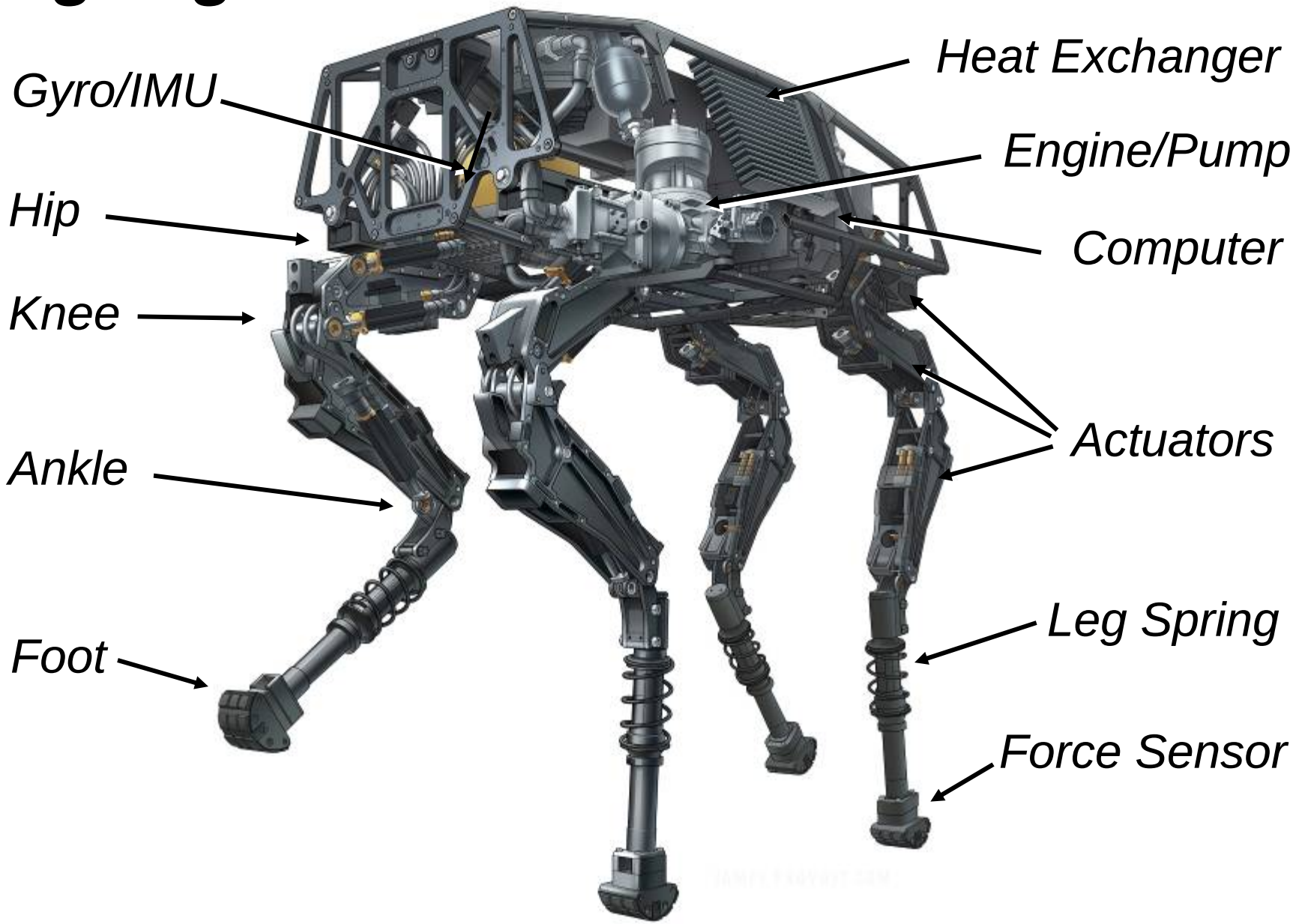
BigDog Overview

November 22, 2008

BigDog Architecture

Boston Dynamics



Engine

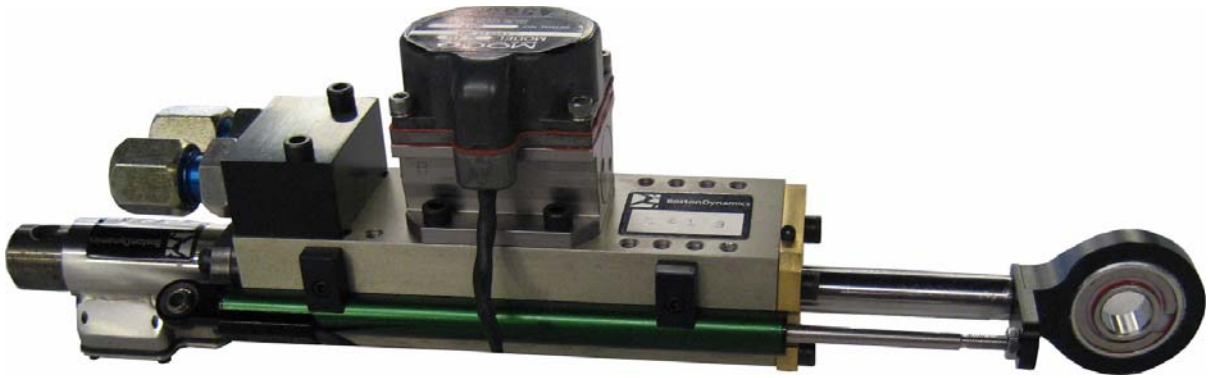
Boston Dynamics

- Leopard go-kart engine
- One cylinder
- Two stroke
- Water cooled
- 9,000 rpm
- ~15 hp
- Electric starter

Hydraulic System

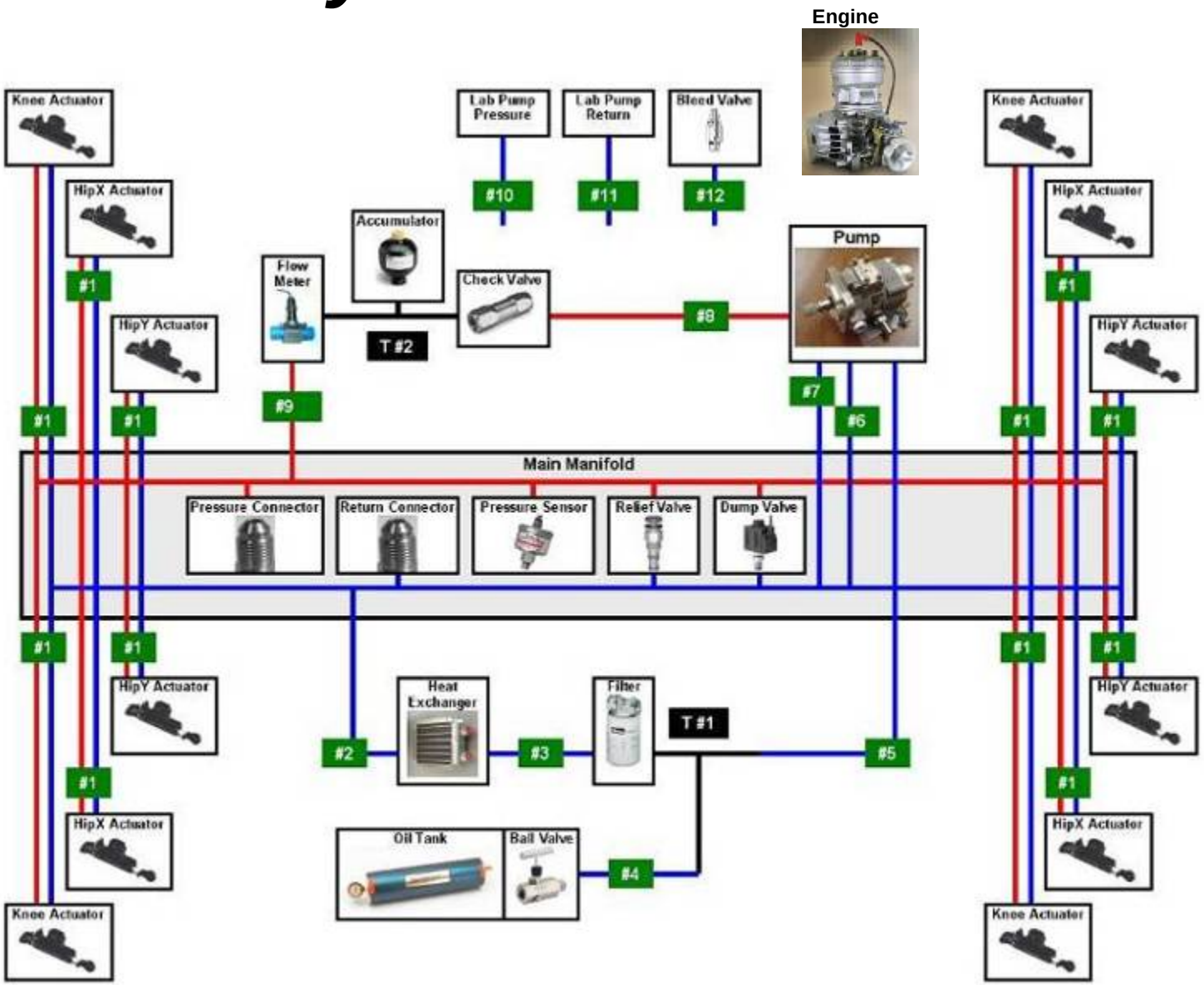
- Variable displacement hydraulic pump (3,000 psi)
- Custom actuator package (x16)
  - Low-friction hydrodynamic seals
  - 2-stage electro-hydraulic servovalve
  - Position sensor
  - Force sensor
- Heat exchanger
- Various filters, manifolds, accumulators, and valves

Hydraulic Actuator Package



Hydraulic System

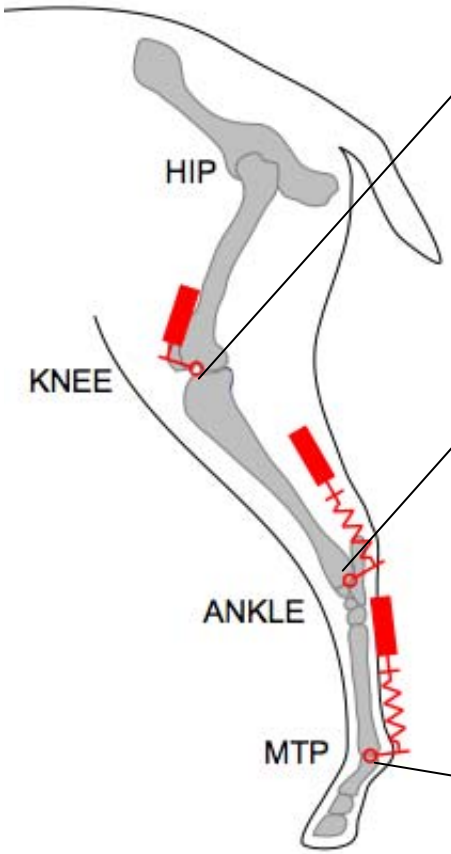
Boston Dynamics



Multi-jointed Legs

Boston Dynamics

Animal



Actuation

Compliance + Actuation

Compliance + Dissipation

Less actuation

More compliance

BigDog

Actuation

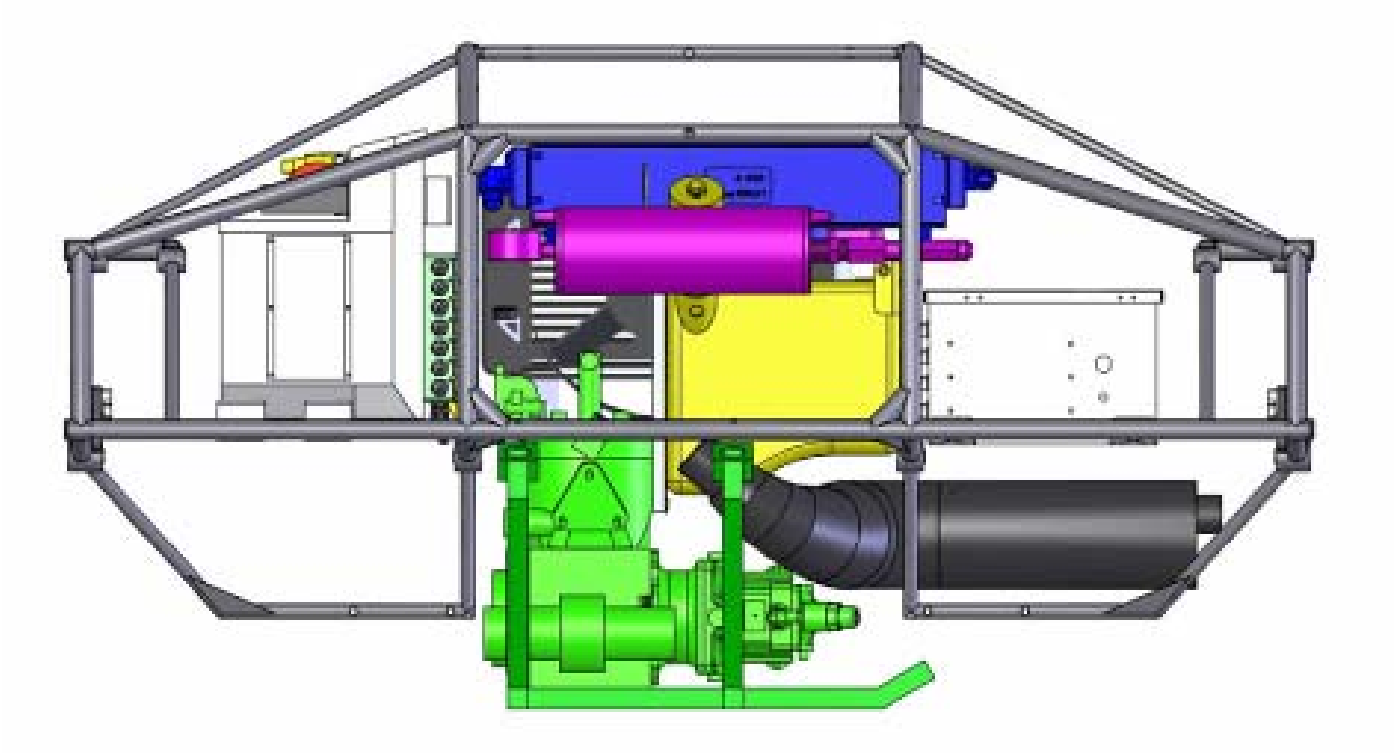
Compliance + Actuation

Dissipation

CONCORD FIELD STATION
HARVARD UNIVERSITY

Component Layout

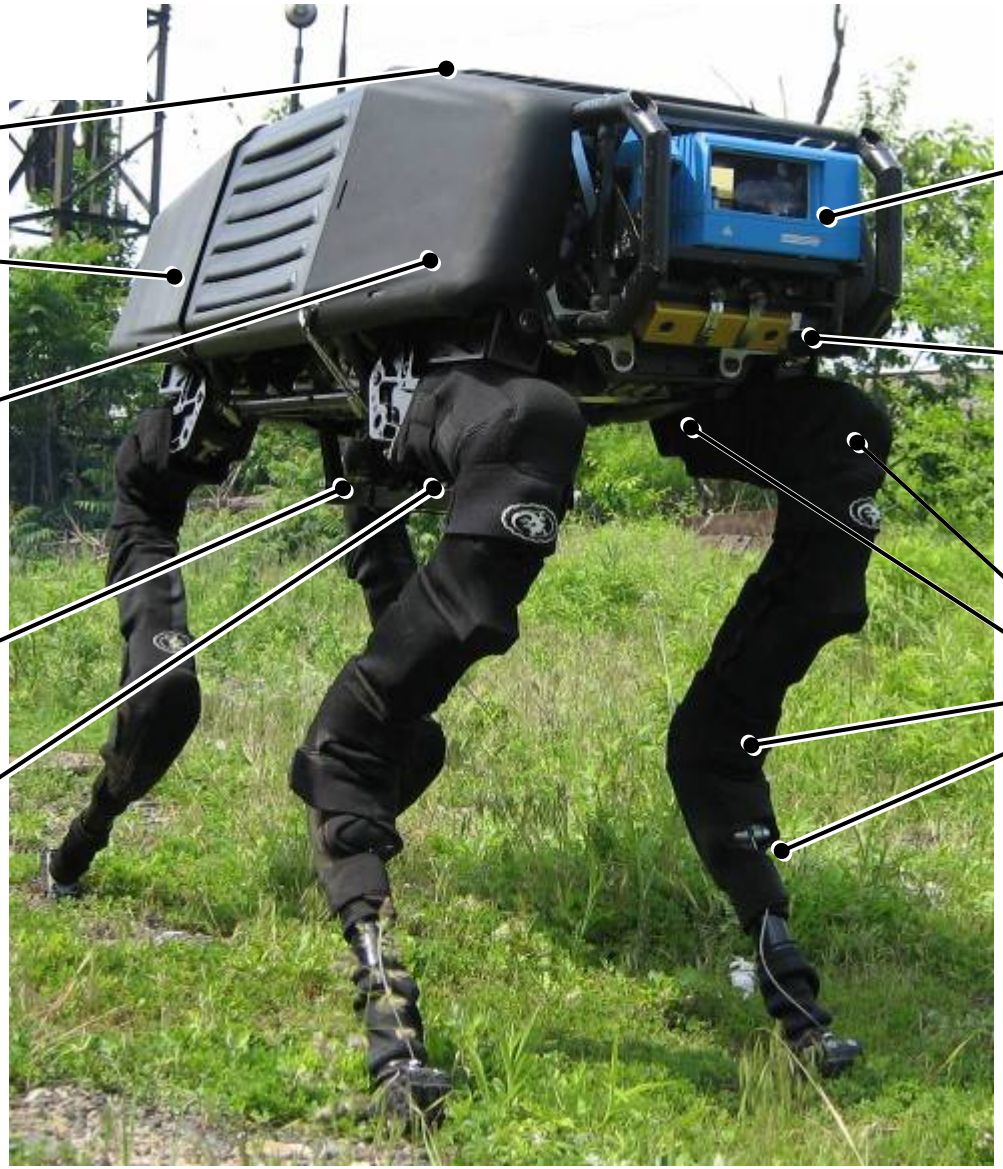
Boston Dynamics



Component	Weight
Heat Exchanger	9.62 lbs
Engine / Drive / Pump:	26 lbs / 1.42 lbs / 6.5 lbs
Fuel tank / Fuel:	2.1 lbs / 10.4 lbs
Oil tank:	3.6 lbs

Sensors

Boston Dynamics



BigDog Sensors

Boston Dynamics

Type	Measurement Quantity	Location	N
Linear Pot	Joint displacements	Knee, Hip (2), Ankle	16
Load Cell	Actuator, ankle force	Legs	16
Current Sensor	Servo valve current	eBox	16
Stereo Vision	Obstacles, Optic Flow Ground Slope	Body	3
LIDAR	Human Tracking	Body	1
Gyro	3 angular rates 3 linear accelerations	Body	6
Temperature	Engine, Oil temperature	Body	3
Flow	Oil flow	Body	4
Pressure	Oil pressure	Body	2
Governor	Engine RPM Battery voltage	Body	2
Total			**69**

Proprioception

Exteroception

Homeostasis

Onboard Computer

Boston Dynamics

- PC104 stack
- Pentium CPU
- QNX real-time OS
- Code: C++
- Custom I/O interface boards
- Functions Performed:
  - Control
  - Sensing
  - Data Collection
  - Communications
  - Electric Power Distribution

Software Architecture

Boston Dynamics

HUMAN FOLLOWING 10Hz
- LIDAR
- Object Tracking
- Terrain Map
- Visual Odometry

PLANNING 2Hz
- Position
- Terrain Map
- Laser Data
- Cost Map
- Planned Path
- Smoothed Path

DATA LOGGING 200Hz
- 30 Sec Fault Log
- Long Term Data Log 5k vars

POSE ESTIMATION 200Hz
- IMU
- GPS
- Visual Odometry
- Leg Kinematics
- World Position, Orientation

CONTROL 200Hz
- IMU
- Smoothed Path
- Joint Data
- Steering Command
- Gait Control
  - IK
  - TDLO
- Actuation Commands

802.11

Engineering Interface

DEVICE DRIVERS 1kHz
- IMU
- Joint Data
- LIDAR
- GPS

ACTUATION 1kHz
- Position Servos
- Force Servos

900 MHz RF

Operator Interface

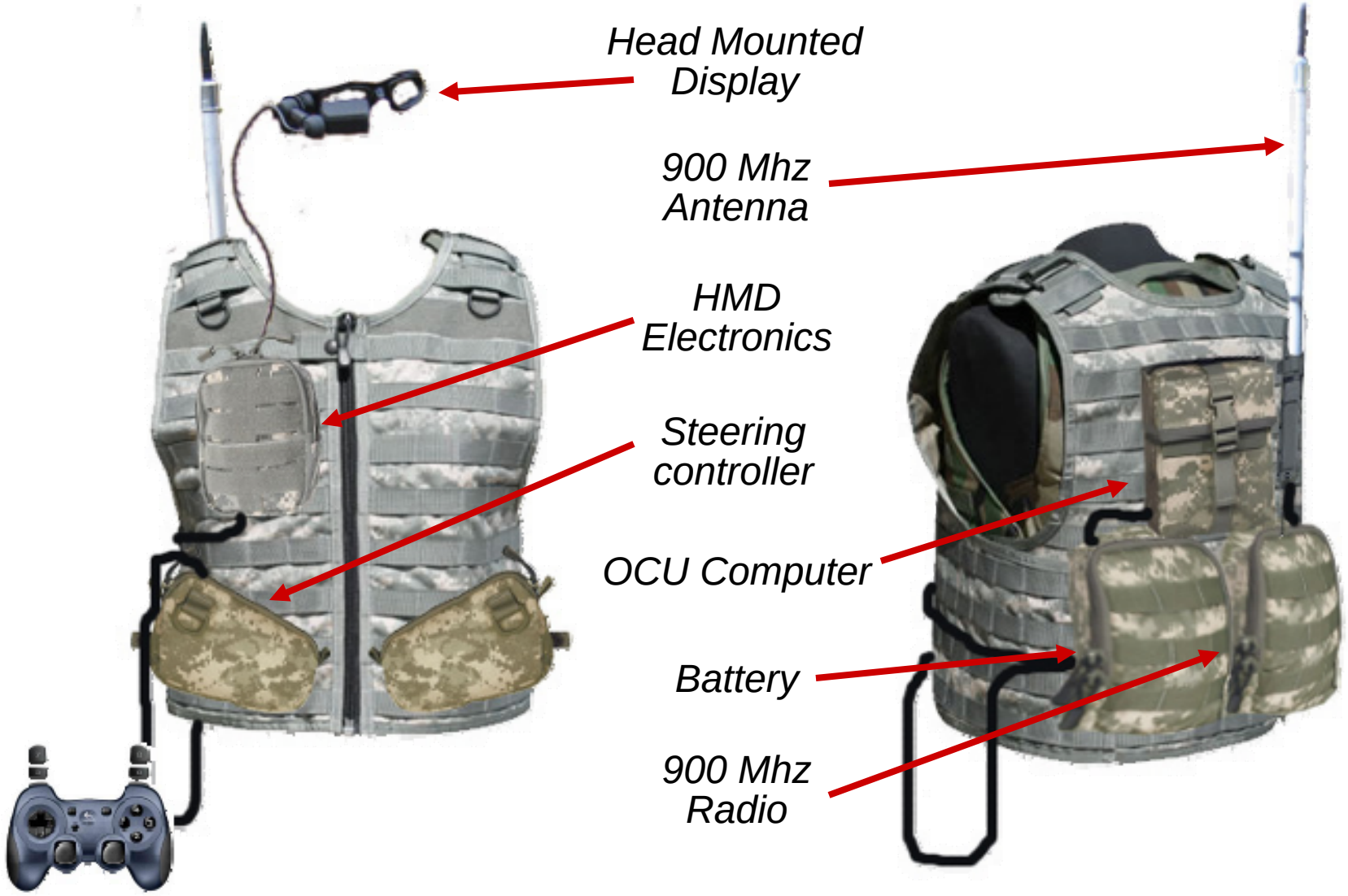
Software Processes

Boston Dynamics

Function:	**Control**	**Servo**	**Logging**
Description:	Main process. Balances and steers robot, odometry, communicates with operator.	Joint control, read sensors, command actuators, engine control.	Log engineering data for performance development and failure analysis.
Update Frequency:	200 Hz	1,000 Hz	200 Hz

Vest Operator Control Unit (OCU)

Boston Dynamics



Control Principles

Boston Dynamics

***Support** - Bounce on springy legs*

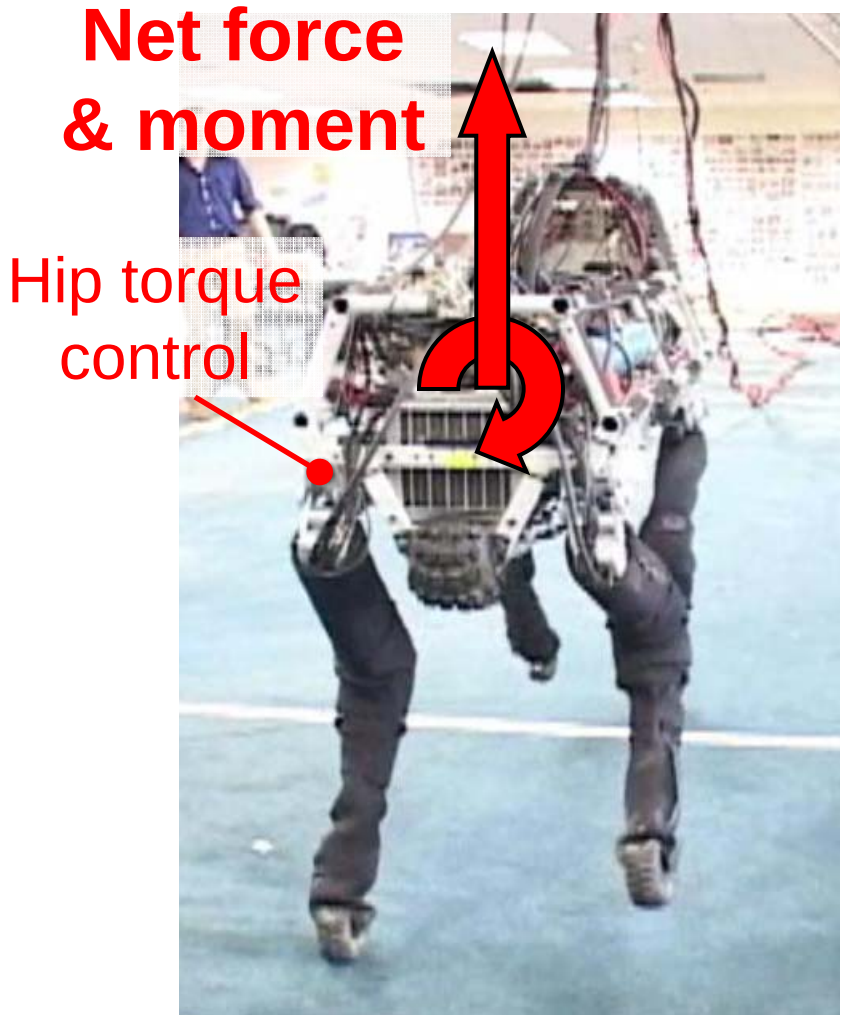
***Balance** - Move legs with symmetry to achieve balance*

***Posture** - Keep body level using stance legs*

Control – BigDog

Maintain Body Posture

- Control of body posture through force control



Control – BigDog

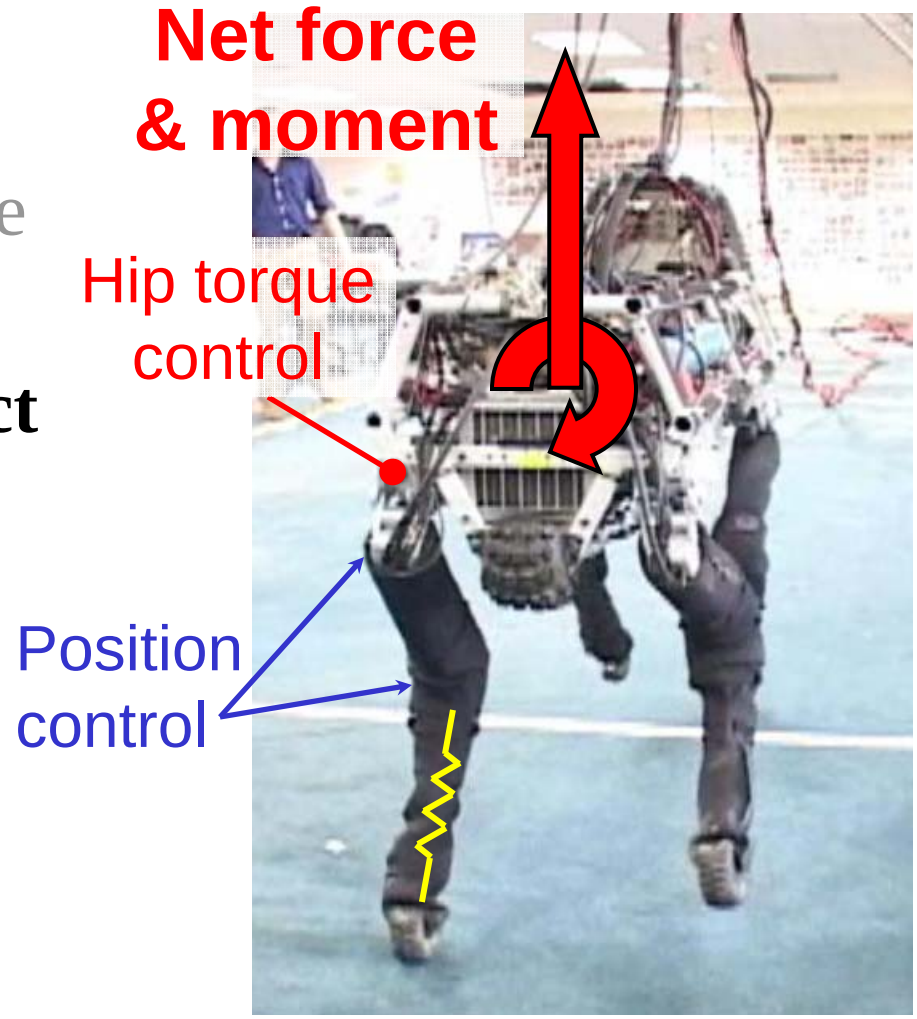
Boston Dynamics

Maintain Body Posture

- Control of body posture through force control

Maintain Ground Contact

- Force control through compliant leg shock



Control – BigDog

BostonDynamics

Maintain Body Posture

- Control of body posture through force control

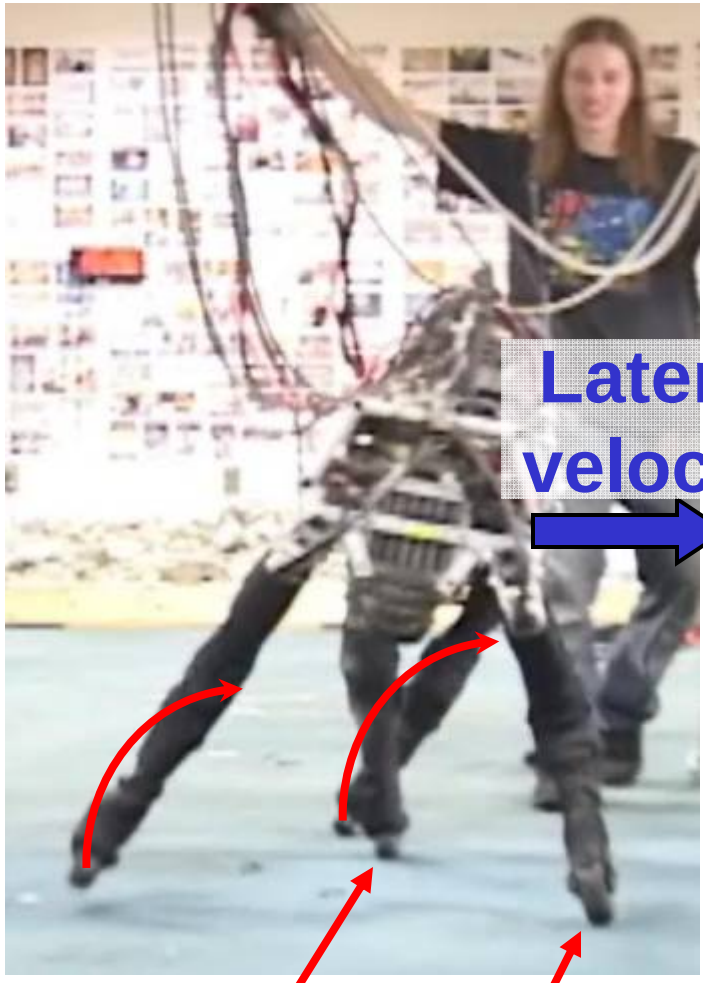
Maintain Ground Contact

- Force control through compliant leg shock

Maintain Lateral Balance

- Place feet to control body lateral velocity

Stance leg motion predicts lateral veloc. and accel. for swing leg placement



Additional Controls

Boston Dynamics

- *Estimate ground plane using history of leg kinematic data and odometry*
- *Adjust posture to optimize leg strength while maintaining reach on terrain*
- *Use traction control to avoid, detect and recover from foot slips*
- *Move legs to avoid leg collisions*
- *Determine ego-motion using kinematic, inertial and visual odometry*

Trot Control Features

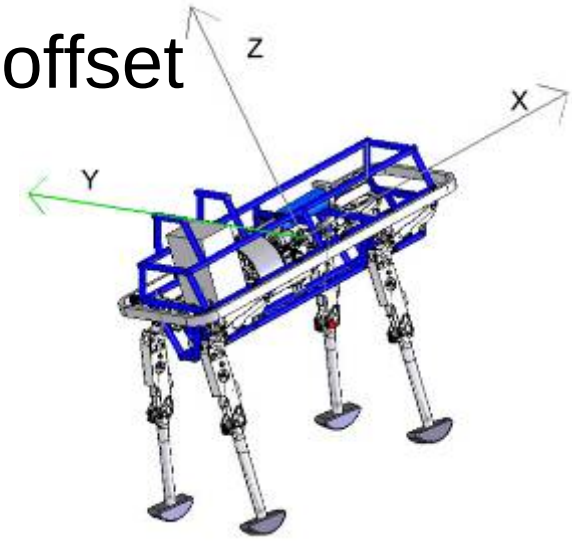
Boston Dynamics

- Engine Power Control.
  - Engine RPM regulated in response to actual and predicted load.
  - Ground steepness, ground roughness, and lateral body velocity predict demand.
- Leg Collision Avoidance.
  - Adjacent legs have overlapping workspace.
  - Swing leg trajectories avoid hitting adjacent stance legs.

Trot Control

BostonDynamics

- **X** – Closed loop. Speed error corrected by x direction foot forces.
- **Y** – Lateral foot position chosen to offset unwanted lateral body velocity.



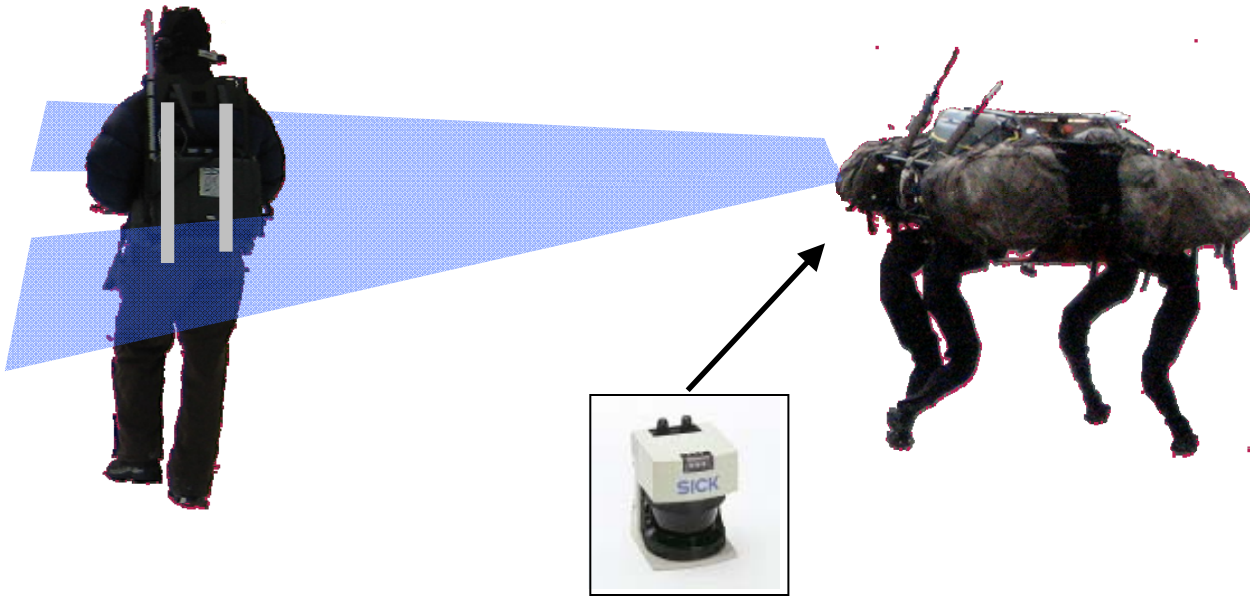
- **Z**
- **Roll**
- **Pitch**
- **Yaw**

Coupled Controller. Corrections for height and Euler errors map to y and z direction foot forces.

LIDAR Leader Tracking

Boston Dynamics

- Follow leader without direct driving and without GPS:
  - Leader wears retro-reflective marker
  - SICK LIDAR used to locate leader and generate steering signals
  - BigDog follows at approximate fixed distance

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