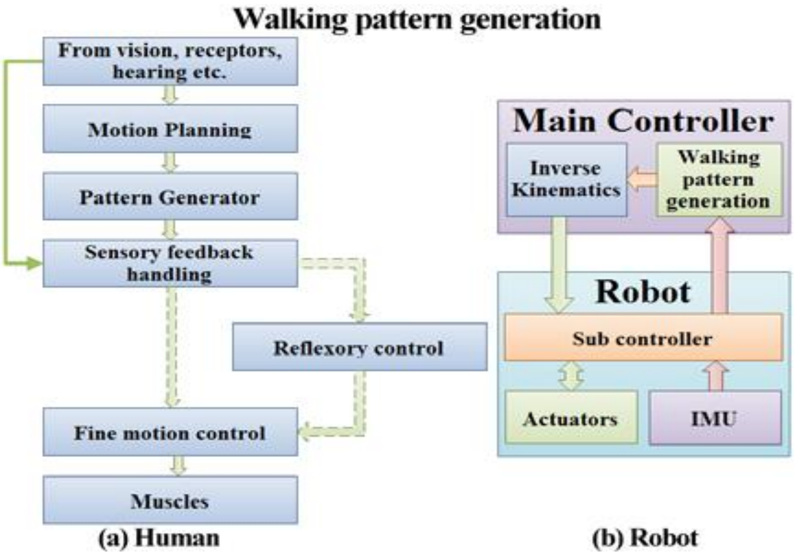

Figure 6: Block diagram of walking pattern generation in (a)human, (b)robot (D. et al., 2012)

Control

In this section, issues pertinent to the concept of control will be briefly presented. From the control and walking pattern generation perspective, the research on Biped Humanoid Robots (BHRs) can be classified into two categories. The first group requires the precise knowledge of robot dynamics, whereas, the second group uses only limited knowledge of dynamics.

The method proposed in the first category is called Computed Torque Control. In order to prepare the walking patterns, it requires the precise value of mass, location of CoM and inertia of each link and the method relies on a non-linear feedback system. The method proposed in the second category is called Joint Position Control. Nevertheless, since the inverted pendulum model is used, the method might be called Inverted Pendulum Approach. This method requires only some data, like the location of total CoM or total angular momentum.

Field Programmable Gate Array (FPGA) vs General-Purpose Processor (GPP)

Robotic computing systems, artificial intelligence (AI) and control are usually implemented using GPP because they provide an adequate balance between cost and performance and are easily programmed. However, this approach for embedded robotics restricts several optimisation opportunities and may not always satisfy performance, cost, and energy requirements. FPGAs can be considered a good execution platform for complex robotics algorithms, offering more opportunities to fine tune the overall system. However, programming hardware devices have always been perceived as a challenge for developers, resulting in low productivity, and a barrier to the widespread adoption of FPGAs robotic systems. Nevertheless, the growing complexity of robotic applications still makes a case to consider the adoption of FPGAs as a platform to solve those problems. NanoBridge based field-programmable gate array (NB-FPGA) is utilised as a configuration switch for applications in harsh environments. The NB-FPGA was implemented in a humanoid robot and compared with that of the conventional FPGA. Results demonstrated that NB-FPGA reveals little variation in performance over a broad range of temperature $\Delta T > 200$ °C, and possess considerable immunity for power source voltage fluctuations. Miyamura et al, (2017).

Within this context, several questions have been raised focusing on embedded robotics to address challenges and opportunities to adopt FPGAs in robotic projects, some of these questions were; 1) Adequacy of FPGAs for computing and control in mobile robotics?, 2) Identifying which of the requirements that renders FPGA may tend to be better than GPP?, 3) Is a hybrid computing system a good solution for mobile robots (attaching GPP to custom computing in FPGA)?, 4) Are the current digital design tools sufficiently high-level for robotic systems developers? and finally, 5) Is there a need for robotic-orientated FPGA architectures and electronic design automation EDA tools? (Paul & Bongard, 2001).

Since the size and weight of humanoid robots are limited, control hardware should be embedded to make more rooms to accommodate another necessary hardware. The limitation of the output port of commercial processors marks another difficulty in this context. Hardware technologies such as Digital Signal Processors (DSPs) or microprocessors allow real-time control implementation. Unfortunately, limited output ports of the DSP jeopardising the suitability of using it to control humanoid robots. The possible alternative solution for the humanoid robots is FPGA. It will reduce their size and weight, and consequently their cost (Bindal & Hamedi-Hagh, 2016). Adding the fact that the design of the integrated circuit reaps the results of development revolution that makes it possible to efficiently integrate embedded processors Intellectual Properties (IPs) into the FPGA. Hence, highly sophisticated algorithms with heavy computations can be realised in the software of FPGA. Some FPGA-based solutions have been reported in the field of robotics (R. Brooks et al., 2015). (Sánchez-Solano, Cabrera, Baturone, Moreno Velo, & Brox, 2007) present an implementation of fuzzy logic controller for robotics using an FPGA in a neural network controller on FPGA for a humanoid robot arm (Kim & Jung, 2008); (H.-C. Huang & Tsai, 2009). The sense of touch is a vital capability to human and the use of hands. Therefore tactile sensors must be functionally integrated into robotic hands to enhance them. However, tactile sensing technology has not reached the level of maturity to tackle the required tasks yet and used as a useful tool. One reason for this limitation is the necessity to simultaneously acquire and incisively process large amounts of data to implement an articulate manipulation. Oballe-Peinado et al., (2017) presents the realisation of electronics for an FPGAs-based tactile sensor suite and directly interfaced with the raw sensor with a serial communication protocol that links the fingertips with the palm; while (Tsui, Masmoudi, Karray, Song, & Masmoudi, 2008) apply fuzzy logic and neural network based controller.

Model of robot stance control

Figure 7A shows a robot stance control employing ZMP compensation. The ankle-joint angle is regulated using negative feedback control as seen from Loop1. While in human, the stance is controlled and stabilised by using ankle proprioception as identified by the equivalent Loop 1 shown in Figure 7B. In this control problem, corrective torque, T_c, is generated by the controller to stabilise the inverted-pendulum body which is inherently unstable. Also, the value of T_c is proportional to the angular position, and velocity of body sway combined. The gain constants K_P and K_D in the controller determine the amount of torque as related to position and velocity, respectively. Due to the gravity factor and to counteract the destabilising torque, the value of K_P must be more significant than *mgh*. The magnitude boundary of K_P and K_D is further limited to prevent lifting the feet off the ground by postural corrections generated torque and keeping ZMP away from the edge of the base-of-support. Other than these mentioned binding constraints, K_P and K_D values can be selected based on relevant design criterion like; torque limitations, energy considerations, or specific stability (Peterka, 2009).

The COP is proportional (to a great extent) to T_c in a freestanding human or robot in both 'static' and 'dynamic' situations, exerted about the ankle joint by the stance control system. Specifically (van der Kooij, van Asseldonk, & van der Helm, 2005)

$$X_{COP} = \frac{Tc}{mg} \quad (1)$$

where m is the body mass (excluding the feet), and g is the acceleration due to gravity.

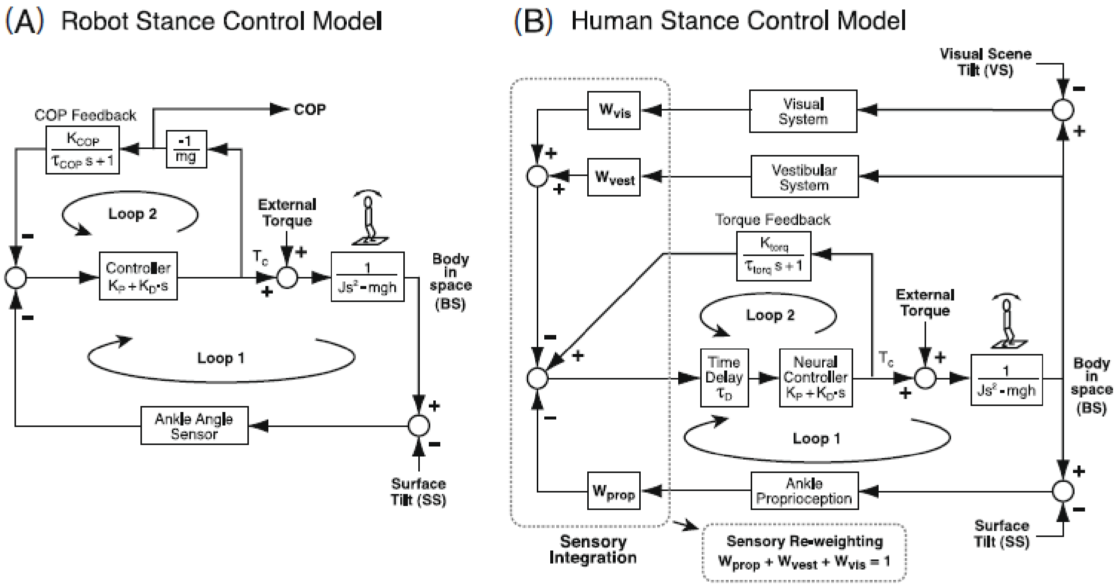

Figure 7: Block diagram model of robot stance control using ZMP compensation and a simplified model of human stance control(Peterka, 2009),

There are different ways to make use of ZMP information for robot stance compensation. Loop 2 implements ZMP compensation. The linear control scheme utilised by (Caballero, Armada, & Alarcón, 2006) which resemble most a mechanism utilised by humans. A non-linear control scheme that is not represented by the continuous control model in Figure 7A, as used by (Prahlad, Dip, & Meng-Hwee, 2008). In the latter, the force sensor information is used to detect a ZMP that was outside of a specified threshold and then used the ZMP value to calculate a new ankle-joint reference offset command angle for the ankle-joint control loop (Loop 1). While in the first force sensors information in the robot's feet is used to calculate the COP location. However, from equation (1), COP is calculated based on corrective torque T_c , the signal multiplied by the gain factor K_{COP}, filtered through LPF with time constant τ_{COP}, then the difference between the Support Surface (SS) tilt position and the body-in-space sway angle with respect to earth-vertical, BS is obtained (Peterka, 2009).

Structure material

Thinking of robot structure dictates an intuitive knowledge in materials. Therefore, when deciding to design a robot, the candidate material selected to build it have to be investigated. The basic requirements these materials must satisfy include; it must be light enough to minimise energy consumption, though strong to perform the required tasks, and, possibly, economically viable (MORO, 2010). Table 4 lists the main characteristics of a robot material.

Table 4: Main characteristics of the materials considered for the structure of the robot(MORO, 2010)

	Density [g/cm^3]	Young's modulus [GPa]	Tensile strength [MPa]	Cost level
Polycarbonate	1.2	2	65	Low
Aluminium alloy	2.7	69	310	Medium
Titanium alloy	4.4	110	1000	High
Stainless steel	7.9	193	570	Medium

Light Weight Structure: Design Approach

(Kaneko et al., 2001), stresses the importance of structural parts' weight of a humanoid. In their experience in designing HRP-2L humanoid, they found that structure weight to total humanoid weight is mounted up to more than 60%. Moreover, 20% of the overall weight is due to screws (Gienger, Loffler, & Pfeiffer, 2001). Therefore, casting several links helps in reducing the weight of humanoid.

Magnesium alloy is used for HRP-2L humanoid because of the specific gravity of 68% of the value of aluminium alloy. Due to the hardship experienced in casting links using magnesium alloy and the occasional presence of blow holes led to the idea of casting several links after modifying them using an aluminium alloy for HRP-2P. Such modification during design phase kept structure to be light weight (KÖSE & TATLI, 2016).

Sensors
Sensors are highly essential for humanoid operation and performance in many aspects. They are the tools that empower the humanoid for interfacing environment, means to enhance and sustain stability, and finally, it represents the media that human can interact and understand humanoid, and modify its behaviour. Focusing on types of sensors that of relevance to humanoid control, naming three main types (Gupta, Barlow, & David, 2011); foot pressure sensors, gyroscopes and an Attitude Heading Reference System (AHRS). Table 5 summarised some types of force sensors commercially available and used in the humanoid robot.

Table 5: Types of force sensor used in humanoid robot

Types of the force sensor	Condition / Area of application	Properties
Interlink FSR	Used when large changes in force are applied at a relatively high frequency. (humanoid robot)	Robust
LuSense PS3	Used when large changes in force are applied at a relatively high frequency. (humanoid robot)	
Tekscan FlexiForce sensor	Used when large slowly-varying forces are applied infrequently for long durations	Sensors provide better response regarding linearity, repeatability, time drift, and dynamic accuracy.

Materials and actuators
Material choice for humanoid structure and actuators represent a key parameter that influences performance efficiency and energy consumption. Advancement in material science and engineering pave the way to use alternative light materials with mechanical properties exceeds the human bones benchmark or even its counterpart in conventional materials like aluminium, stainless steel, or titanium alloys (Martinez-Hernandez, 2016).

Modern bio-composite material with nanotechnology fuelled inventive continuum approach, where the current state of the art based on current researcher's mindset of segregation school of thought towards a futuristic insight where all components like actuators, sensors, controllers, and power source embodied together with the fusion of their features in an innovative smart material with quasi-rigid or soft target materials to insinuate themselves into every potential aspect of technology (Ting et al., 2014).

Currently, actuators technologies belong to the 19th century that meets the required measures of performance of the past and provides the required specifications of force, time response, and stroke. However, they are bulky and consequently heavy and power hungry, usually require complex support infrastructure which renders them unfeasible solution for nowadays requirements and as a long-term solution.

Power source management for biped humanoid robot
Onboard power source sub-system that drives robot systems performing very sophisticated tasks, where the increasing demands on the power supply play a critical role. Operation breakdowns are unpredictable unless the state of the power source components is known, and the overall system performance should be adjusted according to reliable remaining capacity estimations (Lucas, Codrea, Hirth, Gutierrez, & Dressler, 2005).

Current research focuses on multiple power source components termed as ‘hybridisation’ packaged as integrated power modules to power up humanoid robots with extended endurance (Koushanfar, 2010; Koushanfar & Mirhoseini, 2011; Thangavelautham, Gallardo, Strawser, & Dubowsky, 2011; Winter & Brodd, 2004). Such ambitious targets indeed mean to release a humanoid robot with a high degree of autonomist as far as power is concerned. With this plans and requirements in mind, proper and efficient power management deems necessary to drive the presumably efficient target object ‘humanoid’ as long as possible. To improve performance potential, several concepts must be embedded, integrated and works in the continuum. Some of these concepts are; targeting substantial increase in the efficiency of power transmission and application in robots several hundred folds, others are concerned with employing the smart charging-discharging system to ensure minimum energy waste while ensuring reliable delivery of required energy and power. Optimisation strategies (Wang, Dai, Guan, Dong, & Wu, 2014) that include power generation and co-generation, power transmission, power conversion, and delivery plays an important role to excel power performance (Lucas et al., 2005).

Another important factor dictates endurance parameters is the actuation mechanism and its power requirements. Biological organisms have evolved to consume energy very efficiently for movement and activities. Their structure constituting components tends to cooperate to perform optimally using as little energy as possible. If the humanoid robot actuation efficiency can approach that of human actuation, the range of feasible robotic applications will greatly increase and robot design limitation due to power plant considerations will be greatly minimised (Furuta et al., 2001).

Elibol et al., (2016) conducted an analyses research to find a correlation between current and stiffness of individual joints NAO humanoid robot. Moreover, identifying the effects of variable stiffness values of each joint during standing up. Then, developing an algorithm to determine the desired current usage hence stiffness value for each joint. The proposed method concluded that a new stiffness value could be calculated to reduce current withdrawn comparably for each joint without jeopardising robot normal process. Therefore, a considerable reduction of load current was achieved in the standing up process. Mazumdar et al., (2017) investigate the parallel elastic elements to reduce energy consumption. STEPPR bipedal walking robot was used as a research platform. The core concept is to relieve the motors from a substantial amount of load by supporting the torques using a quasi-static element in parallel with the active joints during walking. This step proved to increase locomotive energy efficiency. Xie et al., (2018) propose an extension to the dynamic window approach DWA for used for obstacle avoidance. The new proposed energy model is utilised in the extended EDWA approach for trajectory planning. Then by modifying the objective for power minimisation, autonomous navigation with reduced energy is proposed through the combinational cost objectives of low power consumption and high speed. Numerous experiments are conducted to validate the energy consumption model.

Finally, tackling energy problem always dictates supplementation through alternative sources, namely renewable energy sources, Iqbal and Khan (2017). What it makes it more attractive is harvesting wasted energy like heat and convert it into usable energy through what is known as co-generation or converting unwanted vibration to electricity using piezoelectric generators to harvest the vibration energy.

The major power subsystems are: (1) Power Generation/Conversion, (2) Energy Storage, and (3) Power Management and Distribution. Power generation/conversion subsystems include power generators, fuel cells, and energy harvesting devices. Power Management and Distribution includes power distribution and transmission, conversion and regulation, load management and control (Lee et al., 2008).

Power systems are characterised by some performance parameters. One parameter of great importance is specific power (W/kg) that indicates how much power can be delivered per unit mass of power system. Other related parameters include specific energy (Wh/kg) and energy density (Wh/ m3) (Winter & Brodd, 2004). However, power systems are not always malleable to simple characterisation regarding a single variable such as specific power. Other supplementary features can be equally important. These might include temperature sensitivity, operational life, storage volume, storage life, resistance to harsh environment. As humanoid missions shift more and more from the confined and controlled environment to missions with increasingly harsh environments, these other factors become more important.

Communication for humanoid robotics

Environmental signals are varied and heterogeneous both temporally and spatially. Localisation and characterisation of these signals by humanoid robots must take into account the design and performance of on-board robotic communication subsystems, namely; sensors and transmitters. The development of robotic sensors allows the humanoid robot to be actively linked to the environment. Perception of the environment and workspace poses unique constraints on both sensor technology and deployment. Wireless technology, mobility, embedded computing and miniaturisation about communication and sensors were merely the forefront aspects that have been recently extensively researched topics (Gupta et al., 2011; Ma, Liu, Alhussein, Zhang, & Chen, 2015).

Figure 8 demonstrates specific communication structure implemented for rescue operation scenario which involves humanoid robot as a rescue team member shows intra and intercommunication substructure. Camera, infrared, microphone are implemented so they can classify target objects, the source of hazards and unknown. Camera with their expert module, for example, can classify target object characteristics like a human face, or other targets based on images stored in the database. Infrared-expert can act as a trainer for its expert classifier which can distinguish different light sources within its spectrum. Whereas, may be tuned to recognise human voice using computed Power Spectral Density (PSD) signature obtained via fast Fourier transformation. Then feature can be extracted by calculating the ratio of the power of the bandwidth where the human voice is commonly present and the overall power of the sound signal.

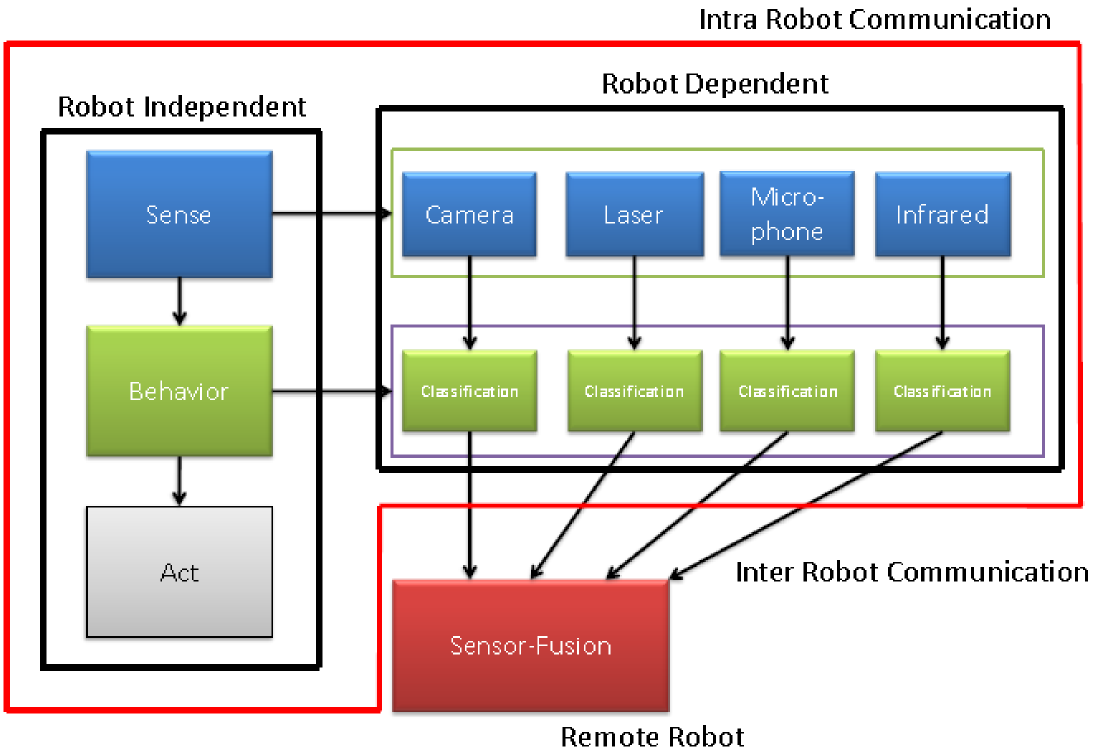

Figure 8: Overview of communication structure

Intra-robot communication

Intra Robot communication refers to communication between mechanically linked elements and modules within the same robot. Intra communication is performed via well-known technology initially designed for the automotive industry and later were widely adopted for industrial environment, known as CAN bus technology. It offers remarkable advantages, mainly, transmission speed, augmentation of the diagnostic system, embedded control augmentation become easier (Wan, Xing, & Cai, 2009).

Inter-robot communication

Inter-robot communication, whether between other robots, control station and master subsystem module in specific target robot. Another well-established communication technology mainly developed and widely used in office environments and computer peripheries were adapted for this purpose, known, as Blue-Tooth (BT) technology. BT protocol usage diminishes the need for wiring. However, it is characterised with the expensive constraint of low data transmission rate and the limited number of nodes 'blue tooth devices within one network' that can be interfaced within the specific network (Haartsen, Naghshineh, Inouye, Joeressen, & Allen, 1998). Table 6 presents a comparison between BT and Wi-Fi communication technologies.

Table 6: Wireless communication: A comparison

Type	T_r Speed	Frequency	Range	Interference	Device
Bluetooth	721 (Kbps)	2.44 GHz	10 m	Easy	Connector
Wi-Fi	(a/g) 54 (Mbps) (b) 11 (Mbps)	(a) 5 GHz (b/g) 2.4 GHz	50 m	Not Easy	Access Point

Applications of humanoid robots

Lai et al (2018) identifies intelligent robots according to their environment and application scope. Intelligent robot can be classified into intelligent industrial robot, intelligent agricultural robot, intelligent service robot and intelligent specialized robot. Once humanoid robots fully matured, they will be useful in various applications. Listing all possible and potential applications still need careful examination because the domain is rapidly expanding with the evolution and advancements in technology and achievement in other interrelated infrastructure. However, already now, several possibilities have been presented and underway for implementation, some of which are as follows.

Home applications

There exist many possibilities where the humanoid robot can be exploited for home applications. Usage profile is continuously enhanced and extended to cover various home tasks (Clotet, Martínez, Moreno, Tresanchez, & Palacín, 2015). Ranging from watching eye as a security guard to the level of performing house maid tasks while the homeowner leaves their premises occupied by the humanoid. Moreover, conditions at home can be effectively perceived via mobile phone or the internet were developed a decade ago (Sawasaki et al., 2003). The advancement in features for a humanoid robot with the emerging IoT applications. Humanoid robot is aggregating an impressive list of attributes such as responding to queries, controlling states of connected smart devices, and recording. Erol et al. (2018) utilise pattern recognition and machine learning techniques such as Convolutional Neural Networks as a new approach for autonomous navigation by identifying markers or objects from images and videos. Then by using the RGB-depth camera, computational intelligence techniques are implemented along with Robot Operating System to navigate the humanoid robots towards the designated objects incorporating a deep neural network object detectors.

Education

Robot-aided education deeply rooted in Human-Computer Interaction (HCI) discipline through the new direction of thought towards the Human-Robot Interaction (HRI) discipline. Since recent advancements in robotic science and technology, this research topic has been under vigorous scrutiny. Noticeable activities have been accredited to Korea in this field (Chin, Wu, & Hong, 2011). Through promoting students' learning interest, increased concentration and augmented by active interaction. An interesting comparison study (Han, Jo, Jones, & Jo, 2008) was conducted in 2008, weighing non-computer based media, web media instruction, and robot-assisted learning referred to as r-Learning. The outcome of the study revealed the superior performance of r-Learning over the others due to several advantages and positive features like; gestures, motions and facial expressions. These findings push towards ascertaining the position of robots as a potential new educational medium (Ting et al., 2014). Recent study conducted by Cheng et al. (2018) investigate the essential applications of educational robots through 3 directions, 1) Systematic review of the literature, 2) Experts interview, 3) Conducting online surveys for instructors from six different levels of education. Then, identifies the scope and environments of these applications. The study concluded that Robotics, language learning, social education are at the top, while the core applications distributed between Robotics, language learning, social and special education. Preschools and primary school possess greater prospective to implement educational robots shortly. Therefore, five essential applications are identified as a whole can be assigned to educational robots; language education, robotics knowledge education, teaching assistants, social skill and special education, and feedback-assisted learning.

Entertainment

Entertainment field is highly diverse, employing humanoid robot for this purpose whether within the context of narrative environments, media arts, or theatre as a performer, circus acrobats who perform gymnastic feats to name a few. The level of autonomy, and consequently, the advancement in technologies dictate the depth of penetration into this field with utilising sensor/actuators to map the interaction envelope with the viewers/recipients represent a major task to the artist who develops material arts and employing humanoid robot as a performer. Finally, there is an interaction area between the entertainment robot and service robot. Several humanoid projects designed with this potential application due to their designed artistic skill like; ASIMO, NAO, SDR-4X, TOPIO, HRP-4C (Fujita, Kuroki, & Ishida, 2003).

Sport

The involvement of humanoid robot in sports application serves dual purposes; the first one capabilities demonstration, whereas the second which is more critical is the design refinement and the technological development associated with these events as a test and evaluation environment for further refinement in; stability, endurance, interaction, cooperative work. RoboCup soccer competition act as developmental arena through performance. Recently, the advanced fuzzy logic approach was adopted as control scheme to extend and enhance the stability profile and envelope for better, smooth, fast and flexible locomotion performance such as; walking, running, turning and kicking (Sulistijono, Setiaji, Salfikar, & Kubota, 2010). Japan is actively planning to organise a Robot Olympics in 2020 alongside the summer games which will be hosted in Tokyo.

Space and military

Space exploration missions and military application highly intersect with the previous potential application as far as risk and danger are concerned. Nevertheless, space and military requirements can vary tremendously due to many factors pertinent to reliability and autonomous nature to name a few.
Replacing human by humanoid in both sectors omit expensive life support package required for human in space and extensive protection measures in the military field. Several advantages can be attained as envisioned by scientists, such as; easier communication, better endurance, repeatability rate and consistency (Stoica & Keymeulen, 2006). As a first stage, Robonaut 2 jointly developed by The National Aeronautics and Space Administration (NASA) and General Motors, served as a astronauts' assistant the International Space Station in 2011 (Diftler et al., 2011). Perez et al (2018) observe that the prospective use of robotics and autonomous systems, the scope and limitations defines the development trends in Robotics and AI for the military purpose. Moreover, Artificial intelligence AI "encompasses the whole conceptualisation of a machine that is intelligent in terms of both operational and social consequences." The military and space application is alarmingly growing despite budget constraints in some countries.

Discussion

The dynamicity of the world of work with accelerating the pace, the internet of things and cloud computing contributed to a great extent in transforming many industries. Robotics, genomics, and biotechnology are conceived to revolutionise the way we live, work, and most important the way we evolve. It is clear that traditional sciences boundaries are retreating and dissolving, where the interface of different disciplines foster exciting innovations, such as nanotechnology and biomimetic. Future economic growth dictates strong, innovative culture to address the 21st century core challenges like expanded urbanisation and overcoming climate changes. Meeting these challenges lie within the capability of acquiring multi-disciplinary skills through new and flexible collaborative technologies. The new global competition is leading innovation, and this race materialise rapidly. This can be noticed through the emergence of the forth industrial revolution 4IR where robotics play an essential role in realising such a revolution.

Conclusion

Despite all achievements in robotics field and exciting advancement which are verified experimentally through various advanced humanoid projects. The need for substantial improvements in hardware, software, and control deemed necessarily crucial to give humanoid the required autonomous and intelligence level that makes them qualified for integration with the structured environment designed for human. Attaining these goals requires comprehensive treatment to all issues involved in an integrated manner. A new school of thought, where subsystems must be interleaved together to achieve the ultimate optimum performance and energy efficiency, is highly needed. Using modern and intelligent control techniques in humanoid robotics research and development open a new corridor for advancement. Techniques such as fuzzy logic control, neural networks, genetic algorithm, and their hybrid or combined versions play an important role and have great potential for solving many problems and core challenges. Smart materials, intelligent power management system, smart integrated sensors, and smart, dynamic mapping algorithm for dynamic localisation. To sustain and extend the progress of Robotics, it is vital to distinguish science fiction from practical reality. The integration of AI with the Robotics dictates a rational and harmonic interaction between visionary research ideas and application specific projects. Unjustified fears and unrealistic enthusiasm may hinder the progress of Robotics. Instead, they should be used as a motivation for responsible development. Robotics and its integration with emerging technologies to lunch the fourth industrial revolution 4IR can be set to transform our future, life, living environment and finally economy.

References

Adams, B., Breazeal, C. L., Brooks, R., & Scassellati, B. (2000). Humanoid robots: a new kind of tool: DTIC Document.

Ajoudani, A., Fang, C., Tsagarakis, N., & Bicchi, A. (2018). Reduced-complexity representation of the human arm active endpoint stiffness for supervisory control of remote manipulation. The International Journal of Robotics Research, 37(1), 155-167.

Alvarado, D., Corona, L., Muñoz, S., Campos, A., & Escamilla, A. (2018). Biped Robot Prototype Based on the Human Anthropometric Measurements. In Improved Performance of Materials (pp. 269-282). Springer, Cham.

Bindal, A., & Hamedi-Hagh, S. (2016). Field-Programmable-Gate-Array (FPGA) *Silicon Nanowire Transistors* (pp. 121-133): Springer.

Blar, N., Azni Jafar, F., Idris, S. A., & Mat Ali, M. (2015). *A Review of Humanoid Robots Technical Characteristics in the Application for Robotic Teacher.* Paper presented at the Applied Mechanics and Materials.

Breazeal, C., Brooks, A., Chilongo, D., Gray, J., Hoffman, G., Kidd, C., . . . Lockerd, A. (2004). *Working collaboratively with humanoid robots.* Paper presented at the Humanoid Robots, 2004 4th IEEE/RAS International Conference on.

Brooks, R., Sussman, M., Williamson, M. M., Goodwin, W. A., Dye, N., & Blumberg, B. (2015). Systems and methods for safe robot operation: Google Patents.

Brooks, R. A. (1996). *Prospects for human level intelligence for humanoid robots.* Paper presented at the Proceedings of the First International Symposium on Humanoid Robots (HURO-96).

Caballero, R., Armada, M. A., & Alarcón, P. (2006). Methodology for zero-moment point experimental modeling in the frequency domain. *Journal of Vibration and Control*, *12*(12), 1385-1406.

Chen, X., Billinghurst, M., Green, S., & Chase, G. (2008). Human-robot collaboration: A literature review and augmented reality approach in design.

Cheng, M. Y., & Lin, C. S. (1997). Genetic algorithm for control design of biped locomotion. *Journal of Robotic Systems, 14*(5), 365-373.

Cheng, Y. W., Sun, P. C., & Chen, N. S. (2018). The essential applications of educational robot: Requirement analysis from the perspectives of experts, researchers and instructors. Computers & Education, 126, 399-416.

Chin, K.-Y., Wu, C.-H., & Hong, Z.-W. (2011). *A Humanoid Robot as a Teaching assistant for primary education.* Paper presented at the Genetic and Evolutionary Computing (ICGEC), 2011 Fifth International Conference on.

Cho, B.-K., Kim, J.-H., & Oh, J.-H. (2013). Balancing strategy using the principle of energy conservation for a hopping humanoid robot. *International Journal of Humanoid Robotics, 10*(03), 1350020.

Clotet, E., Martínez, D., Moreno, J., Tresanchez, M., & Palacín, J. (2015). Development of a High Mobility Assistant Personal Robot for Home Operation *Ambient Intelligence-Software and Applications* (pp. 65-73): Springer.

D., S., P., C. P. R., & M., L. (2012). Design and Development of a Biped Humanoid Robot to Generate Dynamic Walking Pattern. *SAS Tech Journal, Vol 11*(Issue 1).

Diftler, M. A., Mehling, J., Abdallah, M. E., Radford, N. A., Bridgwater, L. B., Sanders, A. M., . . . Permenter, F. (2011). *Robonaut 2-the first humanoid robot in space.* Paper presented at the Robotics and Automation (ICRA), 2011 IEEE International Conference on.

Elibol, E., Calderon, J., Llofriu, M., Moreno, W., & Weitzenfeld, A. (2016). Analyzing and Reducing Energy Usage in a Humanoid Robot During Standing Up and Sitting Down Tasks. International Journal of Humanoid Robotics, 13(04), 1650014.

Erol, B. A., Majumdar, A., Lwowski, J., Benavidez, P., Rad, P., & Jamshidi, M. (2018). Improved Deep Neural Network Object Tracking System for Applications in Home Robotics. In Computational Intelligence for Pattern Recognition (pp. 369-395). Springer, Cham.

Featherstone, R., & Orin, D. (2000). *Robot dynamics: equations and algorithms.* Paper presented at the ICRA.

Flanders, M., & Kavanagh, R. C. (2015). Build-A-Robot: Using virtual reality to visualize the Denavit–Hartenberg parameters. *Computer Applications in Engineering Education, 23*(6), 846-853.

Fujimoto, Y., Obata, S., & Kawamura, A. (1998). *Robust biped walking with active interaction control between foot and ground.* Paper presented at the Robotics and Automation, 1998. Proceedings. 1998 IEEE International Conference on.

Fujita, M., Kuroki, Y., & Ishida, T. (2003). *A small humanoid robot sdr-4x for entertainment applications.* Paper presented at the Advanced Intelligent Mechatronics, 2003. AIM 2003. Proceedings. 2003 IEEE/ASME International Conference on.

Furusho, J., & Masubuchi, M. (1986). Control of a dynamical biped locomotion system for steady walking. *Journal of Dynamic Systems, Measurement, and Control, 108*(2), 111-118.

Furuta, T., Okumura, Y., Tawara, T., & Kitano, H. (2001). *'morph': A small-size humanoid platform for behavior coordination research.* Paper presented at the Proc. of the IEEE-RAS International Conference on Humanoid Robots.

Gienger, M., Loffler, K., & Pfeiffer, F. (2001). *Towards the design of a biped jogging robot.* Paper presented at the Robotics and Automation, 2001. Proceedings 2001 ICRA. IEEE International Conference on.

Goodrich, M. A., Crandall, J. W., & Barakova, E. (2013). Teleoperation and beyond for assistive humanoid robots. *Reviews of Human Factors and Ergonomics, 9*(1), 175-226.

Gupta, G. S., Barlow, P., & David, S. (2011). *Review of sensors and sensor integration for the control of a humanoid robot.* Paper presented at the Instrumentation and Measurement Technology Conference (I2MTC), 2011 IEEE.

Haartsen, J., Naghshineh, M., Inouye, J., Joeressen, O. J., & Allen, W. (1998). Bluetooth: Vision, goals, and architecture. *ACM SIGMOBILE Mobile Computing and Communications Review, 2*(4), 38-45.

Han, J.-H., Jo, M.-H., Jones, V., & Jo, J.-H. (2008). Comparative study on the educational use of home robots for children. *Journal of Information Processing Systems, 4*(4), 159-168.

Heo, J.-W., & Oh, J.-H. (2015). Biped walking pattern generation using an analytic method for a unit step with a stationary time interval between steps. *Industrial Electronics, IEEE Transactions on, 62*(2), 1091-1100.

Hirai, K., Hirose, M., Haikawa, Y., & Takenaka, T. (1998). *The development of Honda humanoid robot.* Paper presented at the Robotics and Automation, 1998. Proceedings. 1998 IEEE International Conference on.

Hirose, M., & Ogawa, K. (2007). Honda humanoid robots development. *Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences, 365*(1850), 11-19.

Huan, T. T., Van Kien, C., Anh, H. P. H., & Nam, N. T. (2018). Adaptive gait generation for humanoid robot using evolutionary neural model optimized with modified differential evolution technique. Neurocomputing, 320, 112-120.

Huang, H.-C., & Tsai, C.-C. (2009). FPGA implementation of an embedded robust adaptive controller for autonomous omnidirectional mobile platform. *Industrial Electronics, IEEE Transactions on, 56*(5), 1604-1616.

Huang, Q., Nakamura, Y., & Inamura, T. (2001). *Humanoids walk with feedforward dynamic pattern and feedback sensory reflection.* Paper presented at the Robotics and Automation, 2001. Proceedings 2001 ICRA. IEEE International Conference on.

Huang, Q., Yokoi, K., Kajita, S., Kaneko, K., Arai, H., Koyachi, N., & Tanie, K. (2001). Planning walking patterns for a biped robot. *Robotics and Automation, IEEE Transactions on, 17*(3), 280-289.

Iqbal, J., & Khan, Z. H. (2017). The potential role of renewable energy sources in robot's power system: A case study of Pakistan. Renewable and Sustainable Energy Reviews, 75, 106-122.

Kaneko, K., Kajita, S., YOKOI, K., Hugel, V., Blazevic, P., & Coiffet, P. (2001). *Design of LRP humanoid robot and its control method.* Paper presented at the Robot and Human Interactive Communication, 2001. Proceedings. 10th IEEE International Workshop on.

Kato, I. (1972). *The hydraulically powered biped walking machine with a high carrying capacity.* Paper presented at the Proc. of the 4th Int. Symposium on External Control of Human Extremities, Dubrovnik.

Kim, J.-S., & Jung, S. (2008). *Hardware implementation of a neural network controller on FPGA for a humanoid robot arm.* Paper presented at the Advanced Intelligent Mechatronics, 2008. AIM 2008. IEEE/ASME International Conference on.

Klug, C., Schmalstieg, D., Gloor, T., & Arth, C. (2018). A Complete Workflow for Automatic Forward Kinematics Model Extraction of Robotic Total Stations Using the Denavit-Hartenberg Convention. Journal of Intelligent & Robotic Systems, 1-19.

KÖSE, C., & TATLI, Z. (2016). Pulsed DC Robotic MIG Welding of Non Heat Treatable Aluminum Alloys. *Int. J. Electrochem. Sci, 11*, 1918-1927.

Koushanfar, F. (2010). *Hierarchical hybrid power supply networks.* Paper presented at the Proceedings of the 47th Design Automation Conference.

Koushanfar, F., & Mirhoseini, A. (2011). *Hybrid heterogeneous energy supply networks.* Paper presented at the Circuits and Systems (ISCAS), 2011 IEEE International Symposium on.

Kuo, A. D. (1999). Stabilization of lateral motion in passive dynamic walking. *The International journal of robotics research, 18*(9), 917-930.

Kuzuoka, H., Yamazaki, K., Yamazaki, A., Kosaka, J. i., Suga, Y., & Heath, C. (2004). *Dual ecologies of robot as communication media: thoughts on coordinating orientations and projectability.* Paper presented at the Proceedings of the SIGCHI conference on Human factors in computing systems.

Lai, R., Lin, W., & Wu, Y. (2018, August). Review of Research on the Key Technologies, Application Fields and Development Trends of Intelligent Robots. In International Conference on Intelligent Robotics and Applications (pp. 449-458). Springer, Cham.

Lee, K., Chang, N., Zhuo, J., Chakrabarti, C., Kadri, S., & Vrudhula, S. (2008). A fuel-cell-battery hybrid for portable embedded systems. *ACM Transactions on Design Automation of Electronic Systems (TODAES), 13*(1), 19.

Lucas, N., Codrea, C., Hirth, T., Gutierrez, J., & Dressler, F. (2005). RoBM2: measurement of battery capacity in mobile robot systems. *GI/ITG KuVS Fachgespräch Energiebewusste Systeme und Methoden, Erlangen, Germany*, 13-18.

Luo, L. P., Yuan, C., Xue, G., Yang, M. Z., & Zhang, X. W. (2015). *Energy Minimization of Humanoid Robot through Combining Dynamic Power Management Method with Real-Time Scheduling Method.* Paper presented at the Applied Mechanics and Materials.

Ma, Y., Liu, C. H., Alhussein, M., Zhang, Y., & Chen, M. (2015). LTE-based humanoid robotics system. *Microprocessors and Microsystems, 39*(8), 1279-1284.

Martinez-Hernandez, U. (2016). Tactile Sensors *Scholarpedia of Touch* (pp. 783-796): Springer.

Mazumdar, A., Spencer, S. J., Hobart, C., Salton, J., Quigley, M., Wu, T., ... & Buerger, S. P. (2017). Parallel elastic elements improve energy efficiency on the STEPPR bipedal walking robot. IEEE/ASME Transactions on Mechatronics, 22(2), 898-908.

Mergner, T., & Lippi, V. (2018). Posture Control—Human-Inspired Approaches for Humanoid Robot Benchmarking: Conceptualizing Tests, Protocols and Analyses. Frontiers in neurorobotics,12.

Miyamura, M., Sakamoto, T., Bai, X., Tsuji, Y., Morioka, A., Nebashi, R., ... & Hada, H. (2017). NanoBridge-Based FPGA in High-Temperature Environments. IEEE Micro, 37(5), 32-42.

MORO, F. L. (2010). Design and intelligent control of an energy efficient humanoid robot.

Nelson, G., Saunders, A., & Playter, R. (2019). The PETMAN and Atlas Robots at Boston Dynamics. Humanoid Robotics: A Reference, 169-186.

Noreils, F. R. (2017). Inverse kinematics for a Humanoid Robot: a mix between closed form and geometric solutions.

Oballe-Peinado, Ó., Hidalgo-López, J. A., Castellanos-Ramos, J., Sánchez-Durán, J. A., Navas-González, R., Herrán, J., & Vidal-Verdú, F. (2017). FPGA-Based Tactile Sensor Suite Electronics for Real-Time Embedded Processing. IEEE Transactions on Industrial Electronics, 64(12), 9657-9665.

Paul, C., & Bongard, J. C. (2001). *The road less travelled: Morphology in the optimization of biped robot locomotion.* Paper presented at the Intelligent Robots and Systems, 2001. Proceedings. 2001 IEEE/RSJ International Conference on.

Perez, J. A., Deligianni, F., Ravi, D., & Yang, G. Z. (2018). Artificial Intelligence and Robotics. arXiv preprint arXiv:1803.10813.

Peterka, R. J. (2009). Comparison of human and humanoid robot control of upright stance. *Journal of Physiology-Paris, 103*(3), 149-158.

Pettersson, J., Sandholt, H., & Wahde, M. (2001). *A flexible evolutionary method for the generation and implementation of behaviors for humanoid robots.* Paper presented at the Proc. of the IEEE-RAS International Conference on Humanoid Robots.

Prahlad, V., Dip, G., & Meng-Hwee, C. (2008). Disturbance rejection by online ZMP compensation. *Robotica, 26*(01), 9-17.

Pratt, J., Carff, J., Drakunov, S., & Goswami, A. (2006). *Capture point: A step toward humanoid push recovery.* Paper presented at the Humanoid Robots, 2006 6th IEEE-RAS International Conference on.

Rocha, C., Tonetto, C., & Dias, A. (2011). A comparison between the Denavit–Hartenberg and the screw-based methods used in kinematic modeling of robot manipulators. *Robotics and Computer-Integrated Manufacturing, 27*(4), 723-728.

Sánchez-Solano, S., Cabrera, A., Baturone, I., Moreno Velo, F. J., & Brox, M. (2007). *FPGA implementation of embedded fuzzy controllers for robotic applications*.

Sawasaki, N., Nakajima, T., Shiraishi, A., Nakamura, S., Wakabayashi, K., & Sugawara, Y. (2003). *Application of humanoid robots to building and home management services.* Paper presented at the Robotics and Automation, 2003. Proceedings. ICRA'03. IEEE International Conference on.

Seward, D. W., Bradshaw, A., & Margrave, F. (1996). The anatomy of a humanoid robot. *Robotica, 14*(04), 437-443.

Spenko, M., Buerger, S., & Iagnemma, K. (Eds.). (2018). The DARPA Robotics Challenge Finals: Humanoid Robots To The Rescue (Vol. 121). Springer.

Stoica, A., & Keymeulen, D. (2006). *Humanoids in support of lunar and planetary surface operations.* Paper presented at the Aerospace Conference, 2006 IEEE.

Sulistijono, I. A., Setiaji, O., Salfikar, I., & Kubota, N. (2010). *Fuzzy walking and turning tap movement for humanoid soccer robot EFuRIO.* Paper presented at the Fuzzy Systems (FUZZ), 2010 IEEE International Conference on.

Tajima, R., Honda, D., & Suga, K. (2009). *Fast running experiments involving a humanoid robot.* Paper presented at the Robotics and Automation, 2009. ICRA'09. IEEE International Conference on.

Tatsch, C., Ahmadi, A., Bottega, F., Tani, J., & da Silva Guerra, R. (2018). Dimitri: an Open-Source Humanoid Robot with Compliant Joint. Journal of Intelligent & Robotic Systems, 91(2), 291-300.

Thangavelautham, J., Gallardo, D., Strawser, D., & Dubowsky, S. (2011). Hybrid fuel cell power for long duration robot missions in field environments. *Field Robotics*, 471.

Ting, C.-H., Yeo, W.-H., King, Y.-J., Chuah, Y.-D., Lee, J.-V., & Khaw, W.-B. (2014). Humanoid Robot: A Review of the Architecture, Applications and Future Trend. *Research Journal of Applied Sciences, Engineering and Technology, 7*(7), 1364-1369.

Tsui, W., Masmoudi, M. S., Karray, F., Song, I., & Masmoudi, M. (2008). Soft-computing-based embedded design of an intelligent wall/lane-following vehicle. *Mechatronics, IEEE/ASME Transactions on, 13*(1), 125-135.

Urata, J., Nshiwaki, K., Nakanishi, Y., Okada, K., Kagami, S., & Inaba, M. (2011). *Online decision of foot placement using singular lq preview regulation.* Paper presented at the Humanoid Robots (Humanoids), 2011 11th IEEE-RAS International Conference on.

Usherwood, J. R., & Bertram, J. E. (2016). Basic Mechanisms of Bipedal Locomotion. *Understanding Mammalian Locomotion: Concepts and Applications*, 369-384.

Vachhani, L., Mahindrakar, A. D., & Sridharan, K. (2011). Mobile robot navigation through a hardware-efficient implementation for control-law-based construction of generalised voronoi diagram. *Mechatronics, IEEE/ASME Transactions on, 16*(6), 1083-1095.

van der Kooij, H., van Asseldonk, E., & van der Helm, F. C. (2005). Comparison of different methods to identify and quantify balance control. *Journal of neuroscience methods, 145*(1), 175-203.

Vukobratović, M., & Borovac, B. (2004). Zero-moment point—thirty five years of its life. *International Journal of Humanoid Robotics, 1*(01), 157-173.

Vukobratović, M., & Rodić, A. (2004). *Contribution to the integrated control of artificial human gait.* Paper presented at the Proceedings of 2nd Serbian-Hungarian Joint Symposium on Intelligent Systems, SISY.

Walker, M. W., & Orin, D. E. (1982). Efficient dynamic computer simulation of robotic mechanisms. *Journal of Dynamic Systems, Measurement, and Control, 104*(3), 205-211.

Wan, X.-f., Xing, Y.-s., & Cai, L.-x. (2009). *Application and implementation of CAN bus technology in industry real-time data communication.* Paper presented at the Industrial Mechatronics and Automation, 2009. ICIMA 2009. International Conference on.

Wang, G., Dai, Z., Guan, Y., Dong, P., & Wu, L. (2014). Power management of hybrid power systems with Li-Fe batteries and supercapacitors for mobile robots. *Advances in Mechanical Engineering, 6*, 270537.

Winter, M., & Brodd, R. J. (2004). What are batteries, fuel cells, and supercapacitors? *Chemical reviews, 104*(10), 4245-4270.

Wolff, K., & Nordin, P. (2001). *Evolution of efficient gait with humanoids using visual feedback.* Paper presented at the Proceedings of the 2nd IEEE-RAS International Conference on Humanoid Robots, Humanoids.

Xie, L., Henkel, C., Stol, K., & Xu, W. (2018). Power-minimization and energy-reduction autonomous navigation of an omnidirectional Mecanum robot via the dynamic window approach local trajectory planning. International Journal of Advanced Robotic Systems, 15(1), 1729881418754563.

Yi, S.-J., Zhang, B.-T., Hong, D., & Lee, D. D. (2012). *Active stabilisation of a humanoid robot for impact motions with unknown reaction forces.* Paper presented at the Intelligent Robots and Systems (IROS), 2012 IEEE/RSJ International Conference on.

Yun, S.-k., & Goswami, A. (2011). *Momentum-based reactive stepping controller on level and non-level ground for humanoid robot push recovery.* Paper presented at the Intelligent Robots and Systems (IROS), 2011 IEEE/RSJ International Conference on.

Yussof, H., Yamano, M., Nasu, Y., & Ohka, M. (2006). *Design of a 21-DOF humanoid robot to attain flexibility in human-like motion.* Paper presented at the Robot and Human Interactive Communication, 2006. ROMAN 2006. The 15th IEEE International Symposium on.

Zhang, M., Meng, W., Davies, C., Zhang, Y., & Xie, S. (2015). A robot-driven computational model for estimating passive ankle torque with subject-specific adaptation.

Zonfrilli, F., Oriolo, G., & Nardi, D. (2002). *A biped locomotion strategy for the quadruped robot sony ers-210.* Paper presented at the Robotics and Automation, 2002. Proceedings. ICRA'02. IEEE International Conference on.