HUMANOID ROBOT
Modular-Joint Design of a TPINOKIO Bipedal Robot

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Abstract: This paper presents the work done in the modular-joint design of a teen-size bipedal humanoid robot. Due to this modular-joint design approach, the robot is able to be modelled as a point-mass system without considering its links' inertia, this is a novelty approach to improve the kinematics and dynamic modelling of the robot, for test-bedding and simulation of various control algorithms. The robot is a cost effective platform which is suitable for both edutainment and engineering research purposes. The TPinokio humanoid robot has a height of around 1.5 meter, and weight around 58 kg. This paper is focused mainly on the robot's mechanical structure and electronics design. The robot's kinematics with point-mass distribution characteristics and it's control approach are briefly discussed.

1 INTRODUCTION

The development of bipedal robot locomotion began more than 30 years ago, some well-known robots are ASIMO, HRP, HUBO, JOHNNIE, LOCH and QRIO. The success of ASIMO triggered a worldwide research fever on humanoid robot. Currently, most of the researchers faced numerous challenges including difficulties in designing a low cost; the fact that a life-size humanoid robots are complex and expensive in cost; and yet robust in mechanical structure robot. The other difficulties are in obtaining a precision sensors feedback reading and difficulties in implementing a high end real-time motion controller.

Stable walking gait pattern generation and real-time on-line control algorithm design remain a very challenging tasks in the humanoid robotics research arena, because it requires precision modelling of the robot's dynamics and kinematics, this include the mass distribution, the location of Center-of-Mass (CoM) and the inertia of each links. Therefore, to obtain a correct and accurate robot's model is crucial. With this in mind, the mechanical structure of TPinokio is in modular-joint form, all the critical masses are concentrated at the joints end, and the links between each joints are made of light-weight aluminum, as such, the moment and inertia of the links are negligible compared to the joints' mass. This results in a more accurate multi-body point-mass system model. TPinokio platform is designed to be suitable for educational learning and engineering research. The design is depicted in Figure (1).

2 TPINKIO DESIGN CONCEPT

This section will outline the design concept of TPinokio, the design concept are relatively low cost, modular-joint and light weight.

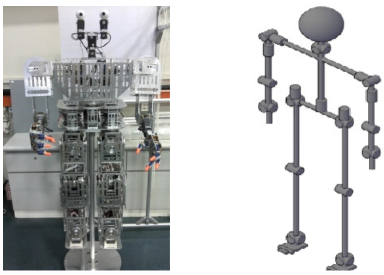

Figure 1: TPinokio modular-joint design and point-mass distribution stick diagram.

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2.1 Special Features

- Compact and modular-joint design.
- Can be easily modelled as ‘point-mass’.
- Robust mechanical structure.
- Simple kinematics.
- Zero backlash.
- Passive toe-joint to achieve better walking speed and higher step climbing, as shown in Figure (2).

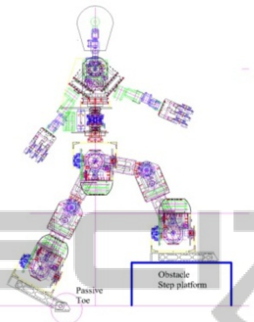


Figure 2: Passive toe joint for higher step climbing.

2.2.1 Comparatively Low Cost

All the components were carefully evaluated before a purchase was made, the total fabrication cost is below US$50k.

2.2.2 TPinokio for Research

The robust, light-weight, modular-joint and relatively low cost design of TPinokio provides an affordable test-bedding platform for researchers.

2.2.3 TPinokio for Education

Due to its light-weight and easy software interface (Labview), a wide range of low cost sensors and electronics gadgets may be added to the upper body of the robot. It is a good edutainment platform to cultivate learning interest in robotics.

2.2 Degree of Freedom (D.O.F)

TPinokio has more than 40 D.O.F, it is around 1.5m and weight approximately 56kg. The general specifications are listed in Table (1).

Table 1: TPinokio Specifications

Height	Approx. 1.5meter
Weight	Approx. 56 kg
DOF	Lower body : 12 DOF Waist (Pelvis) : 1 DOF Upper body (Shoulder, Arm): 12 DOF Hands : 16 DOF Head (neck) : 2 DOF Eyes : 4 DOF Total : 47 DOF
Actuator	Lower body: Harmonic gear, DC motor Upper body (shoulder) : Harmonic gear, DC motor Arm: EX106, RX64, RX28. RX10 Hand : low cost RC servo motor
Sensors	Head : USB Webcam, Hokuyo LRF Pelvis : IMU Foot : FSR Joint : Tilt sensor & absolute encoder
Power	24V DC
Software	LabVIEW 2010

3 OVERVIEW OF DESIGN

3.1 Mechanical Design

The CAD drawing of the TPinokio design is as depicted in Figure (3), a trade-off between cost effectiveness and performance requirements.

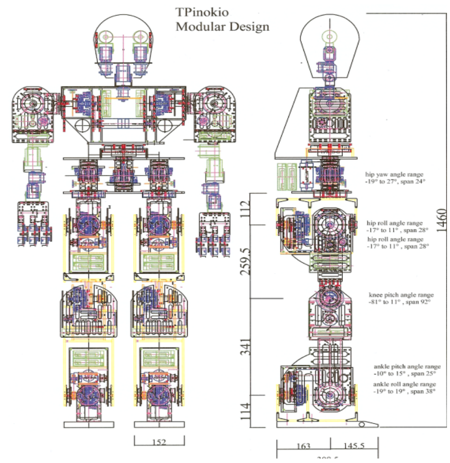


Figure 3: TPinokio CAD drawing.

3.1.1 Modular-joint Design

In total, there are three set of different modular-joint design, namely, hip joint, knee joint and ankle joint respectively. The joint-shaft is driven by a DC motor coupled with a harmonic drive through a pulley-belt system. All the sensors, controller electronics and wiring harness are housed in a compact housing, as shown in Figure (4) and Figure (5). Most of the components are standardised with 85% similarity in specifications, only the motors and Harmonic-gears have different specification due to its different torques requirement for each joints. As such, the modular-joint can be easily swap, reconfigure, or removal for repair and maintenance.

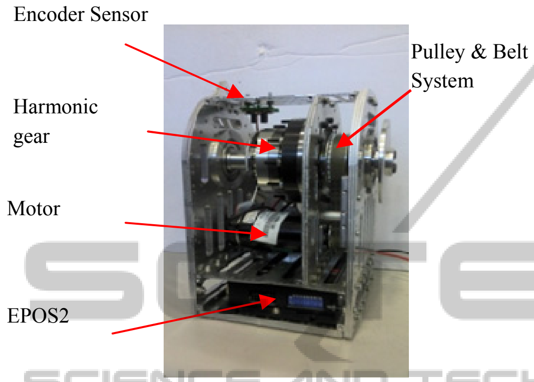


Figure 4: Compact Modular-Joint Design.

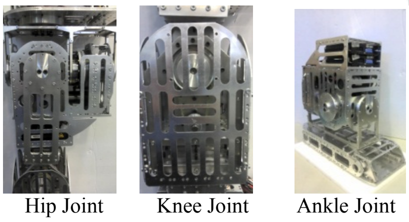


Figure 5: Different set of compact modular-joint.

Communication between each modular-joint is through CANbus interface with a single five-core cable; 3-wires for the CANbus and 2-wires for the power supply; thus, messy cabling is eliminated, as depicted in Figure (6).

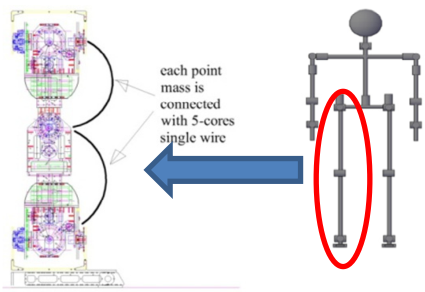


Figure 6: CANbus link between Modular-Joint.

3.1.2 Upper Body Design

The upper body joints are designed with low cost components, the essential parts are listed in Table (2).

Table 2: Upper Body actuators.

Joint		Actuator
Head	Pitch yaw	RX10 RX10
Shoulder	Pitch yaw	Harmonic 14-100:1 and Maxon 90w DC motor
Arm	Pitch yaw	EX-106+ EX-106+
Hand / Wrist	Pan/Tilt Roll	RX64 RX28
Fingers	Pan/Tilt	RC servo

3.1.3 Lower Body Design

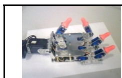
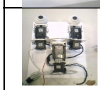
These include the pelvis and both legs. The lower body has a 13 D.O.F, the joints are modular, the pulley-belt system is standard components for all joints, as listed in Table (3).

Table 3: Lower body actuators.

Joint		Harmonic gear	Pulley & belt ratio	DC Motor
Pelvis	yaw	Size 17	2:1	150w
Hip	Roll	Size 17	2:1	150w
	Pitch	Size 20	2:1	150w
	Yaw	Size 20	2:1	150w
Knee	Pitch	Size 17	2:1	200w
Ankle	Roll	Size 14	2:1	150w
	Pitch	Size 20	2:1	150w

3.1.4 Arm, Hand and Head Design

The upper body parts are assembled with low cost components and parts. It is designed mainly for edutainment purposes.

	The fingers are design with HiTec HS-55 RC servo.
	The eyes have two USB webcam , pan / tilt can be controlled by Dynamixel RX10 servo.

3.2 Sensory System

Foot dynamics affect the overall walking performance. TPinokio feet are designed with FSRs mounted at four corners, as shown in Figure (7).

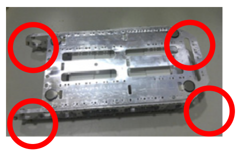


Figure 7: FSRs mounting at the base of the foot.

As shown in Figure (8), an absolute accelerometer sensor is mounted directly on the joint's shaft to provide a prefect zero ground homing angle for the robot with reference to world reference coordinate. This is a unique features for TPinokio, if the robot stands on a slope surface, the reading will be compensated by the IMU sensors.

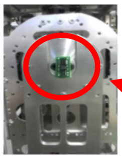


Figure 8: Accelerometer / Joint shaft mounting.

4 SYSTEM ARCHITECTURE

The hardware schematic configuration of TPinokio is as shown in Figure (9), the main communication protocol is based on CANbus.

The GUI is written in LabVIEW, as shown in Figure (10). LabVIEW is chosen because it is user-friendly.

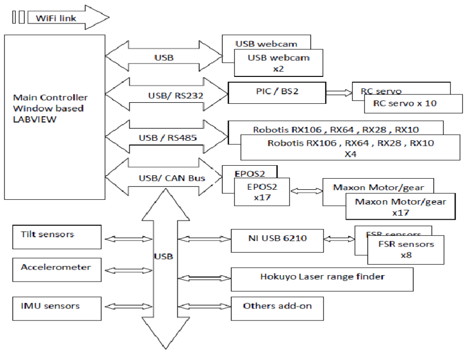


Figure 9: Hardware System Configuration.

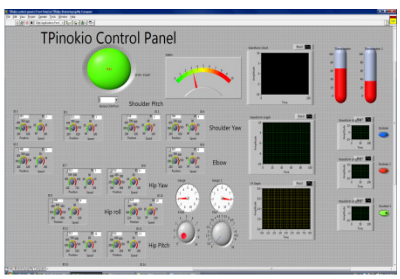


Figure 10: TPinokio GUI with LabVIEW.

5 KINEMATICS

5.1 Simple Kinematics

TPinokio's joints and mechanism are designed to produce simple kinematics structure, due to its modular-joint design and the links to each joints are made of light-weight aluminium, the mass and inertia of the link are negligible compared to the weight of the modular-joint, and the link is also assumed to having point-mass located at the distal end, as shown in Figure (11).

5.2 Inverse Kinematics

The inverse kinematic parameters (Goswami et al. 2009) of TPInokio are as shown in a set of Equations (1).

$$x_L = P_{1x} - P_{5x} \quad ; \quad y_L = -P_{5y} \quad ; z_L = P_{1z} - P_{5z}$$

$$x_r = P_{12x} - P_{5x} \quad ; y_r = -P_{5y} \quad ; z_r = P_{12z} - P_{5z}$$

$$\theta_A = cos^{-1}\left[\frac{L_1^2 + L_2^2 - (x_L^2 + y_L^2 + z_L^2)}{2L_1L_2}\right]$$

$$\theta_B = cos^{-1}\left[\frac{L_1 \sin(\theta_A)}{\sqrt{x_L^2 + y_L^2 + z_L^2}}\right]$$

$$\theta_C = cos^{-1}\left[\frac{L_1^2 + L_2^2 - (x_r^2 + y_r^2 + z_r^2)}{2L_1L_2}\right]$$

$$\theta_D = cos^{-1}\left[\frac{L_1 \sin(\theta_C)}{\sqrt{x_r^2 + y_r^2 + z_r^2}}\right] \qquad (1)$$

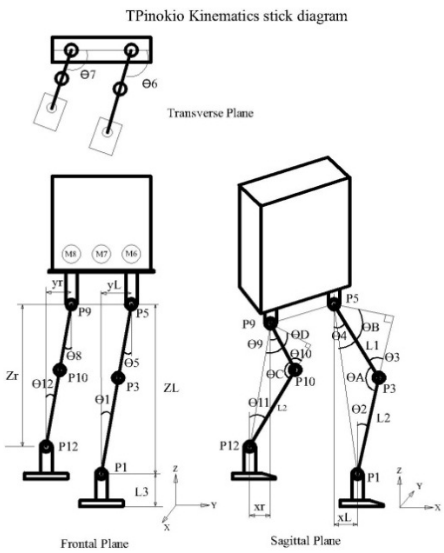


Figure 11: Tpinokio Kinematic Parameters.

The values of the joints' angle $[\theta_1, \theta_2, \theta_3, \dots \theta_{12}]^T$, can be found from these four angular parameters (θ_A, θ_B, θ_C, θ_D) by solving trigonometric equations.

6 ZERO MOMENT POINT

ZMP is defined as a point on the ground where the sum of all the moments equals zero. TPinokio ZMP is obtained by both kinematics and measurement methods. The values are input to the controller for further filtering to determine the actual ZMP location.

6.1 CoM Multi-body Point-mass Model

With the point-mass design, TPinokio CoM ($x_{com}, y_{com}, z_{com}$) can be obtained from direct calculation with the following Equations (2):

$$x_{com} = \frac{\sum_i m_i P_{ix}}{\sum_i m_i} = \frac{m_3 P_{3x} + m_5 P_{5Ly} + m_T\left(\frac{P_{5Ly} + P_{5ry}}{2}\right) + m_9 P_{5ry} + m_{10} P_{10x} + m_{12} P_{12x}}{m_1 + m_3 + m_5 + m_T + m_9 + m_{10} + m_{12}}$$

And the (y_{com}, z_{com}) can be calculated with the same formula,

$$y_{com} = \frac{\sum_i m_i P_{iy}}{\sum_i m_i}; \quad z_{com} = \frac{\sum_i m_i P_{iz}}{\sum_i m_i} \tag{2}$$

The ZMP ($x_{zmp}, y_{zmp}, 0$) is related to the CoM by the following Equations (3).

$$\begin{bmatrix} x_{zmp} \\ y_{zmp} \end{bmatrix} = \begin{bmatrix} x_{com} \\ y_{com} \end{bmatrix} + \begin{bmatrix} \frac{\sum_i m_i \ddot{P}_{iz} P_{ix} - \sum_i m_i \ddot{P}_{ix} P_{iz}}{g \sum_i m_i} \\ \frac{\sum_i m_i \ddot{P}_{iz} P_{iy} - \sum_i m_i \ddot{P}_{iy} P_{iz}}{g \sum_i m_i} \end{bmatrix} + \begin{bmatrix} \frac{\sum_i M_{iy}}{g \sum_i m_i} \\ \frac{\sum_i M_{ix}}{g \sum_i m_i} \end{bmatrix} \tag{3}$$

where M_{ix} and M_{iy} are the moments of the links due to rotation about *x*-axes and *y*-axes, respectively.

6.2 Direct Measurement Model

Direct measurement of ZMP without knowledge of kinematics is also possible by reading the FSR sensors feedback values, Figure (7). The position is calculated by using Equation (4). These values are used in the controller observer feedback loop for ZMP error correction.

$$x_{zmp} = \frac{(f_2 + f_3)x_1 - (f_1 + f_4)x_2}{f_1 + f_2 + f_3 + f_4}; \quad y_{zmp} = \frac{(f_1 + f_2)y_1 - (f_3 + f_4)y_2}{f_1 + f_2 + f_3 + f_4} \tag{4}$$

6.3 Simplified Inverted Pendulum Model

The IPM method is a highly simplified model, during the swing phase, the Center-of-Mass (CoM) of the robot may be modeled as point-mass and is connected to the stance foot like an inverted pendulum, as shown in Figure (13). The simplified ZMP ($x_{zmp}, y_{zmp}, 0$) can be computed with Equations (5).

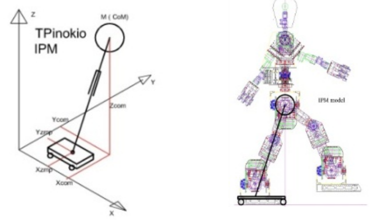


Figure 12: 3D IPM moving cart model.

$$\begin{bmatrix} x_{zmp} \\ y_{zmp} \end{bmatrix} = \begin{bmatrix} x_{com} \\ y_{com} \end{bmatrix} - \begin{bmatrix} \frac{Z_{com}}{g} \ddot{x}_{com} \\ \frac{Z_{com}}{g} \ddot{y}_{com} \end{bmatrix} \tag{5}$$

6.4 Dynamic Model of TPinokio

The TPinokio dynamic model is as shown in Figure (12), the masses are concentrated at the links end, and the links inertia is assumed to be zero, therefore Equation (3) may be reduced to:

$$\begin{bmatrix} x_{zmp} \\ y_{zmp} \end{bmatrix} = \begin{bmatrix} x_{com} \\ y_{com} \end{bmatrix} + \begin{bmatrix} \frac{\sum_i m_i \ddot{P}_{iz} P_{ix} - \sum_i m_i \ddot{P}_{ix} P_{iz}}{g \sum_i m_i} \\ \frac{\sum_i m_i \ddot{P}_{iz} P_{iy} - \sum_i m_i \ddot{P}_{iy} P_{iz}}{g \sum_i m_i} \end{bmatrix} \tag{6}$$

So, when the robot moves at a slow or constant speed, the acceleration term become zero, the highly simplified ZMP can be approximate as:

$$\begin{bmatrix} x_{zmp} \\ y_{zmp} \end{bmatrix} = \begin{bmatrix} x_{com} \\ y_{com} \end{bmatrix} \tag{7}$$

It can be verified that Equation (5) also yields the same result.

7 CONTROL ARCHITECTURE AND GAIT ALGORITHM

The control architectural is as shown in Figure (13).

Biped walking is a periodic phenomenon (M. Xie et al. 2009), to implement the desired CoM/ZMP path, inverse kinematics is required to determine the individual joints angle, an observer (Astolfi et al., 2010) may be designed to determine its velocity and acceleration.

The basic parameters for humanoid walking are step-length (S), pelvis height (Z), foot lifting height

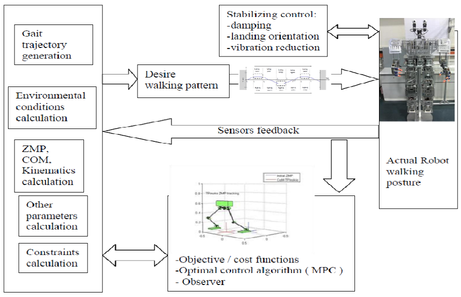


Figure 13: TPinokio Control Scheme / Architecture.

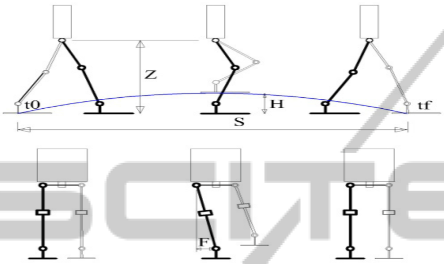


Figure 14: Pelvis / CoM / ZMP motion.

(H) and frontal-shift (F) as shown in Figure (14). Harmonic and cycloid functions are the most common paths (Ill-Woo Park et al., 2006), due to it simpler expression but with disadvantages due to nonlinearity. To make a path start and stop with zero jerk, a seven degree polynomial and eight boundary conditions must be employed, a zero jerk start-stop path of a joint moving from *10^o to 45^o for t=0 to 1 second*, is as shown in Figure (15). The simulation of ZMP-CoM position tracking is as shown in Figure (16).

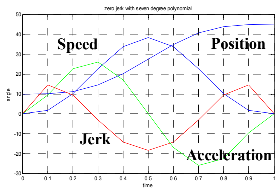


Figure 15: Zero Jerk with Seven Degree Polynomial.

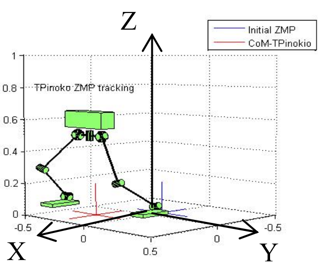


Figure 16: ZMP-CoM tracking simulation.

A simple trajectory that is parabolic, is used for TPinokio testing of the swing leg foot movement

$$x(t) = -S\cos(wt)$$
$$z(t) = \frac{H}{2}[1 - \cos(2wt)] \qquad (11)$$

Where $\boldsymbol{S}$ is the stride (step-length), $\boldsymbol{H}$ is the maximum foot height, **T** is the one step period, and the stride frequency $\boldsymbol{w = \pi / T}$. A sample plot of *T=1s, S=0.2m, H=0.1m,* is shown in Figure (17).

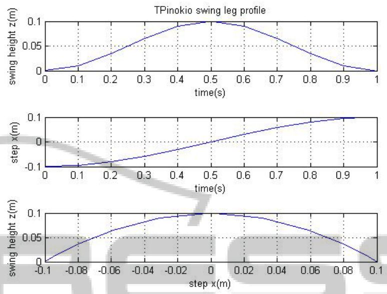


Figure 17: The Trajectory of the swing foot.

8 CONCLUSIONS

This paper presented and focused on the modular-joint design concept, the mechanical and hardware architecture for a new teen-size humanoid robot, TPinokio. The modular-joint design not only provides an accurate point-mass model for testing and simulation, it's also result in creation of a cost effective and easy maintenance robot for both research test bedding and educational learning.

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