Humanoid Robot Control: A Mixed-Signal Footstep Planning SoC with ZMP Gait Scheduler and Neural Inverse Kinematics

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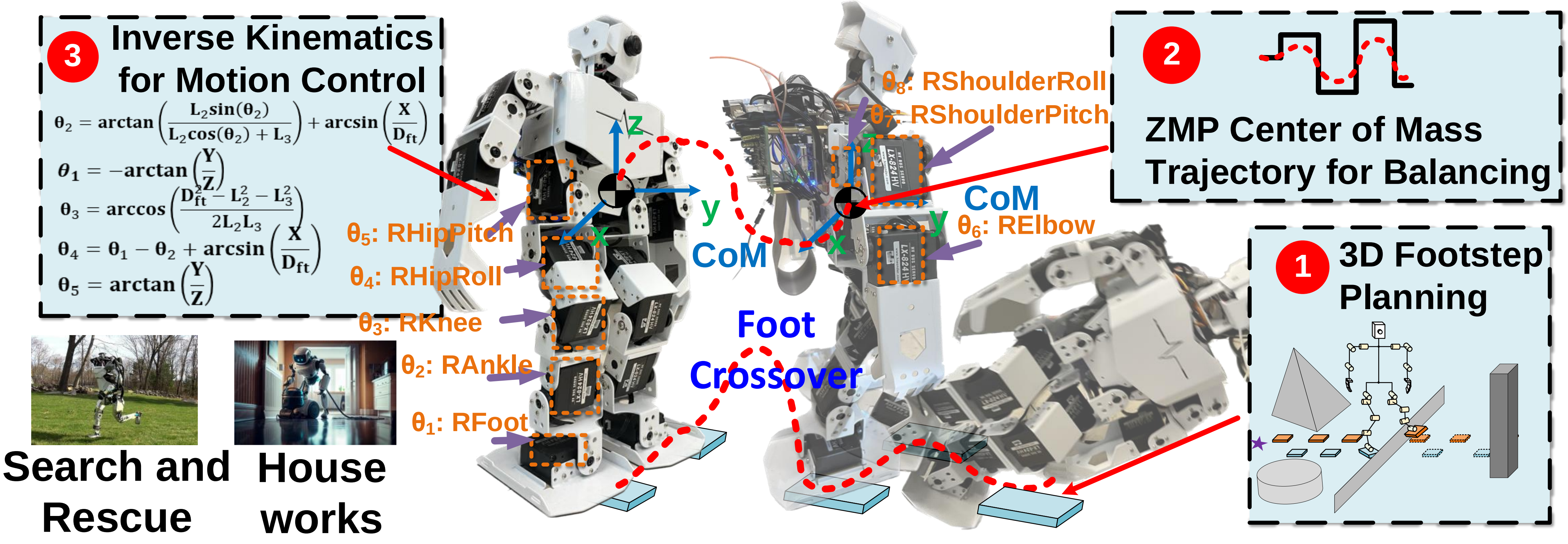
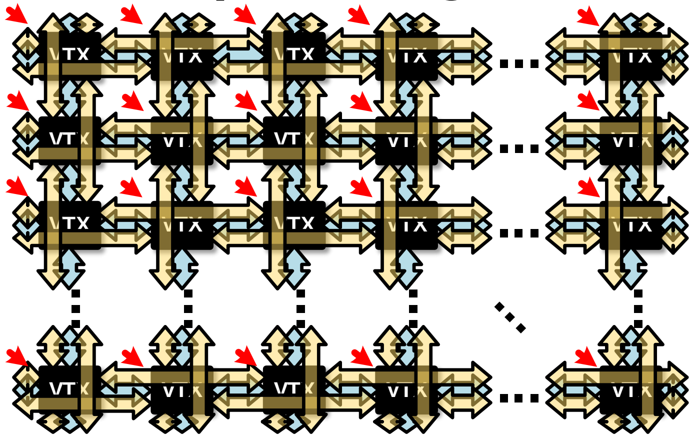
Challenges of Humanoid Robot Control



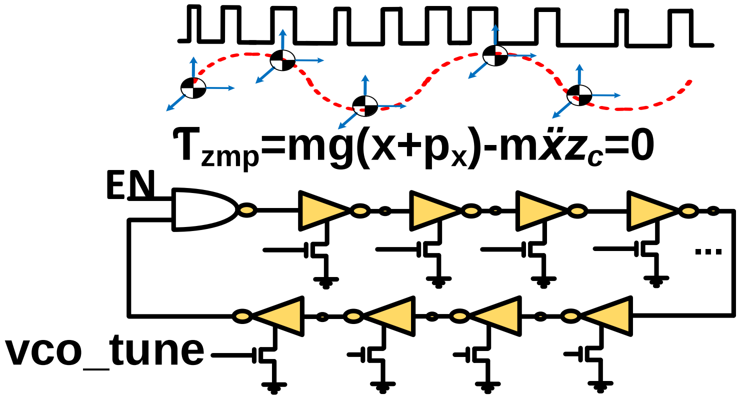
- Computationally heavy for 3D footstep planning on humanoid robot
- Special trajectory control of the robot’s center of mass (CoM) for balancing
- High computation for 10-20 DoF robot joint control compared with wheeled robot

Contribution of This Work

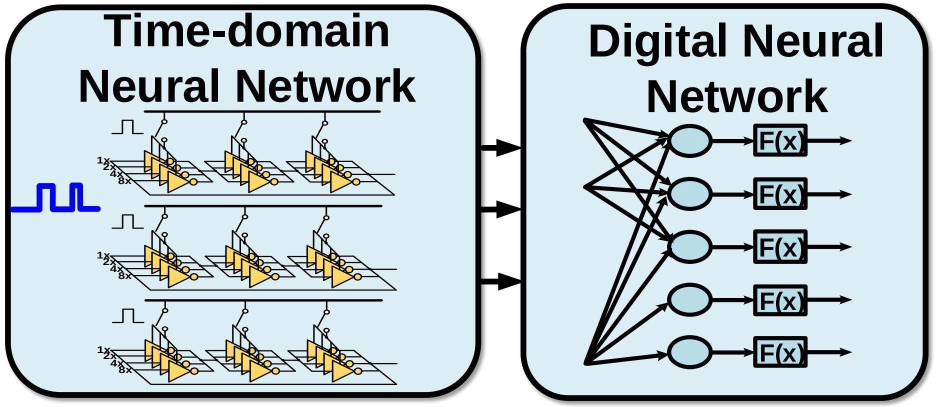
- Time-domain Graph Search Engine for 3D Foot planning



- Mixed-signal Circuit for Efficient ZMP Pattern Generation



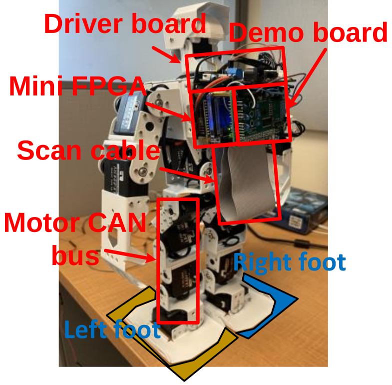
- Neural Network Approximator for Inverse Kinematics



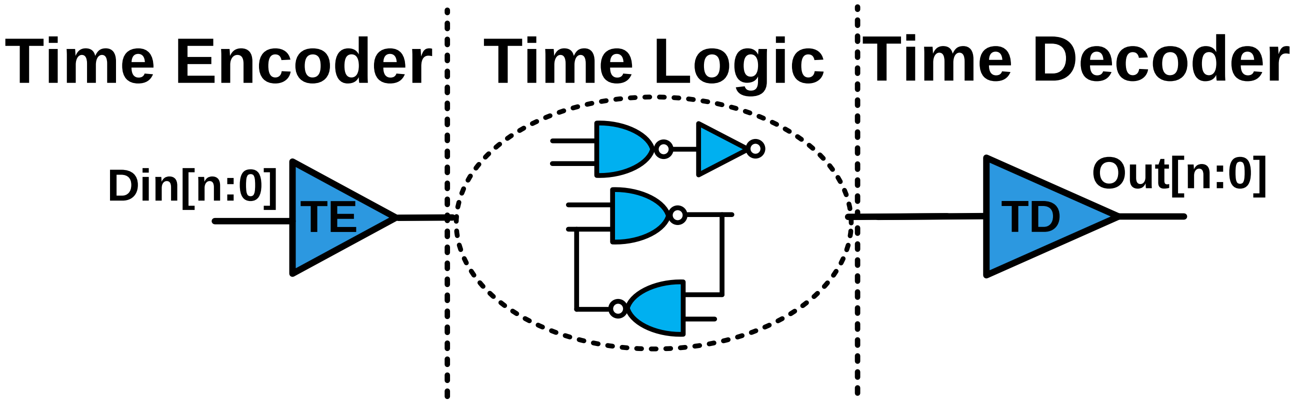
- In-situ Demo on Humanoid Robot

Front view of robot

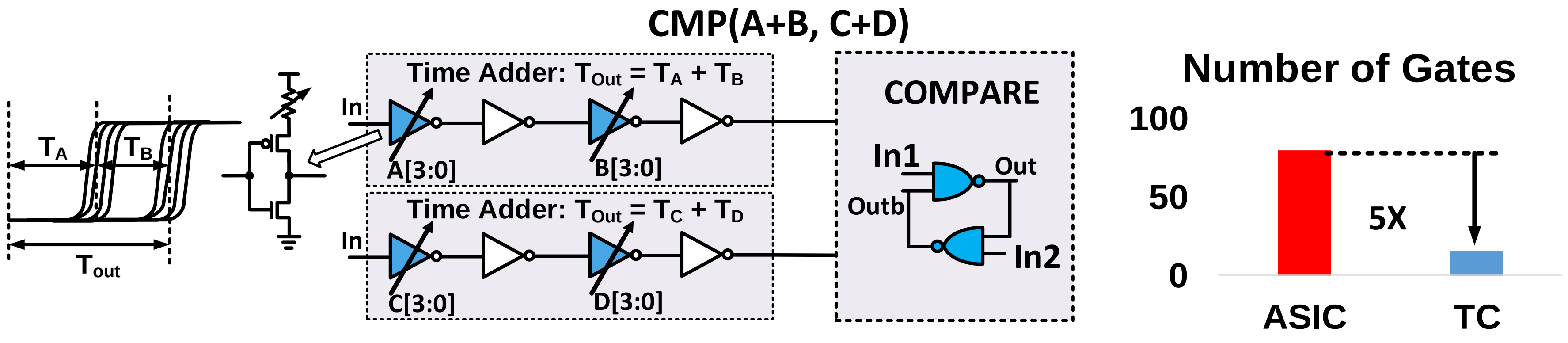
Back view of robot and foot steps



Time-Domain Computing (TC)

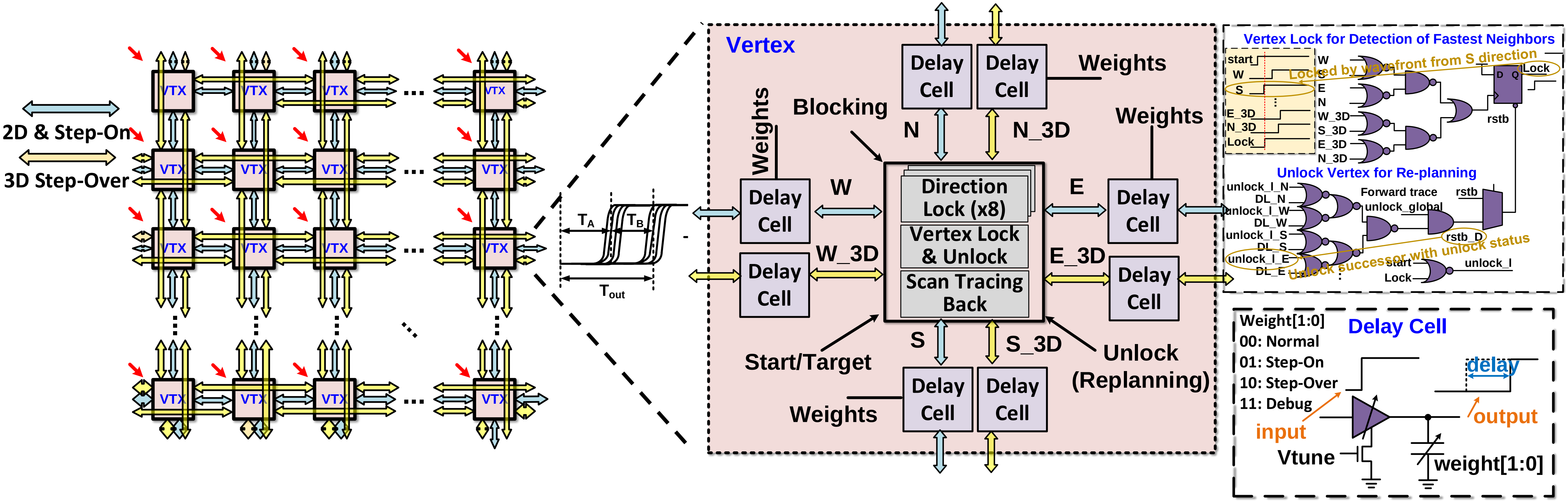


- **Encode and process information in “Time”**



- **Key benefits:** energy/area efficiency, digital implementation

Novel Time-domain Graph Search Engine

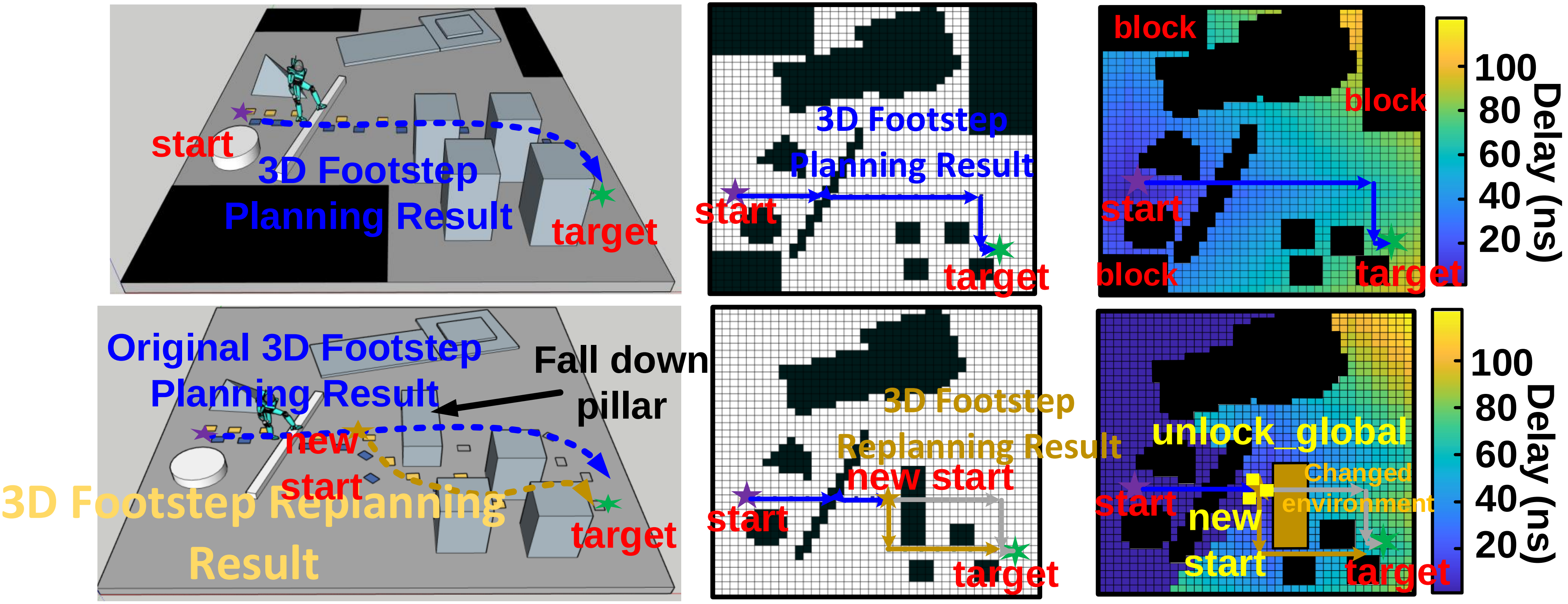


- A 40x40 vertex array is deployed for mapping information
- Each vertex consists of eight directions
  - four planar directions & four 3D directions

D* Algorithm: 3D Footstep Planning

Example of footstep replanning

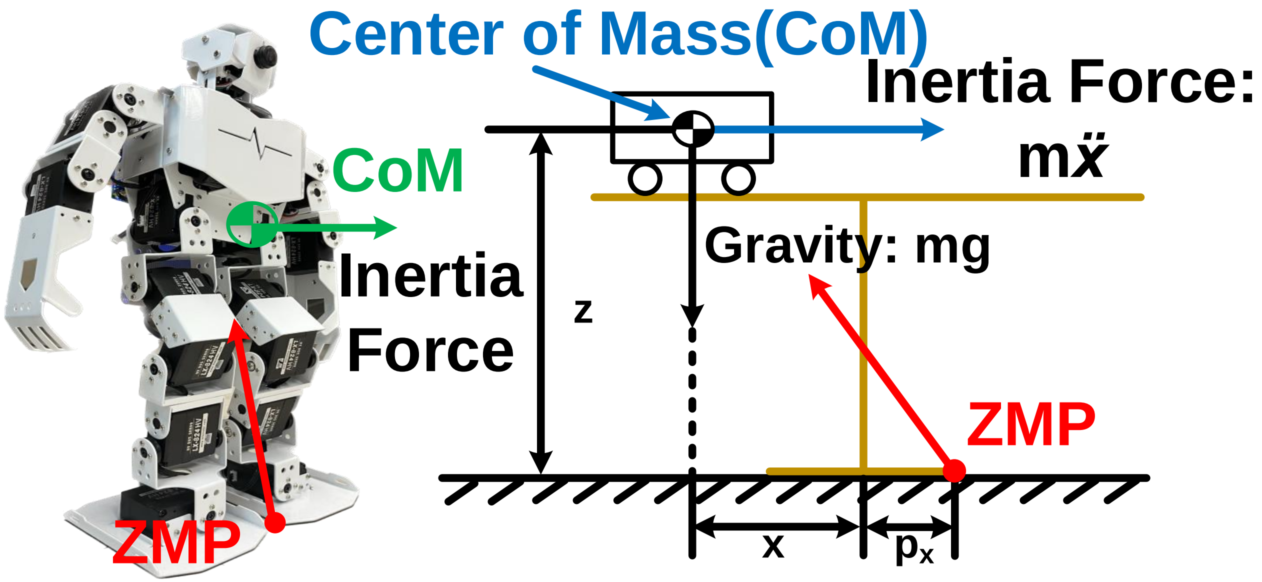
Time-domain Wavefront Propagation



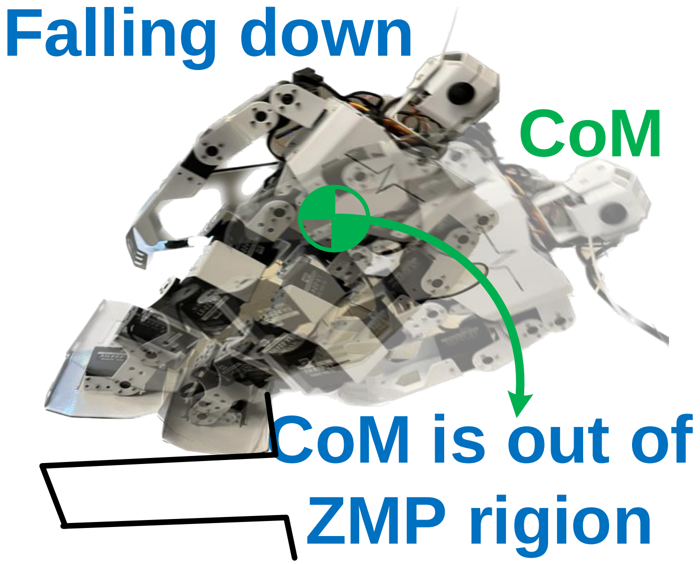
- Time-domain Graph Search Engine
  - 10.5X improvement over digital counterpart

Zero Moment Point (ZMP) Gait Scheduler for Balancing

Cart-table model



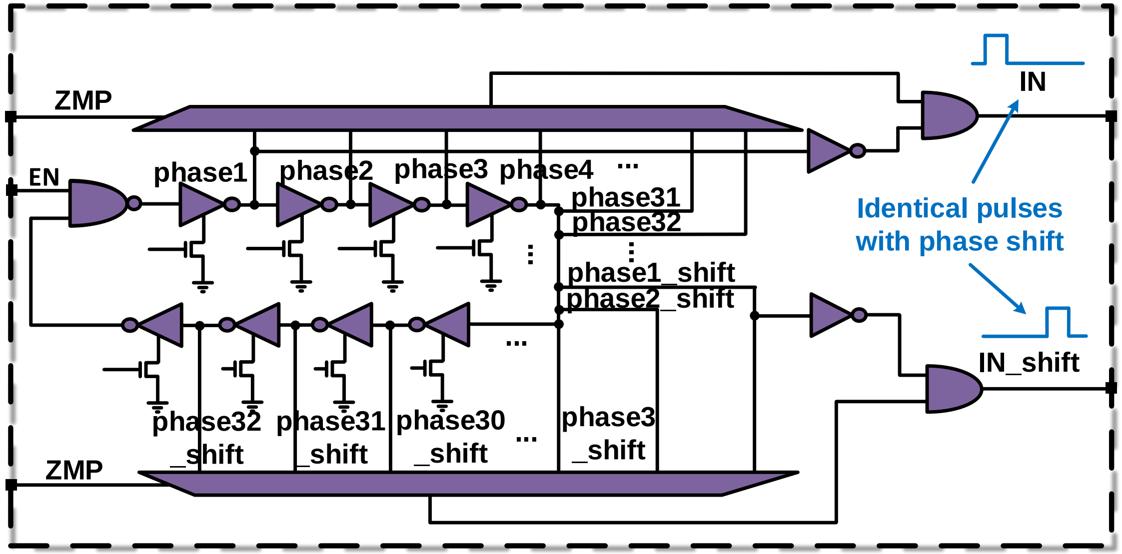
$$\tau_{zmp}=mg(x+p_x)-m\ddot{x}z_c=0$$



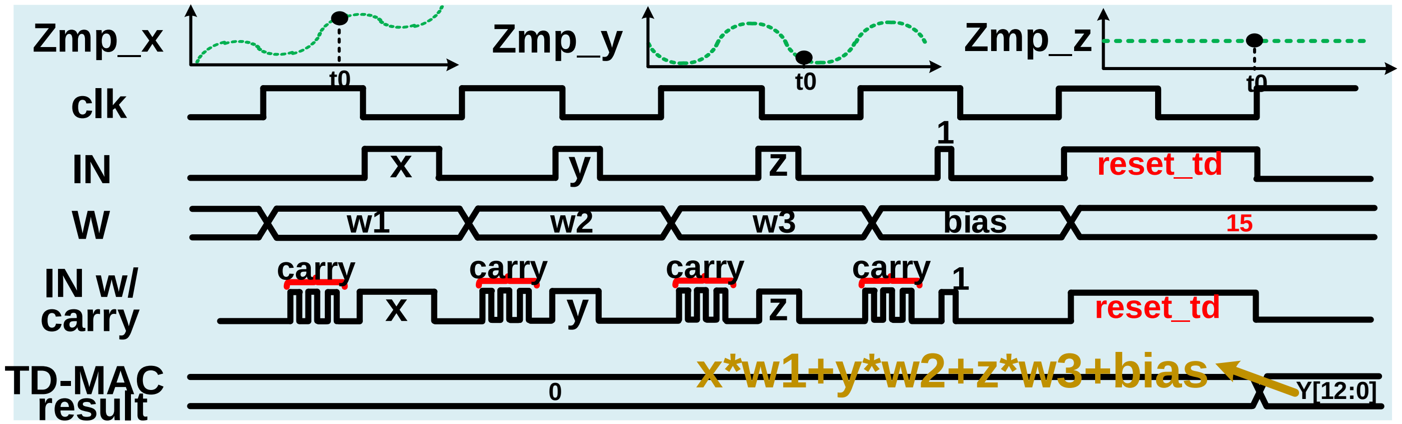
- Balancing for fall prevention
- Zero moment point of the cart-table model
  - robot’s total moment at the ground is zero

Mixed-signal Circuit for ZMP-based Fall Prevention

Circuit implementation



Waveform of ZMP phase generator



- Synthesize the targeted sinusoidal-like CoM trajectory
  - 3.4X power saving compared with equivalent digital counterpart

Neuro-Kinematics for Complex Inverse Kinematics

$$\theta_1 = -\arctan\left(\frac{Y}{Z}\right)$$

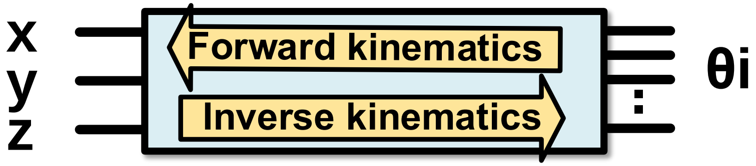
$$\theta_2 = \arctan\left(\frac{L_2\sin(\theta_2)}{L_2\cos(\theta_2) + L_3}\right) + \arcsin\left(\frac{X}{D_{ft}}\right)$$

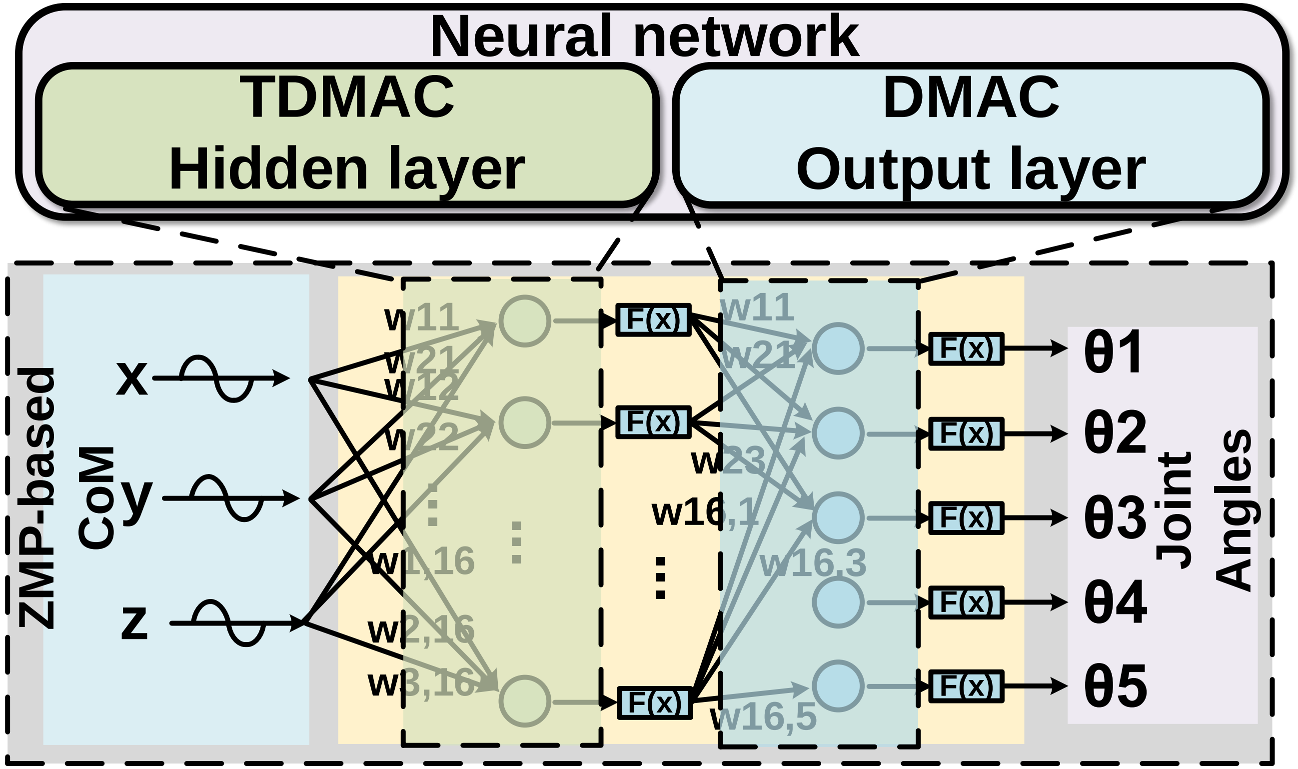
$$\theta_3 = \arccos\left(\frac{D_{ft}^2 - L_2^2 - L_3^2}{2L_2L_3}\right)$$

$$\theta_4 = \theta_1 - \theta_2 + \arcsin\left(\frac{X}{D_{ft}}\right)$$

$$\theta_5 = \arctan\left(\frac{Y}{Z}\right)$$

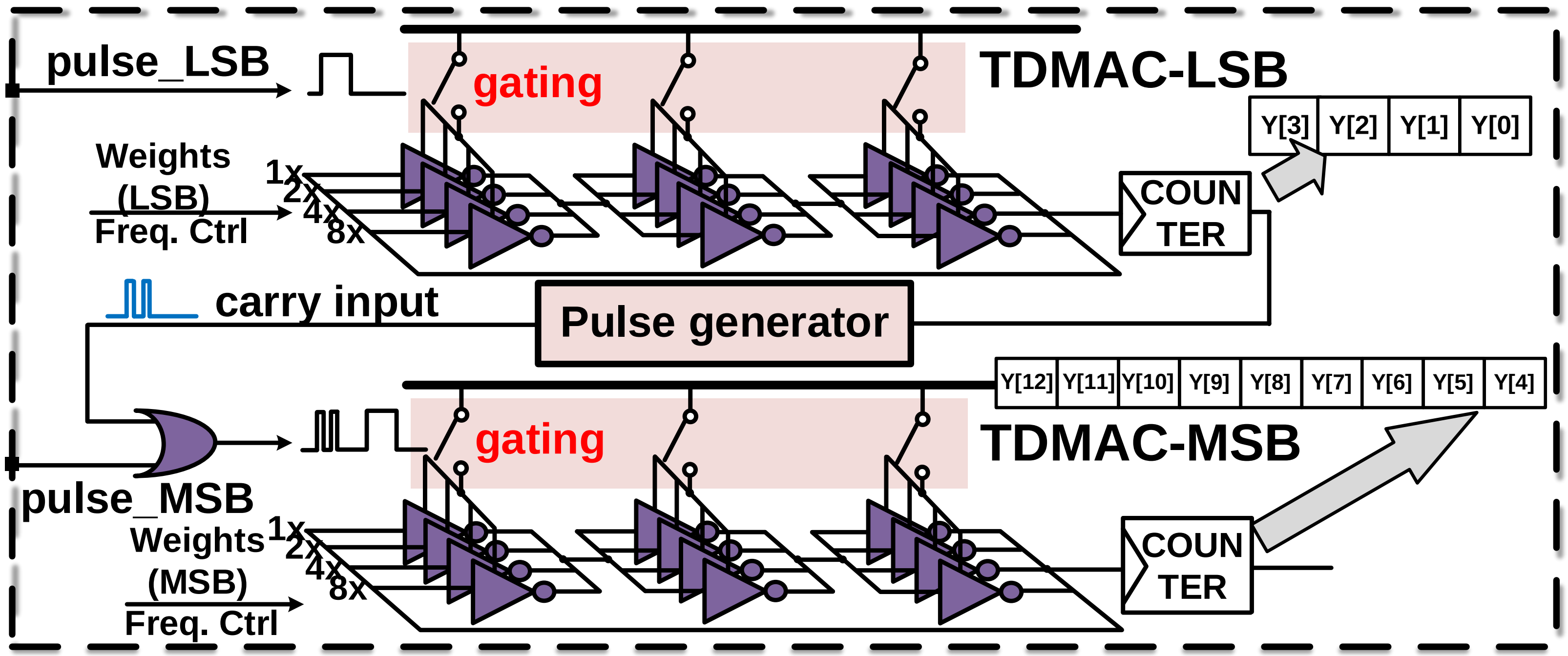
Cartesian Space Joint Space

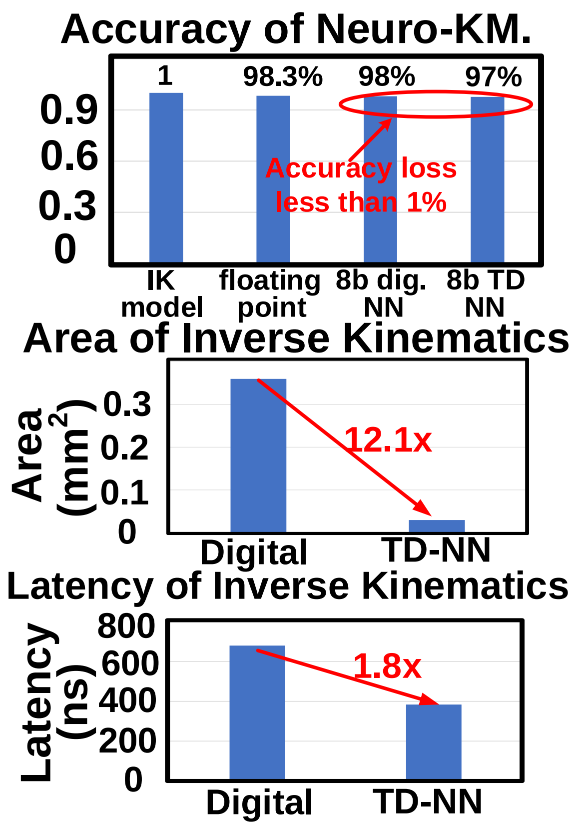




- A neural network is used to approximate the calculation
  - 21.8X energy saving over complex trigonometric calculation

Hardware Implementation of Neuro-Kinematics

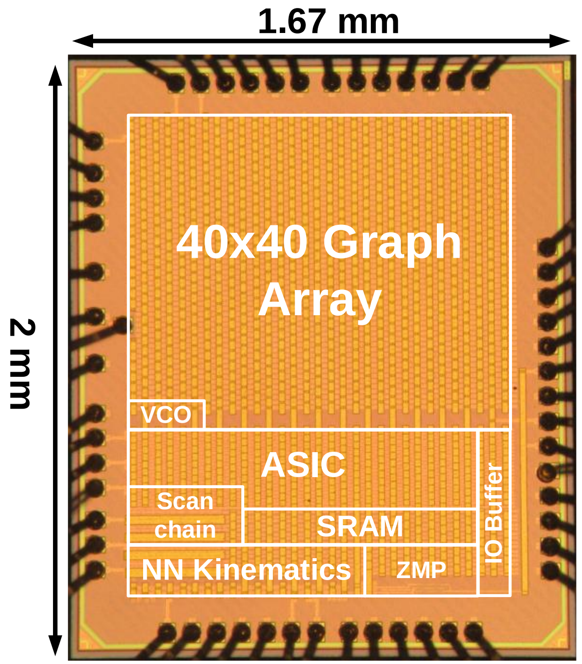




- A hybrid neuro-kinematic circuit consists of 8-bit MAC
- A 2% loss of accuracy is observed using neuro-kinematics

Chip Implementation and Comparison Table

Chip die photograph



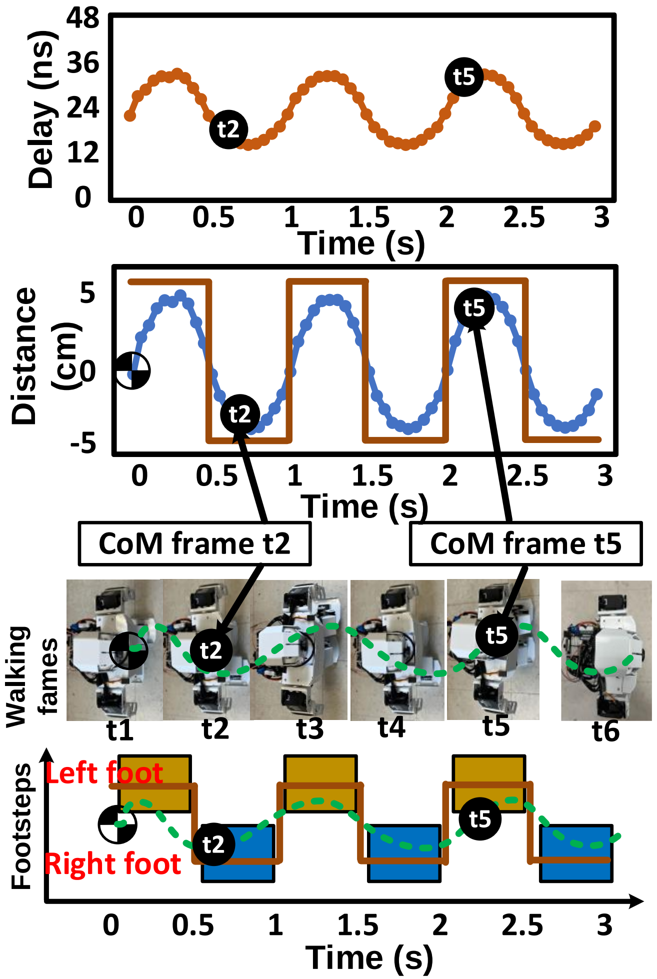
		ISSCC'18 [3]	ISSCC'20 [4]	ISSCC'19 [5]	ISSCC'23 [6]	This work
Application		A* shortest path	SLAM	Swarm intelligence	Motion control	3D footstep planning+ Motion control
Hardware		65nm/Time	Mixed-signal	65nm	28nm/Digital	65nm/MS Time
Graph size		40 x 40	7x7	-	-	40 x 40
Total area (mm^2)		0.4	5	2	3.56	3.34
Memory size		2.3 kB	37.9 kB	16 kB	-	22 kB
Frequency		-	78.2-130.8MHz	1kHz-1.5MHz	200MHz	1MHz
Peak Power		26.4 mW	17.87mW	3.4uW	142mW	432.8uW
Energy Efficiency	for control	-	-	-	35 Hz/mW	645 Hz/mW 1)
	for NN	-	8.0 TOPS/W	1.1-9.1TOPS/W	-	3.2 - 6.5TOPS/W
Path Planning	Energy per task	1166.2 pJ 2)	-	-	-	424.7 pJ
	Search Rate (edges/sec)	559M 3)	-	-	-	910M 3)

1) Efficiency for control = Control rate/Power (20Hz control rate is used in this work from motor spec.)
2) a 55% cache access energy is used as reported in [3] 3) MTEPS=Million Traversed Edges Per Second

- The Very First Humanoid System-on-Chip Design
- A 18.4x improvement is achieved on energy efficiency of motion control over prior work
- A 2.7X improvement is achieved on energy per task for path planning over prior work

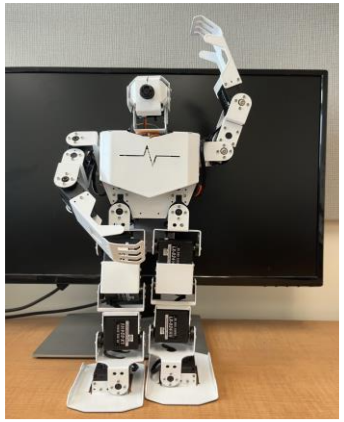
Demonstration on Humanoid Robot

ZMP-based CoM trajectory

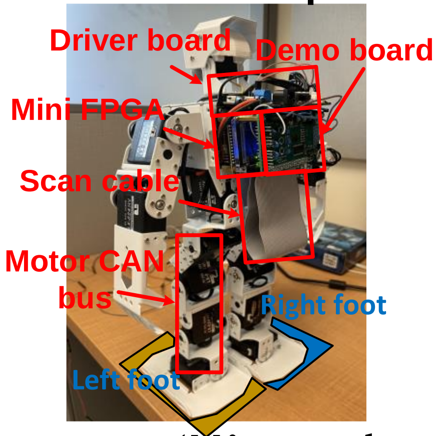


Robot assembly

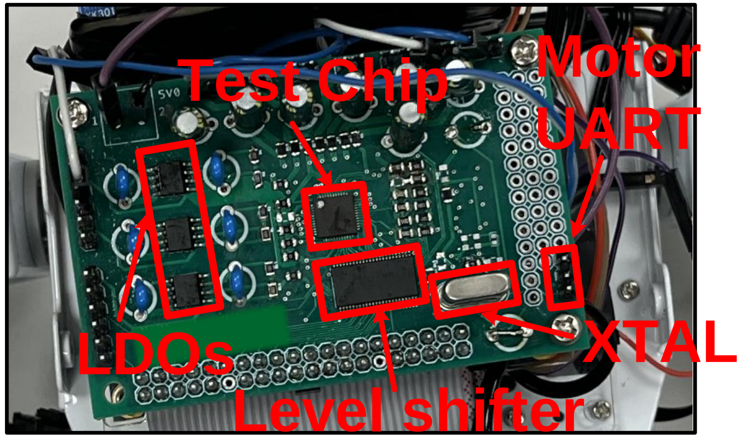
Front view of robot



Back view of robot and foot steps

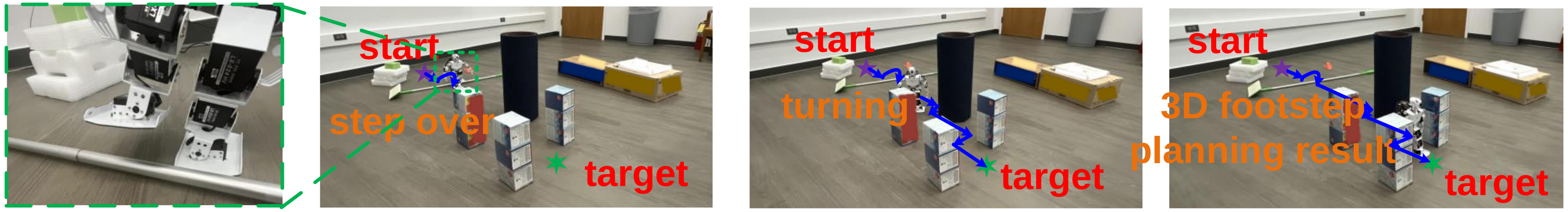


Demo Board



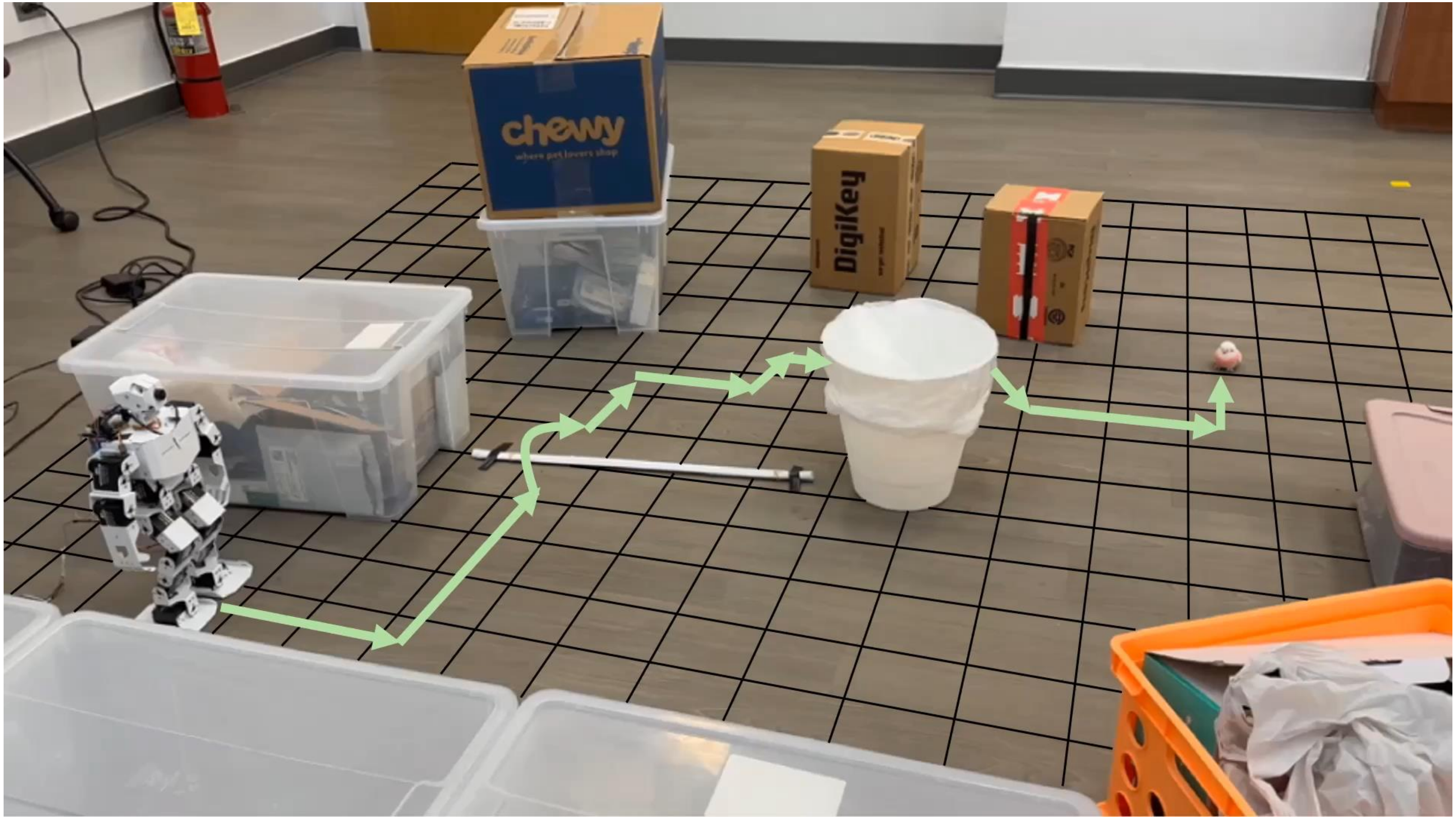
(Hiwonder Robot)

Demonstration



Zoom in view of stepover T0 T1 T2

Demo Video



Conclusions

- This work presents the first footstep planning SoC for humanoid robot
- A time-domain graph search engine for 3D footstep plan is proposed
  - 10X latency improvement over digital solution
- A mixed-signal ZMP-based gait scheduler for robot balance
  - 3.4X Saving over digital solution
- A mixed-signal neuro-kinematic module for inverse kinematics
  - 21.8X improvement over inverse kinematics
- A 2.7X~18.4X improvement is achieved on energy efficiency over prior work

Thank You!