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A Hybrid Humanoid-Wheeled Mobile Robotic Educational Platform – Design and Prototyping

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Abstract

This research presents a novel, cost effective and indigenously developed educational framework for grasping hands-on concepts of Robotics and Mechatronics. The novelty of the platform lies in its ability to transform its shape from a humanoid to a wheeled mobile robot thus increasing the range of experiments that can be conducted using the proposed platform. The kinematics of the robot's legs is derived based on Denavit-Hartenberg (D-H) parameters while its 3D model is designed in CAD software. An aluminum-made DC servo actuated prototype consisting of 17 Degree Of Freedom (DOF) bipedal robot with four wheels is then fabricated. Preliminary experiments with the prototype including dynamically stable gait pattern and successful shape transformation and tentative list of experiments using the proposed framework demonstrate efficacy of the platform potentially useful for robotics community academicians, educationalists and hobbyists.

Keywords: Educational Platform, Humanoid Robot, Hybrid Mechanism, Wheeled Mobile Robot

1. Introduction

History of robotics dates back to 1920s. However, the last two decades witnessed technological as well as social revolution in this domain widening the spectrum of robot applications dramatically. Today, robots are being used actively in rehabilitation[1-5], motion assistance[6–9], cognition[10, 11], haptics/VR[12] and target detection and tracking[13, 14] in addition to Nuclear Power Plants (NPP)[15], Space[16, 17] and numerous other industrial applications[18–20].

The domain of robotics, by definition is highly multi-disciplinary. It ranges in scope from the design of electrical and mechanical components to their control and computer systems to algorithms design. This makes it an extremely difficult task, particularly for a newbie, to fully understand the underlying principles of robotics thus highlighting an urge to have up-to-the-mark educational platforms. These platforms, when integrated with conventional theoretical lectures, facilitate students' learning by bridging the gap between theory and practice. Engineering students who wish to commit themselves to robotics research find these educational frameworks beneficial for laying down firm foundations of the subject area. With these motivations, authors have realized educational platforms including AUTonomous Articulated Robotic Educational Platform (AUTAREP)[21, 22] and mobile robotic platforms[23, 24] for teaching various disciplines of robotics. Such frameworks are beneficial in dual fold; as academic tools, they reinforce engineering education and systematically compile knowledge that helps students and engineers to create innovative designs in their practical career while as research platforms, they can be used to test and validate various reported algorithms related with manipulators e.g. [25–27] and mobile robots[28-30].

The entrance of robotics in adolescence motivated scientists and researchers to explore new locomotion schemes for robots. Broadly categorizing, locomotion can be based on wheels, tracks and rigid links (as in legs and arms). Most of the today's robotics applications demand a robot to be mobile[23]. Recent advances in robotic home

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appliances and personal robots suggest a paradigm shift from the industrial to the service sector[31] thus making research on humanoids potentially beneficial and challenging. Though humanoids have rather limited capabilities, but have so far multitude of real world applications like technology demonstration, space missions, industrial platform, house hold helper, serving robot, war fields and much more. The most visible use of humanoid robot is technology demonstration[32]. Recent years witnessed particular interest in research on biped locomotion, structural, mechanism designs and Artificial Intelligence (AI) aspects of humanoids. It is anticipated that the role of humanoids to serve as assistants and companions for humans in normal routine life as well as in natural disasters will significantly increase in future.

The objective of this research is to propose an academic platform for teaching and training on humanoids. This paper is organized as follows: Section 2 presents literature review of the humanoid platforms with a tabulated comprehensive summary. Kinematic model of the robot's leg is derived in Section 3 while prototype design and fabrication is detailed in Section 4. Results and platform's specifications are presented in Section 5. Finally, Section 6 comments on conclusion.

2. Related Work

Scientific literature reports numerous humanoids developed by academia as well as industry. They vary widely in terms of design concept, Degree Of Freedom (DOF), physical dimensions and sensing capabilities.

Researchers at Waseda Univ., Japan were pioneer in presenting early-stage humanoids during late 1980s. WABIAN (WAseda BIpedal humANoid)-2R[33] is the latest robot in its series which has been developed as a human's partner and human motion simulator. Human like walking has been realized with a 3 DOF trunk motion and a 3-axis Zero Moment Point (ZMP) compensation using the trunk. The joints Range Of Motion (ROM) of the robot corresponds to human's one to mimic human movements. The robot can lean on a walk-assistance by controlling forearm. ASIMO (Advanced Step in Innovative Mobility)[34] by Honda, released in 2000, is regarded as the world most advanced humanoid. The robot, designed to be a multi-functional mobile assistant, can execute high level planning and give rapid response based on vision and auditory systems. With the capability to climb stairs, the robot can change its direction while running. It can walk at 2.5 km/h and also run at 3 km/h. Considering ASIMO as a benchmark, Korean researchers developed KHR-3 (KAIST Humanoid Robot)[35]. Its physical parameters and number of DOF were similar to that of ASIMO. The robot, offering improved mechanical stiffness of links, can emulate human like movements like walking, somersaulting, climbing steps and doing back flips etc. The walking speed was limited to 1.25 km/h. iCub[36] is an open source key research tool that resembles a 2.5 years old child. The robot, first released in 2008, has been developed with a focus to provide a world class testbed for research in humanoid, cognition and brain sciences. It has variety of sensors for hearing, seeing and touching. Distinguishing abilities of the platform include object grasping, crawling, avoiding collisions, solving complex mazes, expressing facial emotions and offering force based control. NAO[37], another open-source platform, initially released in 2006, is considered as a star in the world of education. The platform is well known with reference to RoboCup, an international soccer competition. The robot's walking is based on a linear inverted pendulum dynamic model and quadratic programming. Other examples of humanoid platforms include HRP-3[38], ARMAR-III[39], H6[40], PetMan[41] and Johnnie[42].

Table 1 presents comparative review of the most popular humanoid platforms. These platforms are far beyond reach of many academic institutions primarily due to their extremely high cost. E.g. iCub is of more than 250000 Euros worth. Also, most of these platforms are not open source. Being sophisticated platforms, they may be well suited for professionals working in big research groups and industry, but for Undergraduate engineering students and hobbyists, a cost-effective, low weight and open-source platform having capabilities of humanoid as well as Wheeled Mobile Robot (WMR) would certainly be a more optimum choice. The present work attempts to meet this choice. Figure 1 illustrates 3D CAD model of the proposed platform. The wheels can be seen in Figure 1(b).

3. Kinematic Model

Given the joint angles of a robot, forward kinematics computes position and orientation of the end-effector. For a serial link robot, literature repots various kinematic modeling techniques[43] including Denavit-Hartenberg (D-H) parameters, Hayati-Roberts (H-R) representation, screw theory, geometric based approaches etc. In this research, D-H parameters have been used to derive the legs kinematics owing to versatility, simplicity, and acceptability of this method to model any number of joints and links of serial manipulators despite of their

Table 1. Comparative Summary of Humanoid Robots

Robot	Developed by	Weight (Kg)	DOF	Height (cm)	Sensors	Actuators	Ref.
WABIAN-2R	Waseda Univ., Japan	64	41	148.7	- 6 axis force/torque sensor - Photo sensor - Magnetic encoder - Gyro sensor	- DC servo motors	[33]
ASIMO	Honda	50	34	130	- Gyroscope - Accelerometer - 6 axis Foot Area Sensor	- DC servo motor - Harmonic drive	[34]
KHR-3	KAIST, Korea	55	41	125	- 3 axis F/T sensor - Inclinometer - Rate Gyro	- DC servo motor - Harmonic drive	[35]
iCub	Italian Inst. of Tech., Italy	23-25	53	104	- Gyroscopes - Accelerometers - Encoders - Force/torque sensors - Capacitive tactile sensors - Stereo Cameras - Mic	- Brushless motors - DC motors	[36]
NAO	Aldebran Robotics, France	4.3	21-25	58	- IMU - FSR - SONAR range finder - Encoders - IR RX/TX - Capacitive tactile sensors - Pressure sensors - HD cameras - Mic and speakers - Bumpers	- Brush DC Coreless	[37]
HRP-3	AIST, Kawada Industries, Japan	68	42	160.6	- 3 axes vibration gyro - 3-axes velocity sensor - Scanning range finder - Stereo camera	- DC servo motors - Harmonic drive	[38]
ARMAR-III	Karlsruhe Inst. of Tech., Germany	135	43	175	- Motors encoders - LRF - 6D inertial sensor - Axis sensors - 6D force-torque sensor - Dragonfly cameras - Mic	- DC motors - Harmonic drives - Fluidic actuators	[39]
H6	Univ. of Tokyo, Japan	51	33	136	- Accelerometer - Inclinometer - FSR - Pressure sensor - Stereo cameras	- DC motors - Harmonic drive	[40]
PetMan	Boston Dynamics	80	27 (actuated)	175	- IMU - LIDAR - Stereo cameras	- Hydraulic actuators	[41]
Johnnie	Tech. Univ. of Munich, Germany	40	17	180	- Incremental encoder - Force sensors - Gyroscopes - Accelerometers	- Brush DC motors	[42]

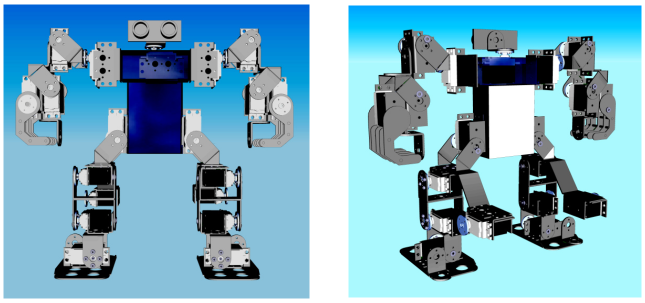

Figure 1. 3D CAD Model of the Proposed Platform (a) Front view (b) Back view

complexity[44]. D-H method considers each link as a rigid body where four parameters $\{\alpha_{i-1}, a_{i-1}, d_i, \theta_i\}$ respectively represent twist angle, link length, link offset and joint angle[45]. For the sake of symmetry, only the kinematics of right leg is presented here. Attaching an orthonormal coordinate system to each link of the leg (Figure 2), D-H parameters obtained are tabulated in Table 2.

Expressing joint *i* in its previous neighboring joint *i-1*, for each link of the leg, the corresponding transformation matrices have been written. Exploiting the compound transformation feature, the link matrices have been then

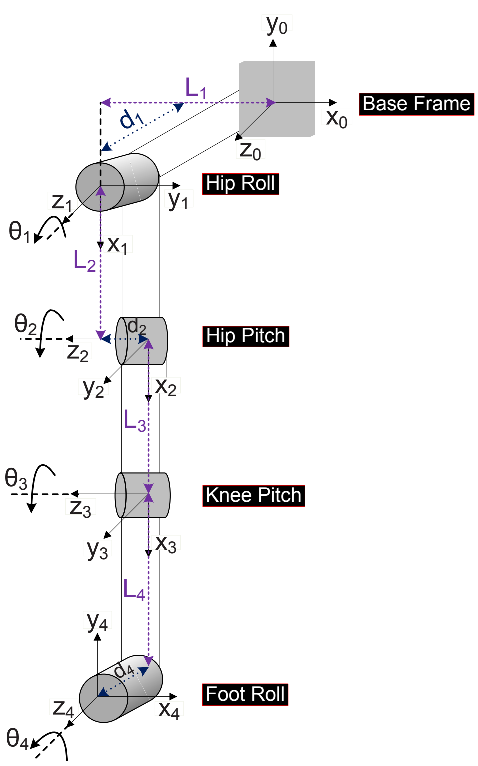

Figure 2. Right Leg Showing Joints and Frame Assignment

Table 2. DH Parameters of Right Leg

I	α_{i-1}	a_{i-1}	d_i	θ_i
1	0	L_1	d_1	θ_1
2	–90°	L_2	d_2	θ_2
3	0	L_3	0	θ_3
4	90°	L_4	d_3	θ_4

multiplied yielding an overall matrix that transforms end-effector coordinates into base of the robot.

$$^{Base}_{End}T = {}^0_4T = {}^0_1T\,{}^1_2T\,{}^2_3T\,{}^3_4T$$

$$^0_4T = \begin{bmatrix} \cos\theta_1 & -\sin\theta_1 & 0 & L_1 \\ \sin\theta_1 & \cos\theta_1 & 0 & 0 \\ 0 & 0 & 1 & d_1 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \cos\theta_2 & -\sin\theta_2 & 0 & L_2 \\ 0 & 0 & 1 & d_2 \\ -\sin\theta_2 & -\cos\theta_2 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \cos\theta_3 & -\sin\theta_3 & 0 & L_3 \\ \sin\theta_3 & \cos\theta_3 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \cos\theta_4 & -\sin\theta_4 & 0 & L_4 \\ 0 & 0 & -1 & -d_3 \\ \sin\theta_4 & \cos\theta_4 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Considering following nomenclature (symmetric for *cos* and *sin*),

$c_a = \cos(a)$

$c_{ab} = \cos(a+b) = c_a c_b - s_a s_b$

The resultant transformation matrix can take the form of

$$^0_4T = \begin{bmatrix} r_{11} & r_{12} & r_{13} & p_x \\ r_{21} & r_{22} & r_{23} & p_y \\ r_{31} & r_{32} & r_{33} & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad (1)$$

where the coefficients are

$r_{11} = c_1 c_4 c_{23} - s_1 s_4$

$r_{12} = -c_1 s_4 c_{23} - s_1 c_4$

$r_{13} = c_1 s_{23}$

$p_x = L_1 + L_2 c_1 + L_3 c_1 c_2 + L_4 c_1 c_{23} - d_2 s_1 + d_3 c_1 s_{23}$

$r_{21} = s_1 c_4 c_{23} + c_1 s_4$

$r_{22} = -s_1 s_4 c_{23} + c_1 c_4$

$r_{23} = s_1 s_{23}$

$p_y = L_2 s_1 + L_3 s_1 c_2 + L_4 s_1 c_{23} + d_2 c_1 + d_3 s_1 s_{23}$

$r_{31} = -c_4 s_{23}$

$r_{32} = s_4 s_{23}$

$r_{33} = c_{23}$

$p_z = -L_3 s_2 - L_4 s_{23} + d_1 + d_3 c_{23}$

The 3X3 matrix in (1) comprising of first three rows and first three columns is the rotation while the last column (p_x, p_y, p_z) represents the position of end-effector w.r.t. base. The kinematics has been simulated using MATLAB ToolBox for Robotics[46]. A typical pose of right leg corresponding to joint angles {θ_1, θ_2, θ_3, θ_4} as {0, 90°, 90°, 0} is illustrated in Figure 3.

4. Prototype Design and Fabrication

The proposed platform has been prototyped in-house. Various phases of development and fabrication are presented here. The first prototype (Figure 4a) having 6 DOF consisted of two legs without trunk. It was made from ice-cream sticks glued together. This prototype was made primarily to facilitate conceptual understanding of humanoid motion. The structure was weak since the sticks used to bend. The same structure was then fabricated in acrylic (Figure 4b). The prototype was strong though too heavy. The structure was capable of sliding since the robot could not lift its feet. For lighter and more optimum structure, the third prototype (Figure 4c) was fabricated in aluminum. This structure also lacked trunk. We used standard C, L and servo brackets joined firmly with nuts and bolts for fabricating the robot. This structure supported efficient walking. A trunk and dummy arms were then added exhibiting 12 DOF mechanism together with Ultrasonic ranging sensor for collision avoidance in the fourth prototype (Figure 4d).

The final prototype (Figure 5a) has 4 DOF/leg, 2 DOF/arm, 2 DOF/hand and 1 DOF for head. Grippers are controlled with servo motors. To permit mechanism hybridization (Figure 5b), the biped robot is equipped with two motorized wheels and two free wheels. The active wheels are driven by two dedicated continuous rotation servos. The embedded system is centered on two controllers working in Master-Slave configuration. Slave controller (Pololu-Mini Maestro 24-channel) drives the motors while Raspberry PI Model B intelligent controller acting as master interfaces Ultrasonic module and possible other visual sensors including camera. The on-robot Wi-Fi module permits off-site programming and remote operation.

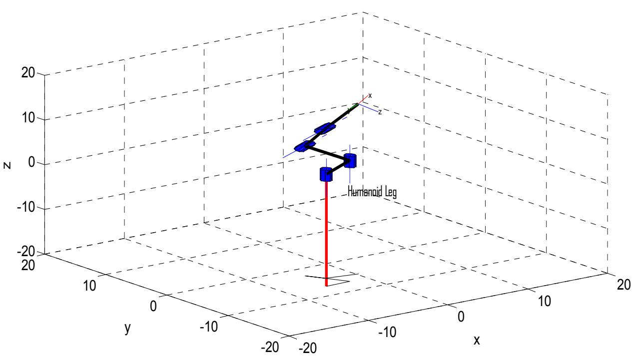

Figure 3. Simulated Leg at Typical Pose

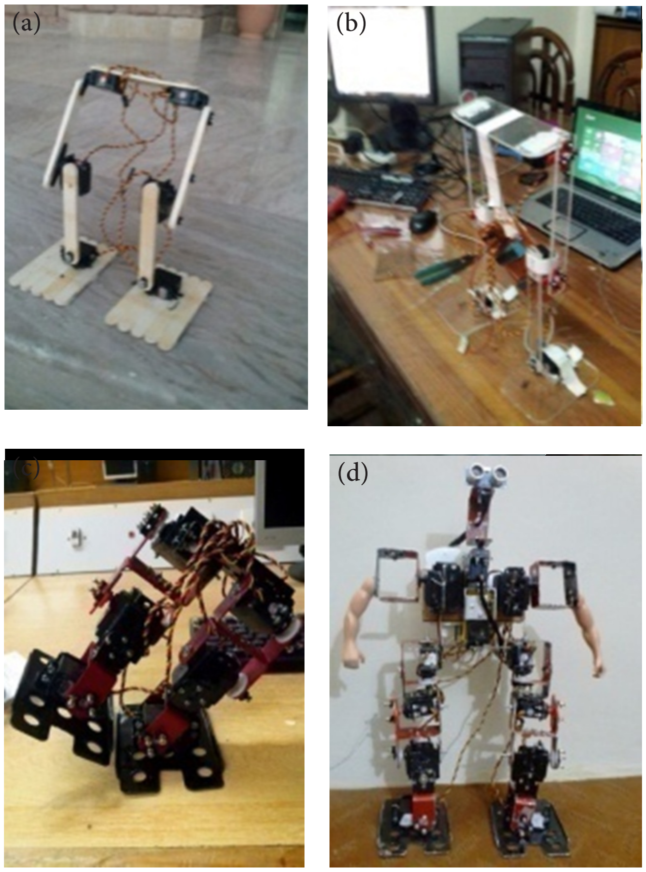

Figure 4. (**a-d**) Preliminary Prototypes Showing Design Phases.

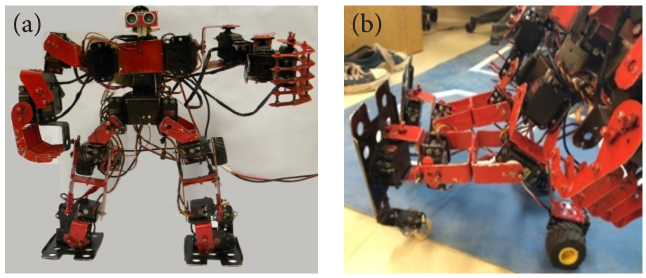

Figure 5. Final Prototype in: (a) Humanoid and (b) Wheeled Configuration.

5. Platform Specifications and Results

The main specifications of the proposed hybrid platform are summarized in Table 3.

In order to verify the effectiveness of the proposed hybrid platform, two preliminary experiments have been carried out on a flat horizontal plane; walking and shape transformation. Figure 6 (a-j) presents results of walking pattern while shape transformation is illustrated in (k-l). Initially, the robot is standing on the start line (a). For walking, it is tilted to left to shift Center of Gravity (CoG) (b). The left foot is first moved forward in air (c) and then placed back on ground (d). The robot tilts right with left foot placed ahead (e) followed by sliding and placing down the right foot as shown in (f)

Table 3. Main Specifications of the Proposed Platform

Parameter	Specification
Height	31 cm
Weight	2.3 Kg
Degree Of Freedom (DOF)	17
Actuators	DC Servo motors (Qty: 19) - 8 Hitec HS-645MG for Legs - 9 Futaba S3003 for Torso - 2 Spring SM-S4303R for Wheels
Sensors	Ultra Sonic (HC SR-04)
Operating System	Linux (Raspbian - Wheezy)
Programming Language	Python
Connectivity	Wi-Fi, Ethernet

Figure 6. Pictorial Results of: (a-j) Robot Crossing the Line (k-l) Robot Transforming its Shape to Wheeled Configuration.

Table 4. List of Experiments Using the Proposed Platform

Level	Title	Robot Configuration H – Humanoid W – Wheeled
	☐ Assembling a robotic mechanism	H + W
Basic	☐ Learn how to program a robot	H + W
	☐ Generating PWM signals	H + W
	☐ DC servo motor control	H + W
Intermediate	☐ Walking on uniform surface	
	☐ Study the coupling effect b/w various joints of a robot	H + W
	☐ Analyzing walking algorithms on irregular terrains	H
Advanced	☐ Investigating balancing strategies	H
	☐ Testing collision avoidance approaches	W

and (g) respectively. It then tilts left to shift CoG (h) and subsequently moves the left foot forward (i) thus aligning both feet so as to cover distance of one step. The robot in (j) is then commanded to transform its shape. Its knees are bend to 90^o (k) so that the rare wheels touch the ground. The knee joint again comes to 0^o (l) to shift frontage weight onto front casters. It is envisaged in near future to utilize advanced walking parameters like ZMP trajectory to realize an efficient walking scheme.

The proposed platform, owing to its diverse range of features, finds potential to practically demonstrate concepts related with mechatronics, control systems, algorithm design, system engineering, robot integration etc. A tentative list of laboratory experiments based on the platform for a beginner to an advanced user is given in Table 4.

6. Acknowledgement

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7. Conclusion

A robotic platform of superior academic impact to practically demonstrate the relevant key concepts has been proposed in this paper. Primary distinguishing features of the presented framework include mechanism hybridization, design modularity, structural flexibility, use of inexpensive components and open architecture. The drawings, schematics, components lists and source codes are available for non-commercial use. Interested readers are requested to send an email to the corresponding author. Skipping licensing costs makes the framework a good source of academic learning. The presented list of experiments that can be conducted based on the proposed platform demonstrate its relevance with academic courses like robotics, control systems, mechatronics etc. Advanced users can tailor the platform by exploiting the open-source custom-developed hardware and software architectures. The modular design of the platform permits easy extension in terms of sensory system. e.g. adding an on-board camera allows conduction of computer vision related experiments.

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