Mobile Robots (Legged)

(Take class notes)
Legged mobile robots

• Mobile robots are robots which can move
• There are two types of mobile robots
  - Legged – two, four, six and eight legs
  - Wheeled – one, two, three and four wheels
• Legged mobile robot has a longer history than manipulators
  - Professor Robert McGhee developed the first walking machine at USC in the 1960’s – he later joined OSU
  - At OSU he developed the hexapod walking robot

Phony Pony

OSU Hexapod
Legged robots were also developed by industry such as the Walking Truck by Ralph S. Mosher of General Electric under a commission from the US Army in 1966.

ASV (adaptive suspension vehicle) developed by OSU in the 80s
Humanoid robots – booming in recent years

- SARCOS
  USA
- Toyota
  Japan
- ASIMO
  Japan
- HUBO
  Korea
- Honda
  Japan
- AIST
  Japan

Toyotas
Japan
Legged robot fundamentals

• Kinematics, inverse kinematics and dynamics of legged robots are similar to robot manipulators, but more complicated
• Consider the body as a mobile “base” and each leg as a manipulator

You can attached a coordinate frame to each link of a limb using the Denavit-Hartenberg convention – do you still remember?
Control the motion

• You need to specify the motion of the body first:
  - The position and orientation of the body in the earth frame: \( ^E T_B(t) \)
    which is function of time
• Then you can specify the position and orientation of each foot with respect to the body according to the required body motion: where \( m = 1, 2, 3, 4, 5, \) or 6

\[
^B T_{Fm}(t) = \begin{bmatrix}
  n_{Fx} & o_{Fx} & a_{Fx} & p_{Fx} \\
  n_{Fy} & o_{Fy} & a_{Fy} & p_{Fy} \\
  n_{Fz} & o_{Fz} & a_{Fz} & p_{Fz} \\
  0 & 0 & 0 & 1
\end{bmatrix}
\]

• The goal is to achieve \( ^E T_B(t) \) through the motions of individual feet
• Collaborated motions of the feet form a gait
Walking gaits

• Animals use a few types of gaits
  - Walk – trot; run – gallop: difference?
  - Gaits are naturally designed to achieve both stability and efficiency
  - In general animals use static or dynamic walking gaits: difference?
    - Static: center of gravity (COG) always falls in a supporting area
    - Dynamic: COG temporarily falls out of the supporting area periodically
  - Running is dynamic
Consider a quadruped gait – using footprints

Stability margin = shortest distance between the COG and the boundary of the supporting area

Which one has better stability margin?
Use trot gait - stability margin is small

Direction of motion
Duty factor

- Duty factor is the percentage of the cycle which a foot is on the ground.
- If the duty factor is greater than 50%, a gait considered as walk, while the one less than 50% is considered run.
- For the two quadruped gaits, the duty factor is greater than 75% - walk: RF: right forelimb, RH: right hindlimb.
Human biped locomotion

- The first paper on human biped locomotion I read is:


- The paper analyzes the human locomotion as a phenomenon of the most extraordinary complexity using connected rigid bodies for illustration – *six determinants in locomotion*
Human locomotion – six determinants

Fig. 10: If the limbs were parallel, there would be excessive lateral displacement of the center of gravity.

Fig. 11: Through the influence of a tribiafemoral angle and of inclination at the hip joint, excessive lateral displacement is corrected.

Fig. 12: The sign of the effects of the several determinants on the pathway of the center of gravity is viewed in true phase relationship.

Compass gait
Six determinants of human locomotion (1)

- **Pelvic rotation**
  - The pelvic rotates about $4^\circ$ in either direction during double support. As a result, the limbs are essentially lengthened in the would-be lowest point of the gait cycle to prevent a large drop of the COG

- **Pelvic tilt**
  - The pelvic on the side of the swinging leg tilts about $4^\circ$–$5^\circ$, which lowers COG at mid-stance

- **Knee flexion at mid-stance**
  - The bending of the knee reduces the vertical elevation of the body at mid-stance by shortening the hip-to-ankle distance
Six determinants of human locomotion (2)

• Foot and ankle motion
  - Ankle motions smooth the pathway of the COG during stance phase

• Knee motion
  - When the ankle is depressed, the knee extends, and when the ankle is elevated, the knee flexes. Knee motion in this way smooths the pathway of the center of mass and thus conserves energy.

• Lateral pelvic displacement
  - Displacement of pelvic towards the stance foot to make sure that the COG is supported by the foot

• Human locomotion is much more complicated than we thought
• The purpose is to make your locomotion most efficient and smooth
Humanoid robots

- Humanoid robot was first developed in Japan in 1973
- In the U.S. first one was CURBi developed in 1986

WABOT-1 – Wasada Un.

CURBi Robot – now at OSU
Consider kinematics and dynamics of human locomotion

• How many degrees of freedom: considering only the lower body – legs and pelvis?
  • Ankle – 3
  • Kneel – 1
  • Hip – 3
  • Total for two legs – 14

• How many degrees of freedom when one foot is in the air?

• How many degrees of freedom when both are on the ground?
  • Number of degrees of freedom – number of constraints
Constraints to robot motions

- When the robot end-effector touches the environment, its motion is constrained. Depending on how it is constrained, the robot loses degrees of freedom
- If the foot cannot move at all – lose six degrees of freedom
- If the foot has to touch the ground only (ballet dancer) – lose three degrees of freedom
- Now consider why the six determinants by the human locomotion is possible from the kinematic point of view
  - Fundamentally during your locomotion, you control the position and orientation of your body such that the COG fluctuates the minimal
  - From the above discussion it is possible when one leg is swinging
  - When both feet are on the ground, it is still possible (14-6 = 8)
Consider dynamics

- It is more difficult since there are more degrees of freedom and there is no base
- We still can use Newton-Euler equations (Homework 11)
- Consider the three link system (mass only), one may have:
  \[ F_1 = M_1 \ddot{X}_1 - M_1 G \]
  \[-F_1 + F_2 = M_2 \ddot{X}_2 - M_2 G \]
  \[-F_2 + F_3 = M_3 \ddot{X}_3 - M_3 G \]
  \[ \tau_1 = F_1 \times \left( \frac{1}{2} \right) L_1 \]
- You need to express \( x_n \) in terms of \( \theta_n \) such that the dynamic equation will be in the form of
  \[ \tau = M(\theta) \ddot{\theta} + V(\theta, \dot{\theta}) + G(\theta) \]
Zero moment point (ZMP)

- Zero moment point (ZMP) is a classical concept and has been used in the programming and control of humanoid robots for a long time.
- It specifies a point, about which the moment of the ground reaction forces should be zero; or alternatively the moment due to the inertia and the gravity forces is zero.
- If the ZMP is in the supporting area, the humanoid robot is stable; otherwise, it is not.
- A humanoid robot cannot be in the none stable case for too long.
ZMP Equations (reaction forces)

Newton-Euler equations:

\[ cF = ma_G - mg \]
\[ cM_X = \overrightarrow{XG} \times ma_G - \overrightarrow{XG} \times mg - \dot{H}_G \]

- The ground reaction force is responsible for providing \( cF \) and \( cM_X \) in the opposite direction

\[ cF = -g_i F \quad cM_X = -g_i M_X \]

- Since \( cM_X \) is related to the reference point \( X \), the point \( Z \) is defined as ZMP if:

\[ g_i M_{zmp} \times n = 0 \]
Legged robot examples

- Hubo crosses over 2x4 and 4x4 bars
Legged robot examples