Legged Squad Support System (LS^3)

Industry Day

12 NOV 08 Arlington, VA

DARPA Tactical Technology Office (TTO)

Industry Day Agenda

0900 – 0920	Welcome & TTO Intro	Mr. David Neyland Director, DARPA TTO
0920 – 1020	LS^3 Program Brief	Dr. Robert Mandelbaum DARPA TTO LS^3 Program Manager
1020 – 1110	LS3 BAA	Mr. Christopher Glista DARPA CMO
1110 – 1200	Q & A Session	
1200	Adjourn	

Nature Inspired

Premise Validated

Mission Required

Legged Squad Support System (LS^3)

Industry Day Briefing

12 NOV 08

Robert Mandelbaum

Tactical Technology Office

Briefing Agenda

- **Program Overview**

  Concept, Objectives, and Vision

- **Related DARPA Efforts**

- **User Interface**

- **Platform Concept Design**

- **Controls**

- **Program Plan & BAA**

Concept

[redacted]

Motivation

Go where dismounts go

Do what dismounts do

Work among dismounts

Program Objectives

- **Carry 400lb of squad equipment**
  - ~50% of Army fires team or USMC squad
  - Keep platform squad sized for dismount maneuvers
    - Volumetric, weight, power, relevant payload constraints
  - Maintain large strength margin for long endurance
  - Provide mobile auxiliary power
- **Sense and negotiate terrain**
  - Perception on bouncing platform
  - Select gait and place feet based on perception of terrain
  - Follow a soldier 5-100m ahead or behind
  - Dynamic environments
  - Complex environments with many occlusions
- **Maneuver nimbly**
  - Multiple gaits coupled to perception and terrain
  - Robust stability for all gaits and gait transitions
- **Operate quietly when required, efficiently for endurance**

LS^3 is a technical solution to a most critical challenge for modern dismounted warfare: Weight and equipment burdens imposed on the dismounted squad

Vision:
Change what we bring to the fight

Goals

- Give the squad platoon-level capability and equipment
- Increase mission effectiveness of dismounted squads
- Bring more to the fight
  - Critical supplies - ammunition, medic equipment, water/food
  - Heavy weapons, mortars & rounds, ladders, forced entry gear
  - Equipment usually in tactical vehicles - Comms amps/radios, battery chargers, tactical network gear (e.g. Blue Force Tracker – brings it to squad tracking)
- Matched to the size and maneuverability of a dismount
- Simple, intuitive command and control

Fundamental issues

- Platform – integration, mechanical integrity, noise mgmt.
- User Interface – perception, following, interaction, dynamic scenes
- Control – stability, actuation sequences, placement, gaits

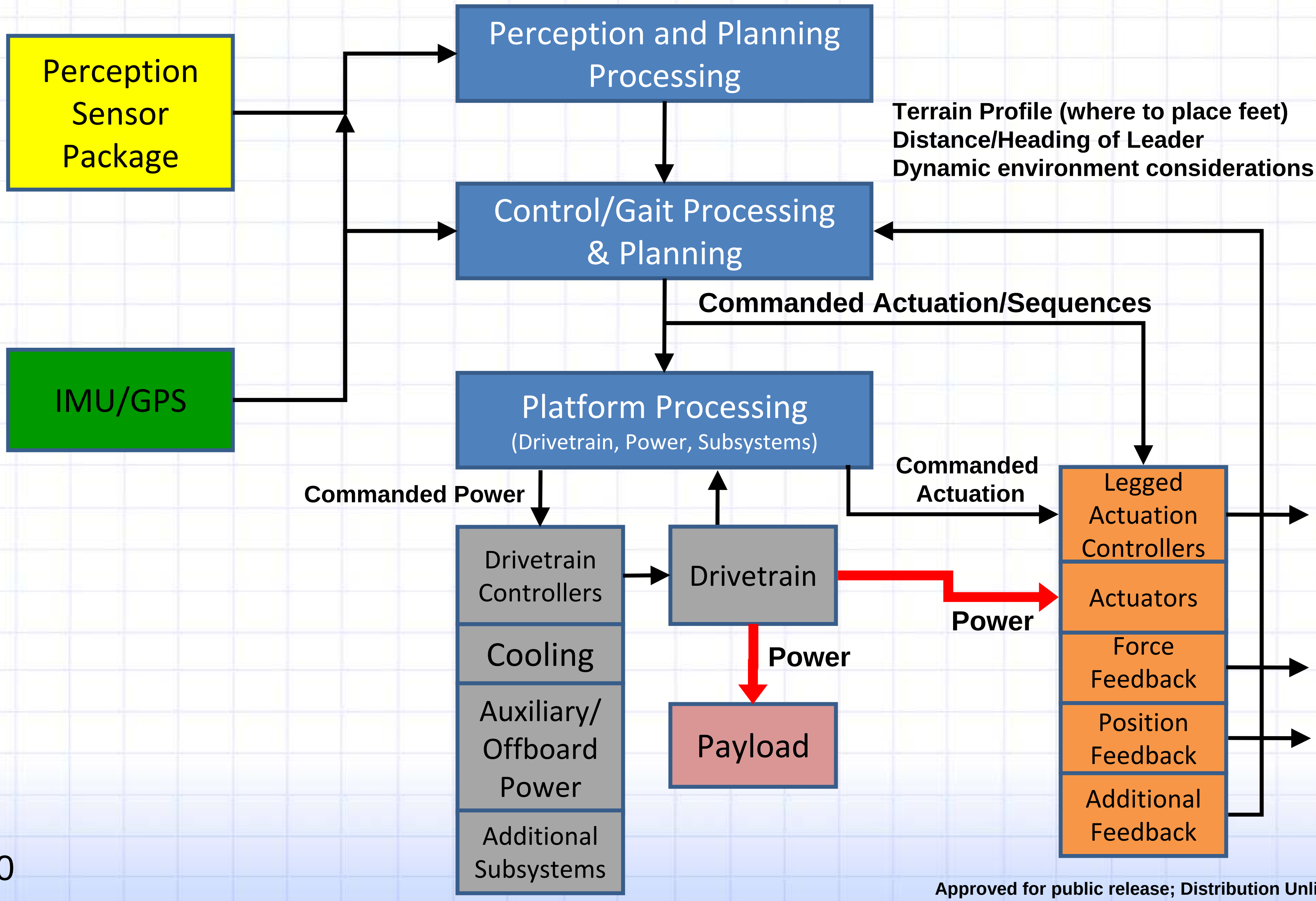
Goal is achievable

- Big Dog has demonstrated the feasibility of military-relevant legged platforms
- Key platform sub-components mature
- Fundamentals of perception demonstrated in less challenging environments

Program goals

	LS^3 Goal	BigDog	Mule
			
Payload	400 lb	80 lb	150 lb
Total Weight	1250 lb	355 lb	1000 lb
Range	20 miles	5 miles	18 miles
Endurance	24 hours	2 hours	8 hours non-stop walking
Speed	3mph walk,5 mph trot, 10 mph burst run	2-3 mph trot	2.5 mph, 5mph trot for very short periods
Autonomy	Follow leader at 100m Short-range landmarks, GPS	GPS	After 5-6 months, can walk the distance between camps unescorted
Terrain	25° incline, 25° sideslope 12" steps, Rugged	25° incline, no sideslopes 6" steps, Rugged	25° incline, 25° sideslope 12" steps, Rugged
Acoustics	70 dB, 40 dB quiet mode	~95 dB	30 dB
Other	Self-righting, 1 stowed in HMMWV/JLTV rear bed w/gear	Limited gaits, primarily human directed	Primarily human-led

LS^3 Block Diagram



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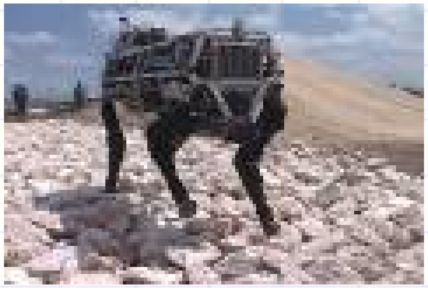
DARPA DSO/TTO BioDynotics: BigDog

Goal:

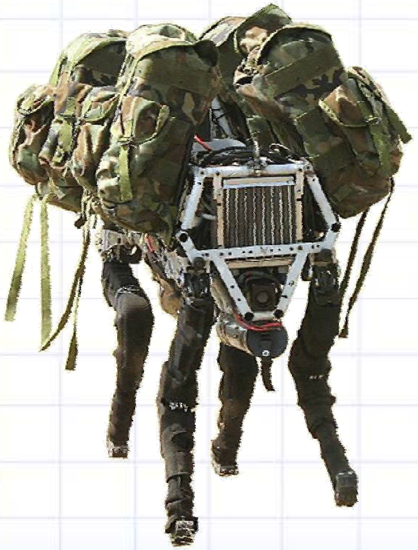
Develop a robotic capability that addresses the needs of dismounted soldiers

- Travel through rough natural and urban terrain
- Carry squad equipment and/or provide resupply



Program Effort

- 18 month Phase III effort – 2 BigDog platforms
- Phase III partnership and MOA with USMC
- Experiments against metrics in 2008



Program Accomplishment:

- First legged system to demonstrate the capability to move over terrain previously off-limits to unmanned systems

Next Step:

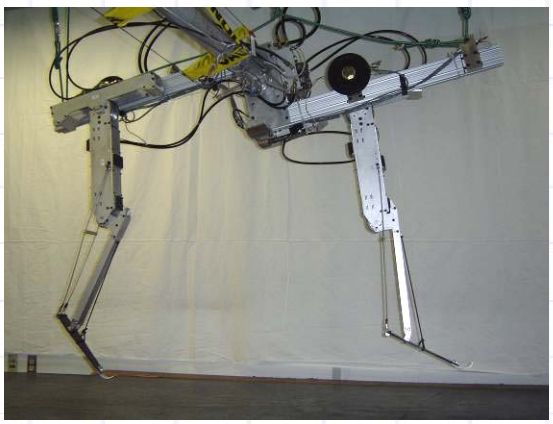
- Demonstrate the ability to haul mission appropriate loads over rough terrain at a speed acceptable to dismounted soldiers

Payoff:

Enhance the dismounted warfighter's capability by carrying heavy loads

BigDog
Platform & Phase Evolution

Phase I



2004 BigDog V1 (HalfDog)

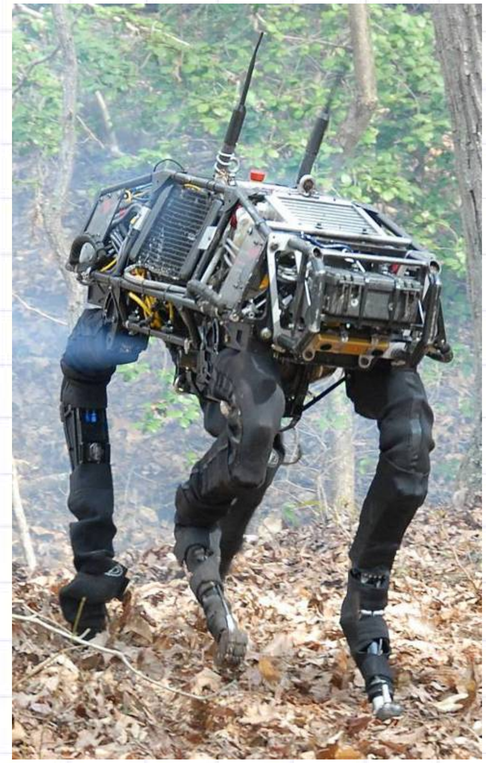
Legs:
- 2 actuated DOF
- 1 passive DOF

Phase II

2005 / 2006 BigDog V2

Legs:
- 3 actuated DOF
- 1 passive DOF

Phase III



2006 / 2007 BigDog V3
2007/2008 Big Dog V3.5

Legs:
- 4 actuated DOF
- 1 passive DOF

Service Partner: USMC

BigDog

May & Aug 2008 Testing at Quantico

Completed and achieved Phase III MOA Testing

- **Endurance - Hike following a leader**
  - 5 miles in 1h 56m uninterrupted, human following
  - 7.8 miles in 3 hrs, uninterrupted, human following
  - 35 miles @ ~2.5mph – total endurance testing w/interruptions

- **200 m climb on Guadalcanal trail with 80mm mortar**
  - Executed complete runs with no failures carrying weight
  - 12 for 12 repeatability
- **Limited Autonomous Navigation**
  - Achieved waypoints following pre-collected GPS paths
    - Ability to select waypoint via interface
    - BigDog starts engine, stands up, moves to waypoint, stops automatically
  - Ability to select new GPS waypoints (assuming no obstacles in its path)
  - Reliable Human Following in uncluttered environment

Big Dog
Testing at Quantico

Hiking Guadalcanal Trail

Big Dog
Testing at Quantico

Engineer's Road Endurance Run

May 2008 – 7.8 miles, 179 minutes

Big Dog
Preliminary walking gait

Travel over rough terrain

Big Dog
Stability

Recovery from slip

DARPA IPTO Learning Locomotion

- Goal
  - Develop a new generation of learning algorithms that enable high degree of freedom unmanned ground vehicles to traverse terrain containing large, irregular obstacles.
- Technical Challenges
  - Lack of perfect simulation
    - Legged robots have a long history of promising results in simulation that do not work on real robots
      - Problems: Friction, Joint "Play", Imperfect perception, Open loop control
  - Generalization to new terrain
    - Each terrain board can only provide a small set of training examples
    - To avoid over-fitting and allow generalization, teams must develop terrain representations that capture key, descriptive features
- Approach
  - Distribute identical vehicles and terrain boards to teams
  - Each team creates and refines algorithms at its own facility
  - Every month, teams send code to DARPA's test facility for evaluation
  - Use of multiple runs to test ability to learn from experience

Teams:	
CMU	MIT
Stanford	USC
IHMC	UPenn **

** Phases I and II

Highlights

- **Program Overview**
  - **Concept, Objectives, and Vision**
- **Related DARPA Efforts**
- **User Interface**
- **Platform Concept Design**
- **Controls**
- **Program Plan & BAA**

LS^3 User interface challenges

LS3 needs to follow dismounts wherever they go



Need	Challenge
Limit burden on operator	Self-sufficiency at the lowest level of control (foot placement): – Use sensors and algorithms to map terrain and analyze for good and bad foot placements – Do this in real time – Do this without GPS or wheel encoders
Follow infantry wherever they go	Track the leader among occlusions. Detect and avoid obstacles. Do this in complex environments with many movers occluding one another.
Safe operations around humans	Be aware of surrounding dismounts' positions and trajectories. Avoid collisions.

LS^3 User interface options

Many potential solution components exist: need to be matured and integrated.

Need

- Leader-following through clutter
- Obstacle avoidance within 10m
- Waypoint-following

- Perception-based speed control
- Footfall planning for simple geometry

Challenge

- Unstable platform
- Spotty GPS / No wheel encoders
- Long-range planning
- Imperfect perception to anticipate terrain features

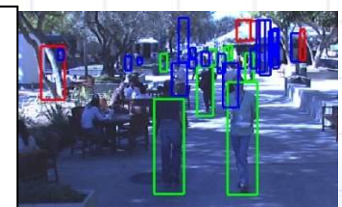
Potential Solution

- Visual odometry
- Image-based navigation
- Human for long-range planning
- Compliant platform

Visual odometry repeatability better than 1.5m over 300m in mixed open/vegetated terrain

Image-based navigation sufficient for short-range planning

Leader tracking obviates need for long-range planning



Perception Concept Design

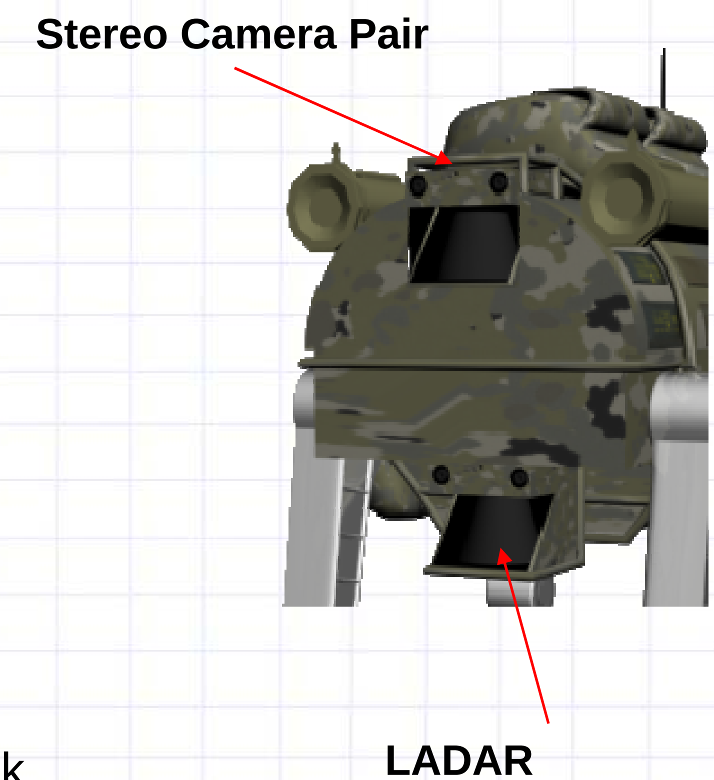
Mission Requirements:
- Predictable and reliable behavior
- Works safely around soldiers and civilians

Notional Sensor Suite:
- Stereo cameras
- Scanning LADAR
- Monocular camera

Notional Algorithms
- Deal with stabilization and localization
- Obstacle Detection and Avoidance
- Leader tracking
- Coarse terrain classification

Notional Processing Hardware Expected
- Multi-core processors
- Flash memory, high speed internal network
- Environmentally sealed, shock mounting, and cooled enclosure
- Simple controllers (e.g. iPod controller)

Conceptual Integration Of Sensors



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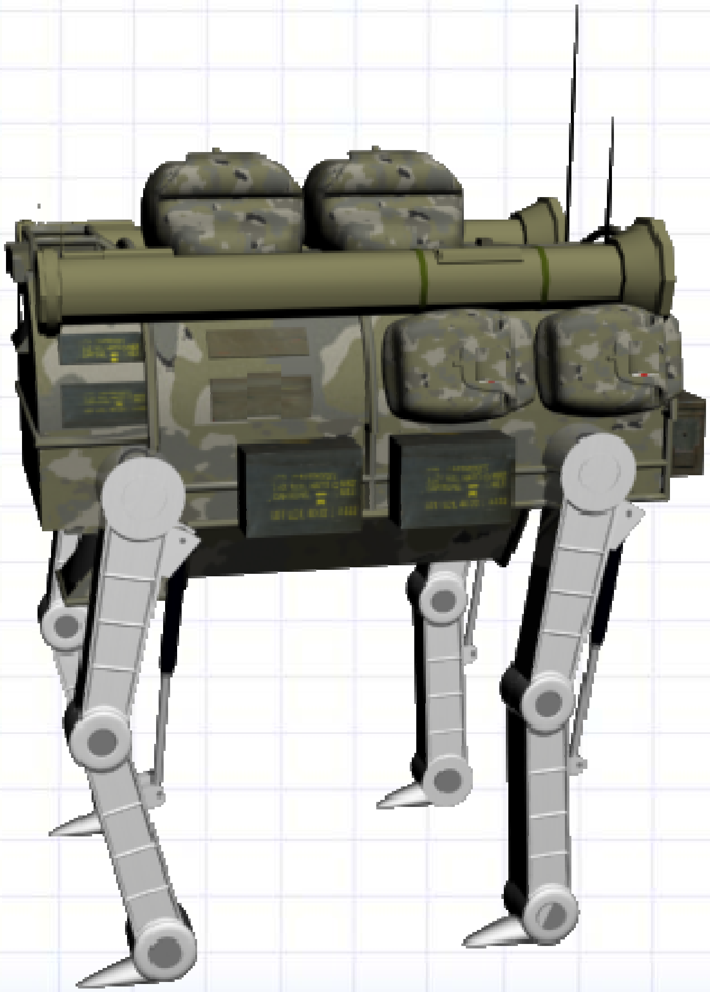
LS³ Platform challenges



Drivetrain Powering

- Low noise signature: 70dB and 40dB modes
- Sufficient power/energy densities for volume conservation
- Low specific fuel consumption: < 0.5 lb / hp-hr

Leg Design

- Structural strength and margin
- High DOF, range of motion
- Actuation – torque/speed trade-offs with low power demands, low actuation losses
- Incorporate energy recovery

Overall integration

- Total system efficiencies – close the design while maintaining small volume
- Avoid excess size and power growth in subsystems (cooling, processing)

Balance with Program Metrics and LS³ Mission Profile

LS³ Powertrain Expected Approaches

Hydraulic

IC Engine → Pump → Hydraulic System (Valves, Actuators)

As on current Big Dog

Electric

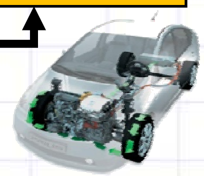
IC Engine → Generator → Electric System (Controllers, Motors)

Typical industrial powertrain
Actuation motors for legged system

Parallel Hybrid Electro-mechanical Hydraulic

- Hybrids allows powertrain load-leveling of legged system peaks
- Offers a silent mode

IC Engine → Transmission
Battery ↔ Motor - Generator → Transmission
Transmission → Pump → Hydraulic System (Valves, Actuators)



Equivalent configuration to a Prius

Series Hybrid (two options)

IC Engine → Motor - Generator → Electrical Power Bus
Battery ↔ Electrical Power Bus
Electrical Power Bus ↔ Either:

- Hydraulic: Motor → Pump → Hydraulic System (Valves, Actuators)
- Electric: Electric System (Controllers, Motors)

Equivalent configuration to UPI Crusher

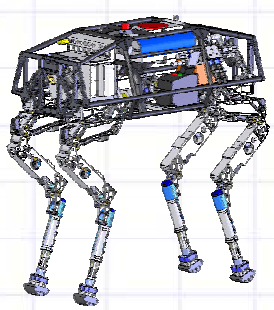
Legend: Mechanical | Electric | Hydraulic

LS^3 Powertrain Feasibility design

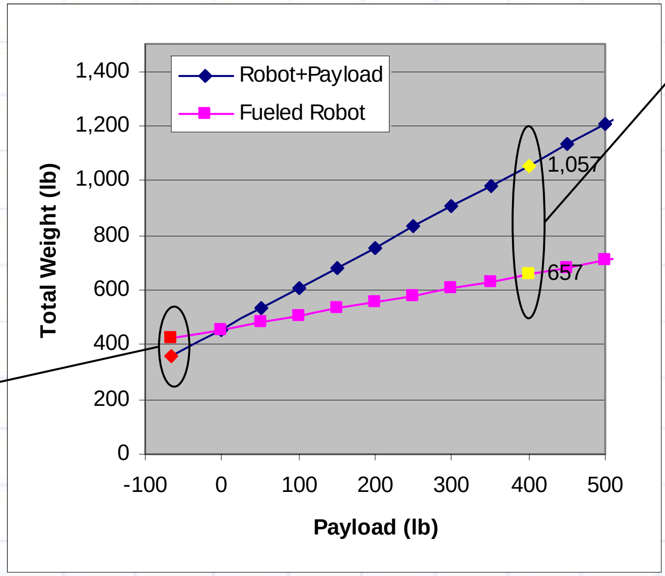
Payload goal can be met by keeping the footprint and mobility of current BigDog and scaling strength only

Increase actuator lateral dimension by 80%.
Strength increases with square (3.2x).
Total weight increases to 1057lb
Payload increases to 400lb

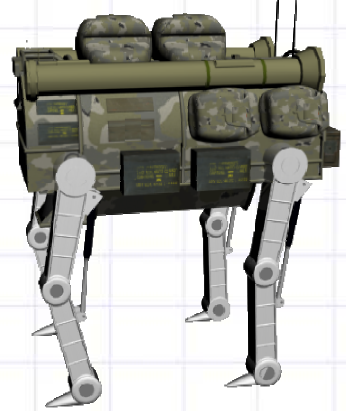
Scaling beyond this point requires leg modifications, causing weight to grow rapidly (5th power of length)



BigDog
Insufficient strength for
- Sensor suite
- 100 lb fuel
- Quieter engine

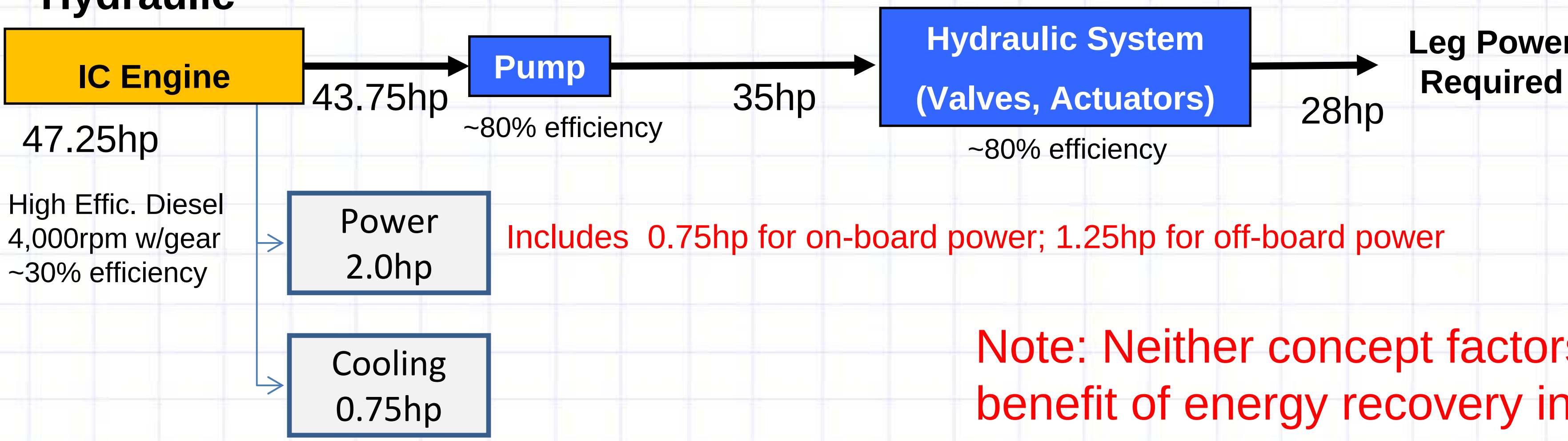


LS^3
Payload 400 lb = 38%



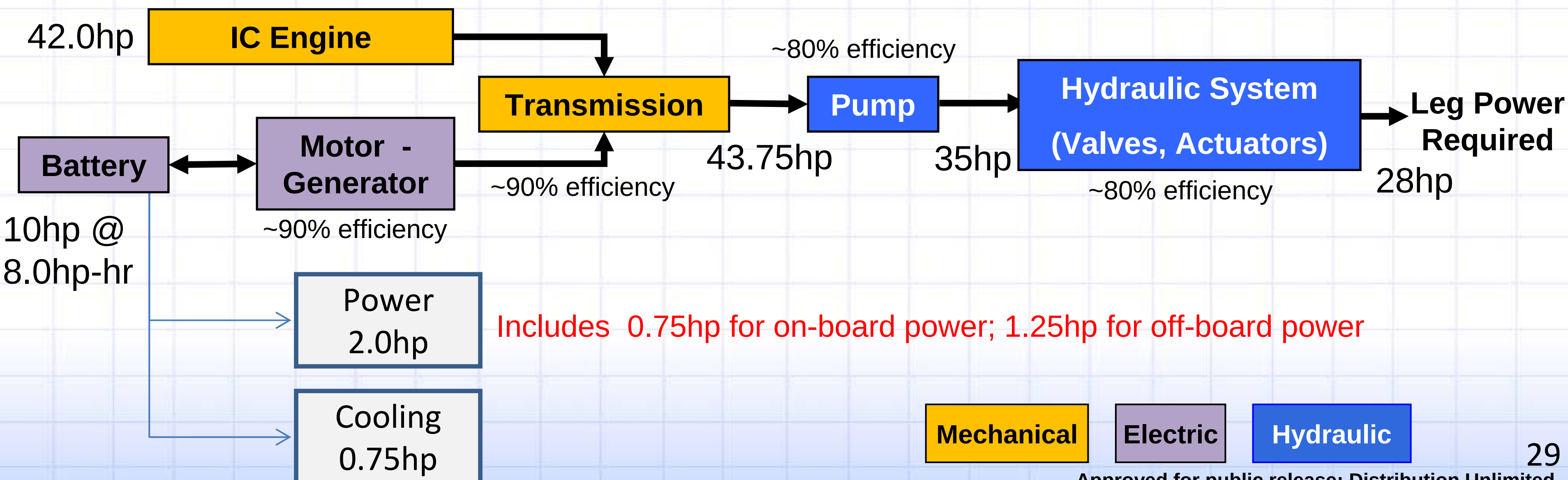
LS³ Notional Concept Sizings

Hydraulic



Note: Neither concept factors in benefit of energy recovery in leg

Parallel Hybrid



LS³ Weight Analysis

	Empty Weight	Margin (10%)	Fuel	Payload	Total Weight	Payload+Fuel / Total Weight	Notes
Current Big Dog	240 lb	0 lb	35 lb	80 lb	**355 lb**	**0.32**	
LS³ - Hydraulic Actuation	502 lb	50 lb	100 lb	400 lb	**1052 lb**	**0.48**	**Simple, Lowest weight, fraction**
LS³ - Parallel hybrid + hydraulic actuators	644 lb	65 lb	100 lb	400 lb	**1209 lb**	**0.41**	**Less installed hp Silent mode**
LS³ - Series hybrid + hydraulic actuators	677 lb	68 lb	100 lb	400 lb	**1245 lb**	**0.40**	**Less installed hp Silent mode**
LS³ – Electric Actuation	902 lb	90 lb	100 lb	400 lb	**1492 lb**	**0.34**	**Heavier**
LS³ - Series hybrid + electric actuators	935 lb	94 lb	100 lb	400 lb	**1529 lb**	**0.33**	**Heaviest**

Empty weight includes: Chassis/subsystems, electrical, hydraulic, engine, perception

Notional Candidate Technologies

Item	Concerns	Notes
Industrial Diesel Engines		• Readily available (except developmental e.g. OPOC) • ~0.4 lb/hp-hr SFC on heavy fuel • Low speed = quiet • 0.25 hp/lb 
2-Stroke Engines	• High speed = loud • Not heavy fueled	• Readily available • 0.4-0.5 lb/hp-hr SFC • 0.3 hp/lb
High Performance 4-Stroke	• High speed = loud • Not heavy fueled	• Available • 0.3-0.4 lb/hp-hr SFC • 0.3 hp/lb
Micro Turbines	• Heavy fueled • Not readily available at estimated power levels	• 0.4 -0.5 lb/hp-hr SFC • 0.3-0.5 hp/lb
Fuel Cells	• Not readily available at estimated power levels	• 0.25 hp/lb • Fuel generation and fuel type adds to power density
Li-Ion Batteries		• Readily available (SAFT, A123, etc.) • Good energy/power densities (150-225 Whr-kg) • Typically used for load leveling at legged system frequency • Estimated 50-80lb battery packs for hybrid systems 
Hydraulic Actuation & Systems		• Available • Light • Robust • Modest losses
Electric Actuation & Systems	• Heavy • Optimized electric actuators not available	• Modest losses
Nastic Actuation	• Developmental	• Highly impulsive • Extremely low efficiency
Hot Gas Actuation	• Low efficiency	• Impulsive • Low system power density
Pneumatic Actuation	• Low efficiency	• Impulsive • Low system power density
Electro-regenerative Actuation	• Not available	

- **Program Overview**

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LS3 Control challenge

Given a terrain map with uncertainty:

Footfalls: Plan footfalls taking into account: actuator strength, reach, overall CG

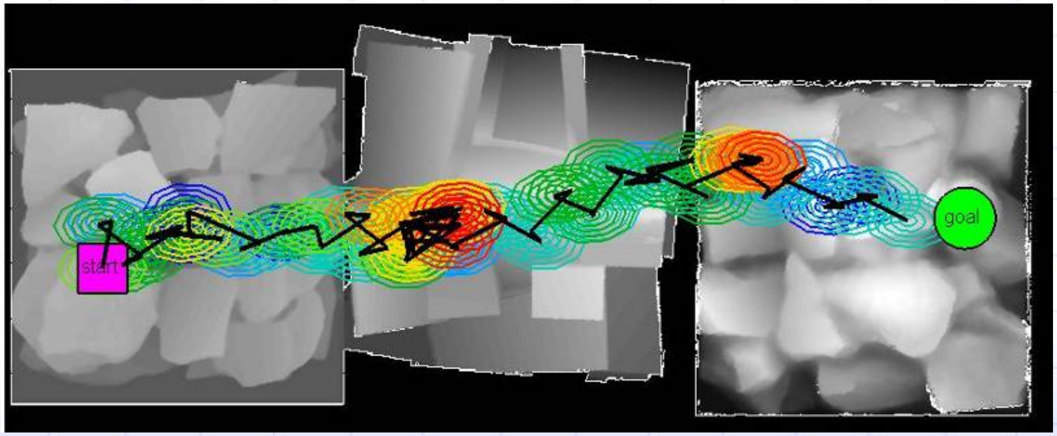
Gaits: Do this for multiple gaits:

- static stability for standing and walking over very rugged terrain
- dynamic stability for speed

Disturbances: Recover from disturbances, caused by joint-play, “sloshing”, snagging, slipping, foot entrapment

Tractability: Do all this at high frequency

Self-righting: Recover from falling



LS³ Control concept design

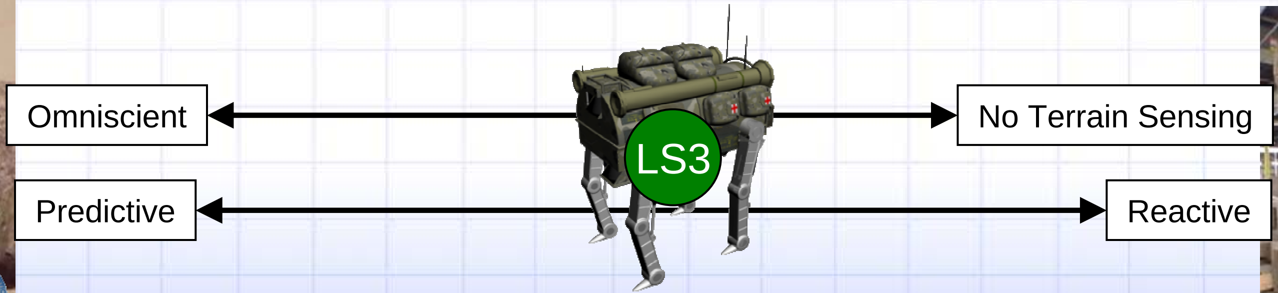
Footfalls: Extend footfall planning approaches from L2 to full-scale vehicle and realistic terrain models

Gaits: Extend BigDog gait control to running, and gait transitions

Disturbances: BigDog has demonstrated robustness to “kicks” and slips.

Compromise between perception accuracy and robustness

LS3 will integrate, on a fieldable system,
- L2 control and foot planning with
- Real-time sensing with
- BigDog compliance and gait control with
- New gaits, gait switching, and self-righting



LS^3 Control opportunities

Proposers have opportunities to reduce platform power loads

Actuators that cost power proportional to force

- Recruit multiple actuators – increases degrees of freedom
- Multi-joint actuators – challenge is to not limit versatility, keep fast reflexes, travel on irregular terrain, minimize weight.
- Could reduce power requirements significantly with commensurate reductions in engine weight and fuel required, or increases in payload and endurance.

Multiple gaits with energy recovery

- Taking advantage of efficient gaits could lower leg powering loads required

Effective Mechanical Advantage

- Reduces required force per actuator, but must be controlled to match terrain

From LS3 BAA: Mission Profile

Table 1, Page 6

Item	Description	Speed	Distance	Time	Noise	Auxiliary Power
1	Moderate Hiking Trail	3 mi/hr	9.0 mi	3.00 hr	70dB	0.75 hp
2	Idle - squatted	0 mi/hr	0.0 mi	0.50 hr	60dB	0.75 hp
3	Easy Road Trail	5 mi/hr	5.0 mi	1.00 hr	70dB	0.75 hp
4	Idle – squatted	0 mi/hr	0.0 mi	0.50 hr	60dB	0.75 hp
5	Complex hiking trail	1 mi/hr	1.0 mi	1.00 hr	70dB	0.75 hp
6	Easy Road Trail	10 mi/hr	0.5 mi	0.05 hr	70dB	0 hp
7	Idle – squatted	0 mi/hr	0.0 mi	0.50 hr	60dB	0.75 hp
8	Moderate Hiking Trail	3 mi/hr	3.0 mi	1.00 hr	70 dB	0.75 hp
9	Moderate Hiking Trail	3 mi/hr	0.5 mi	0.16 hr	40 dB	0.75 hp
10	Easy Road Trail	10 mi/hr	0.5 mi	0.05 hr	70 dB	0 hp
11	Maneuver at objective	1 mi/hr	0.5 mi	0.50 hr	70 dB	0.75 hp
12	Standby - squatted	0 mi/hr	0.0 mi	15.74 hr	40-60dB mixed	0.75 hp
	TOTALS		**20.0 mi**	**24.00 hr**		

- **DARPA developed with service input**
  - Emulates squad maneuver over 20mi/24hrs
- **Mix of speeds, distance, terrain, standby**

- **Program Overview**

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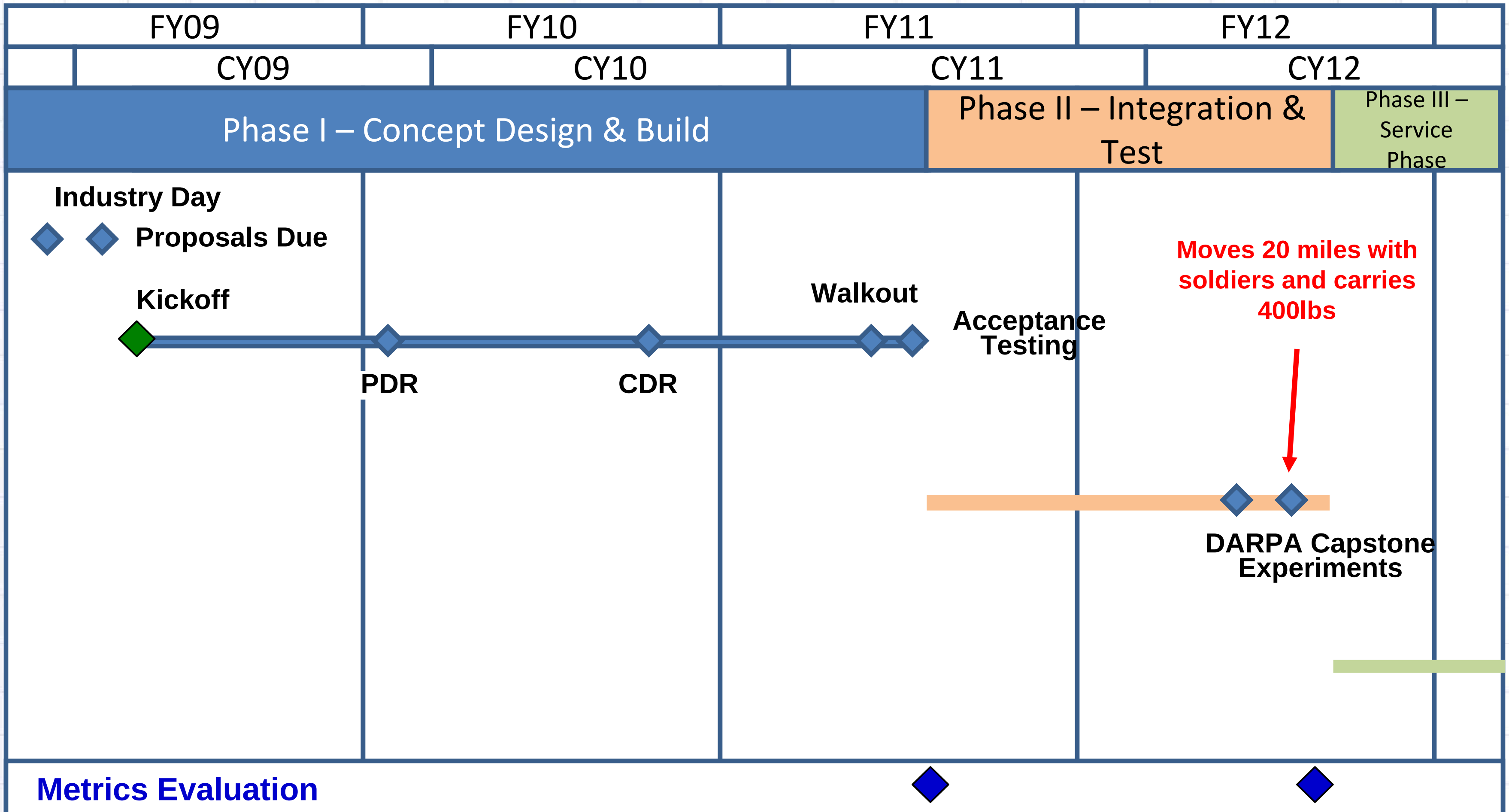
- **BAA and Program Plan**

BAA

- **Two Phase DARPA Effort**
  – Phase I: Design & Build
  – Phase II: Integration & Test
- **Single award anticipated, multiple possible**
- **BAA – Part I – Funding Opportunity Description**
  – Program Overview
  – Program Goals
    - Non-tradeables
    - Mission Profile
    - Expectations
  – Program Structure
  – Phase I Objectives
  – Phase II Objectives
  – Phase I Schedule and Deliverables
  – Metrics

Notional Program Schedule



Program Budget – Determined by performer proposal
Actual Schedule – Determined by performer proposal

Program Plan

w/Notional Dates

- **Phase I – Concept Design and Build (~24 Months)**
  - Preliminary Design Review (Complete: ~Start + 8 months)
    - Design -trades, sizings, CLPP plan
    - Long lead purchasing and building of high-risk subsystems
    - Build Subsystems that prove design validity
    - Complete control theory plan in simulation
  - Critical Design Review (Complete: ~Start + 16 Months)
    - Subsystems testing and results
    - Mature controls simulation
    - Ends with detailed design package, integration plan, results of module tests – CDR-level CLPP
    - Perception experiment on data sets
  - Prototypes Build (Complete: ~Start + 24 Months)
    - Execution of CDR CLPP – prototype build
    - Initial Integration of controls to demonstrate walk and trot
    - Perception hardware integrated
    - End in walkout of 2 prototypes
    - Phase I Acceptance Tests against Phase I Metrics
- **Phase II – Integration and Test (~12 Months)**
  - 9 months – Integration of perception and control developments
  - 3 months - DARPA experiments against Phase II Metrics
  - 1 month – closeout & transition
- **Phase III – Service Phase**
  - User experiments for CONOPS development
  - Incremental improvement of prototypes towards MILSPEC and exact user application

Key Component: Comprehensive LS^3 Program Plan (CLPP)

Program Metrics

LS^3 BAA: Section G, Page 14

Technology	Phase I	Phase II
Platform	Vehicle walk-out	20 miles of maneuver as referenced in Table 1 LS3 Mission Profile in 24 hours, unrefueled, while carrying 400lb or more Maneuver includes complex natural/urban terrain and scenes in the presence of a squad of dismounted soldiers Max vehicle weight = 1250lb, including payload and fuel
	Maneuver at each of the following speeds across even terrain for 400m (parking lot) •1mph (expected gait - walk) •3mph (expected gait – walk to trot) •5mph (expected gait – trot) •10mph (expected gait – run)	
	Maximum 70 dB noise signature, with 40 dB quiet mode	
Controls	Maneuver at each of the following speeds across uneven terrain for 100m •1mph (expected gait - walk) •3mph (expected gait – walk to trot) •5mph (expected gait – trot) •10mph (expected gait – run)	
	Stability despite lateral disturbance (kick)	
User Interface	Produce the following foot and body placements detections over a 50m x 2m natural terrain environment •95% of poor footholds at 3 mph & 95% of good footholds at 3 mph •80% of poor footholds at 5 mph & 80% of good footholds at 5 mph	
	Track as moving obstacles up to 5 squad members at 10 Hz with the intent of safe maneuver around and in coordination with them.	

Program Overview

- **Maneuver robustly and nimbly among dismounted troops through complex terrain**
- **Carry 400lb of equipment as well as sufficient fuel for 24 hours operation**
  - Total weight no more than 1250 lb
- **Sense and negotiate terrain by autonomously selecting appropriate gaits, Planning footfalls, and following a soldier through dynamic, cluttered environments**
- **Operate quietly when required**
- **Build and deliver (2) LS^3 Prototypes**