BRIEF PROJECT OVERVIEW

EATR™: ENERGETICALLY AUTONOMOUS TACTICAL ROBOT

Small Business Innovative Research (SBIR) Phase II Project; Phase II Enhancement/Phase III Commercialization

DARPA Contracts W31P4Q-08-C-0292 & N10PC20223

Presented By:

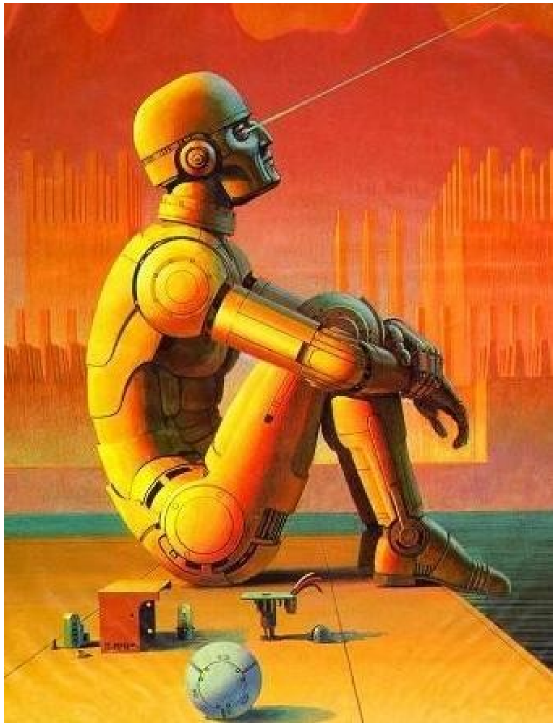
Dr. Robert Finkelstein

President, Robotic Technology Inc.

Office: 301-983-4194

BobF@RoboticTechnologyInc.com

www.RoboticTechnologyInc.com

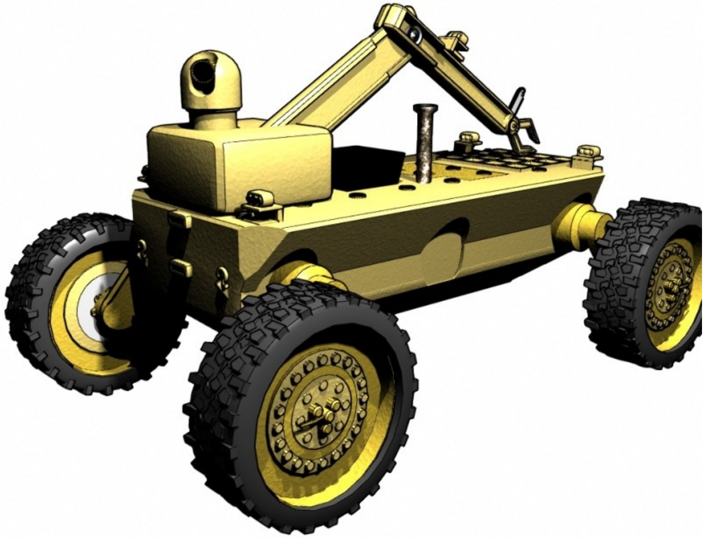


Revised

13 June 2010

ENERGETICALLY AUTONOMOUS TACTICAL ROBOT (EATR™)

- **Concept [patent pending]: an autonomous robotic vehicle able to perform long-range, long-endurance missions indefinitely without the need for conventional refueling**
- **Robotic vehicle forages: biologically-inspired, organism-like behavior the equivalent of eating**
  - **Can find, ingest, and extract energy from biomass in the environment (and other organically-based energy sources)**
  - **In addition to vegetation, EATR™ can also use conventional or unconventional fuels (e.g., heavy fuel, gasoline, natural gas, diesel, kerosene, propane, coal, solar, algae, cooking oil)**



EATR™: RATIONALE AND UTILITY

- **A robotic vehicle's inherent advantage is the ability to engage in long-endurance, tedious, and hazardous tasks such as RSTA (Reconnaissance, Surveillance, and Target Acquisition) without fatigue or stress**
  - **Advantage is diminished by need to replenish fuel supply**
- **EATR™ provides:**
  - **Revolutionary increase in robotic ground vehicle endurance and range**
  - **Ability of robot to perform extended missions autonomously**
  - **Ability to occupy territory and perform missions with sensors or weapons indefinitely**
- **Long-range, long-endurance unmanned ground vehicles (UGVs) can complement the missions of long-range, long-endurance unmanned air vehicles (UAVs)**

HELIOS UAV (NASA)

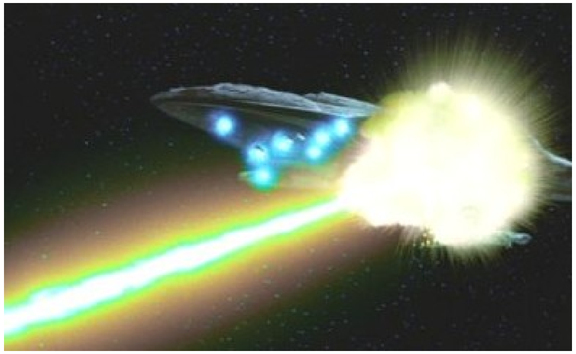
AURORA FLIGHT SCIENCES THESEUS (NASA)

EATR™: OTHER COMBAT MISSIONS

- In addition to missions requiring long-range, long-endurance ability, the EATR™ can provide direct support to combat units without requiring labor or materiel logistics support for refueling
  - EATR™ could forage for its own energy while the unit rested or remained in position
- EATR™, with a heavy-duty robotic arm and hybrid external combustion engine, could provide direct support to combat units by:
  - Carrying the unit's backpacks and other material (the mule function)
  - Provide RSTA, weapons support, casualty extraction, or transport

EATR™: OTHER COMBAT MISSIONS

- **EATR™ as a mobile generator could provide energy for:**
  - **The multitude of rechargeable batteries carried by soldiers, or to provide the electricity for mobile command and control centers**
  - **Swarms of smaller, electrically-powered robots for combat missions (e.g., reconnaissance, surveillance, and target acquisition; tactical defense or offense), or commercial applications (e.g., waste dump cleanup; invasive plant species detection and removal in forests; agricultural tasks; construction; law enforcement)**
  - **Regular or emergency backup power for remote military or civil sites or sensor arrays, in conjunction with solar and wind energy**
  - **High energy weapons (e.g., pulse or CW laser or microwave): about 50 lbs of wood could provide sufficient energy to kill a missile**

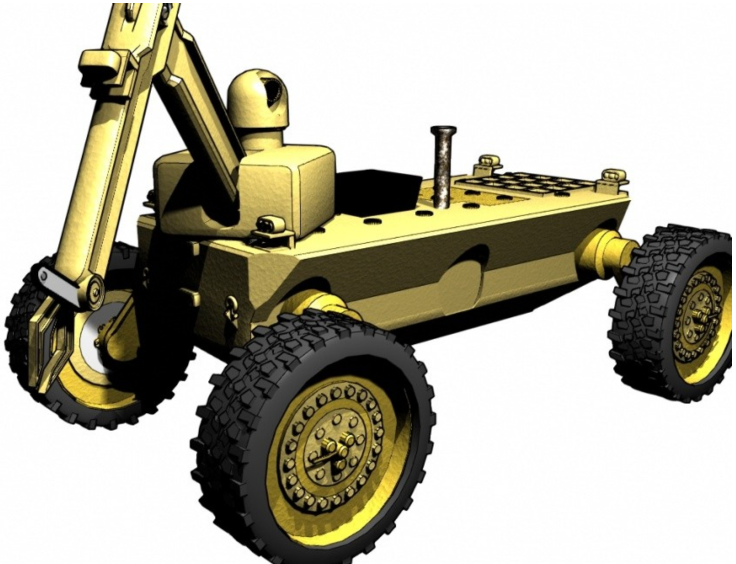


EATR™: COMMERCIAL APPLICATIONS

- EATR™ can be configured on various platforms to perform a variety of applications
- Agriculture
  - EATR™ as an agricultural system can obtain energy by gleaning waste vegetation from the field
- Forestry
  - EATR™ can seek and destroy invasive (or illegal) plant species in forests
- Law Enforcement
  - EATR™ can patrol borders in remote areas or provide long-endurance reconnaissance and surveillance

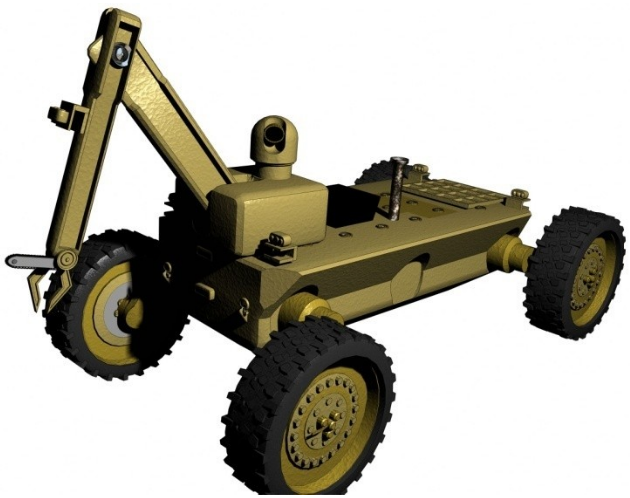
EATR™ PROJECT TECHNICAL OBJECTIVES

- Initial objective is to develop and demonstrate a proof-of-concept system
  - Demonstration of a full operational prototype is the objective for a subsequent Phase III commercialization project
- The project will demonstrate the ability of the EATR™ to:
  - Identify suitable vegetation sources of energy and distinguish those sources from unsuitable materials (e.g., wood, grass, or leaves from rocks, metal, or glass)
  - Spatially locate and manipulate the sources of energy (e.g., cut or shred to size, grasp, lift, and ingest); and
  - Convert the biomass to sufficient electrical energy to power the EATR™ subsystems

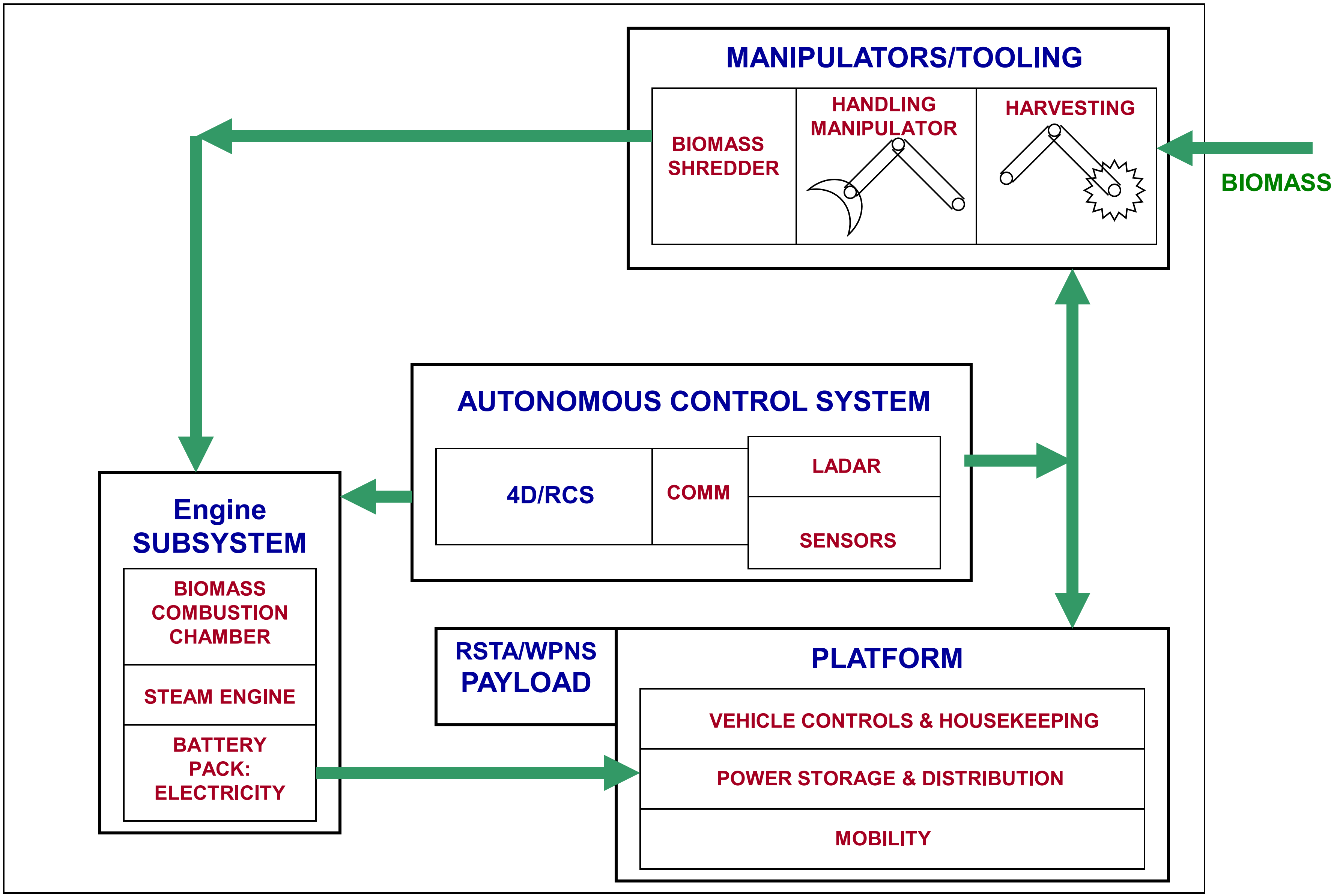


EATR™: TECHNICAL APPROACH

- Four major subsystems:
  - **Robotic mobility platform:** mission mobility, EATR™ support subsystems (batteries, power conversion and conditioning), mission payload, and payload support subsystems
  - **Autonomous control system/sensors :** allow platform to find and recognize suitable biomass energy sources and manipulate material with arms and end effectors
  - **Robotic arms and end effectors:** gather and manipulate combustible energy sources (prepared by shredder which will ingest and process vegetation into combustion chamber)
  - **External combustion engine:** hybrid engine system (combustion chamber, power unit, and battery)

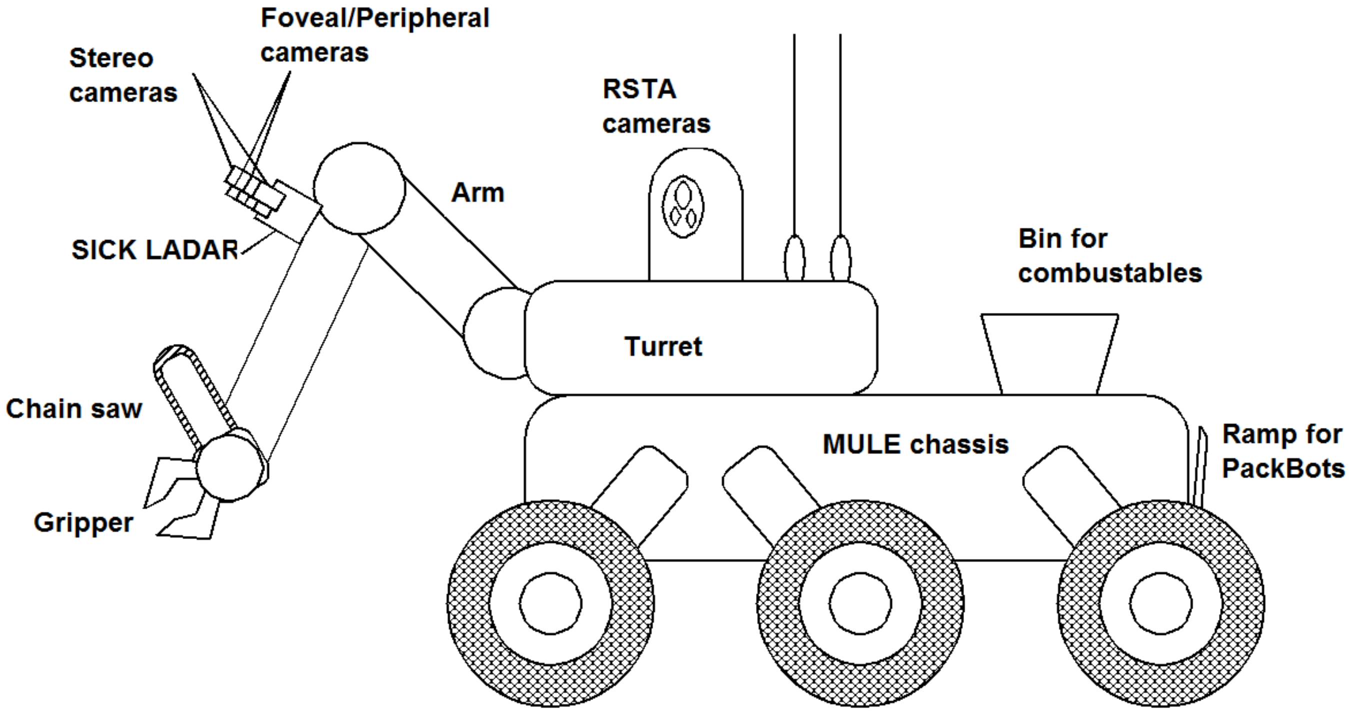


EXAMPLE EATR™ ARCHITECTURE



EXAMPLE EATR™ PLATFORM

- **The autonomous robotic mobility platform is not essential to the EATR™ proof-of-concept demonstration – but it is required for the commercialization phase**
  - **Provides mobility for the mission and mission payload**
  - **May consist of any suitable vehicle**

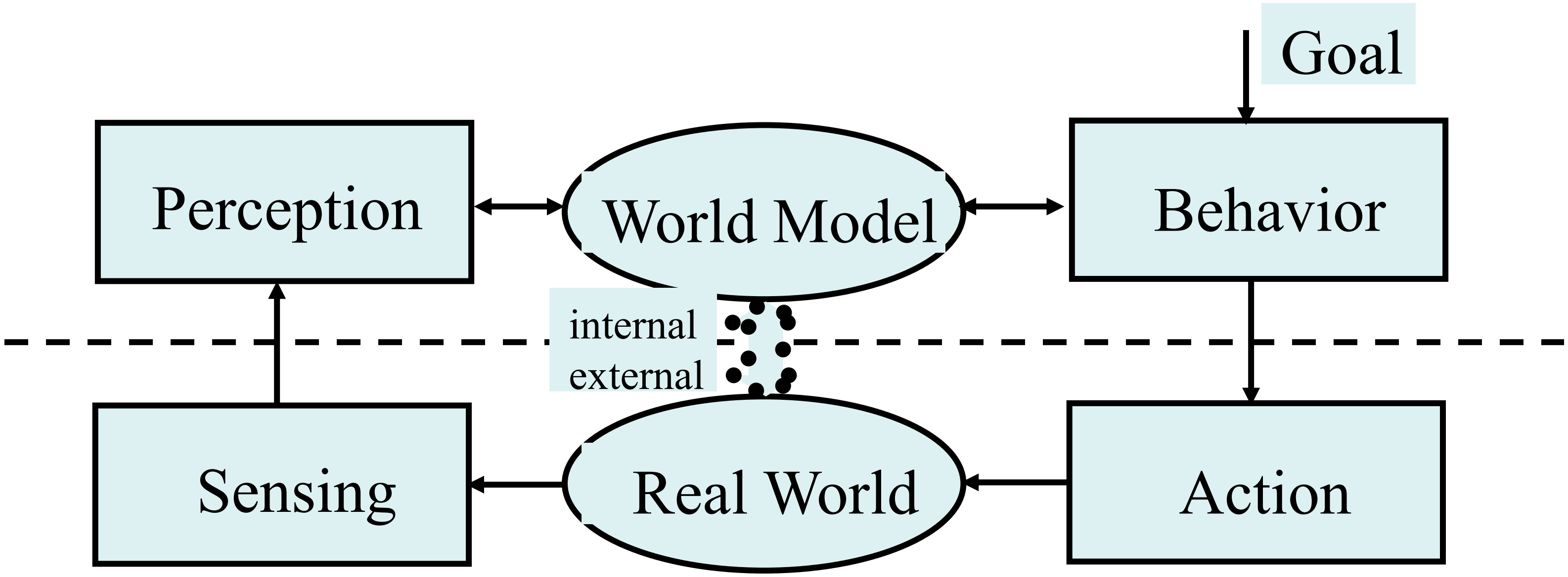


EXAMPLE EATR™ PLATFORM

- **The experimental prototype platform for the commercialization phase may consist of any suitable automotive vehicle, such as a purely robotic vehicle, a robotically-modified High Mobility Multi-Wheeled Vehicle (HMMWV), or a robotically-modified all-electric truck**

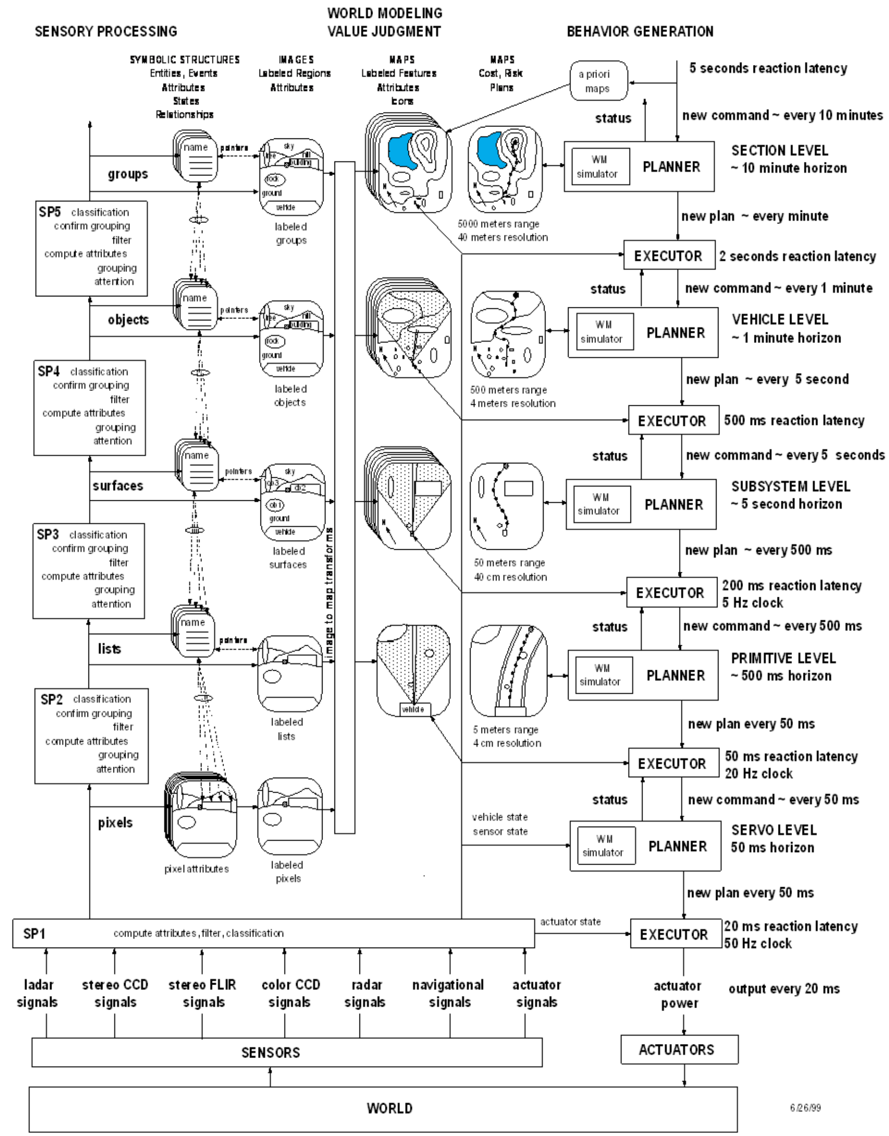
AUTONOMOUS INTELLIGENT CONTROL: 4D/RCS

- **The autonomous intelligent control subsystem will consist of the 4D/RCS (three dimensions of space, one dimension of time, Real-time Control System) architecture, with new software modules which we will create for the EATR™**
  - **Under development for more than three decades, with an investment exceeding $125 million, by the Intelligent Systems Division (ISD) of the National Institute of Standards and Technology (NIST), an agency of the U.S. Department of Commerce**
  - **Demonstrated successfully in various autonomous intelligent vehicles, and a variation of the 4D/RCS, with $250 million in developmental funding, served as the Autonomous Navigation System (ANS) mandated for all robotic vehicles in the Army's Future Combat System (FCS)**
  - **NIST is assisting in the transfer of the 4D/RCS for the EATR™ project**



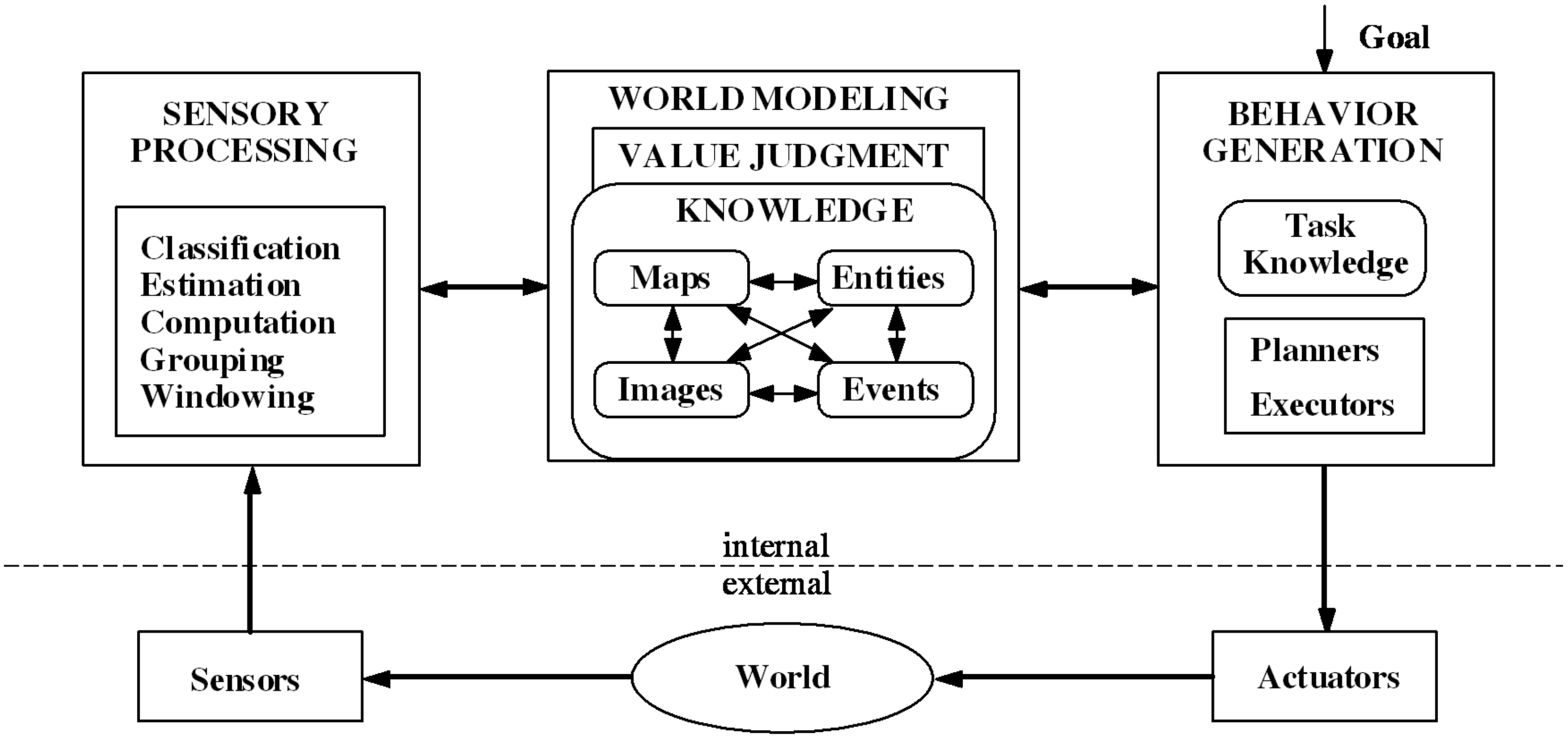
AUTONOMOUS INTELLIGENT CONTROL: 4D/RCS

- The control subsystem will also include the sensors needed for the demonstration (e.g., optical, ladar, infrared, and acoustic)
  - NIST 4D/RCS architecture will provide EATR prototype with autonomous vehicle mobility & allow EATR™ proof-of-concept to:
    - Control the movement and operation of the sensors, process sensor data to provide situational awareness such that the EATR™ is able to identify and locate suitable biomass for energy production
    - Control the movement and operation of the robotic arm and end effector to manipulate the biomass and ingest it into the combustion chamber
    - Control the operation of the hybrid external combustion engine to provide suitable power for the required functions



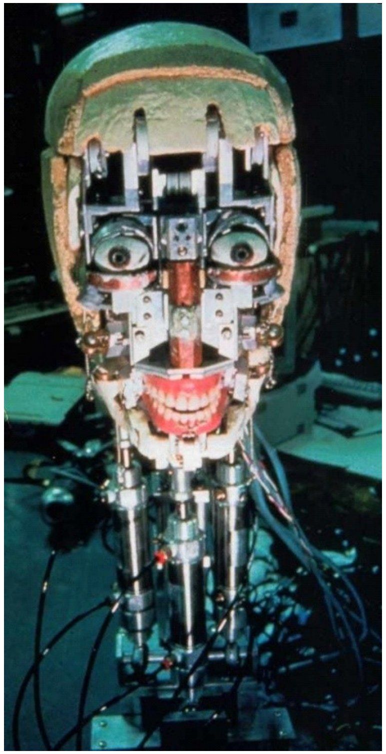
AUTONOMOUS INTELLIGENT CONTROL: 4D/RCS

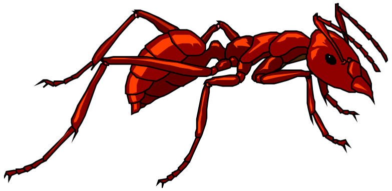
- **The 4D/RCS is a framework in which sensors, sensor processing, databases, computer models, and machine controls may be linked and operated such that the system behaves as if it were intelligent**
- **It can provide a system with functional intelligence (where *intelligence* is the ability to make an *appropriate* choice or decision)**

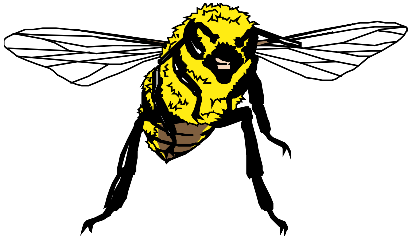


AUTONOMOUS INTELLIGENT CONTROL: 4D/RCS

- The 4D/RCS is a domain-independent approach to goal-directed, sensory-interactive, adaptable behavior, integrating high-level cognitive reasoning with low-level perception and feedback control in a modular, well-structured, and theoretically grounded methodology
  - It can be used to achieve full or supervised intelligent autonomy of individual platforms, as well as an overarching framework for control of systems of systems (e.g., incorporating unmanned and manned air, ground, sea surface, and undersea platforms, as well as serving as a decision tool for system of systems human controllers)

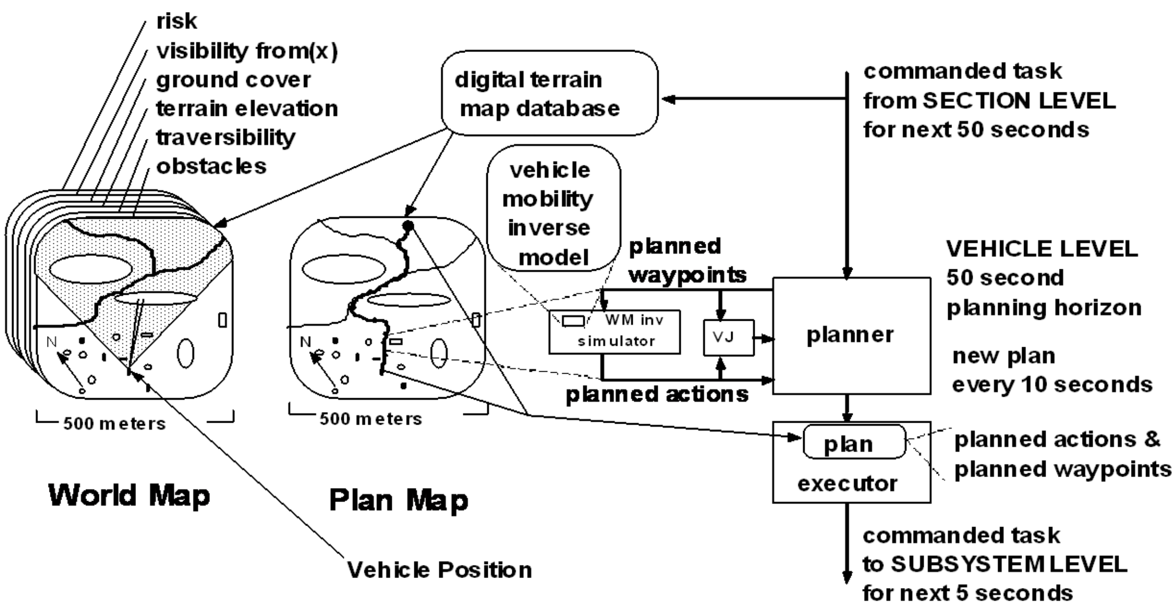






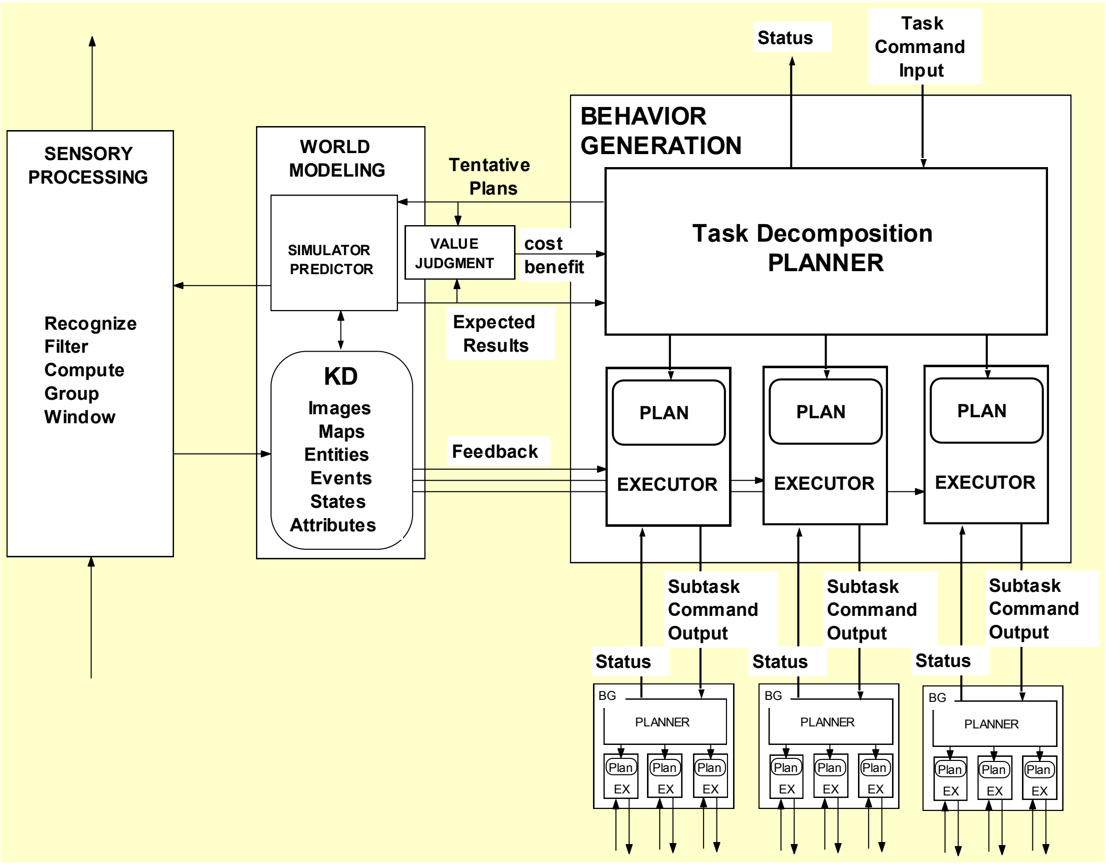
AUTONOMOUS INTELLIGENT CONTROL: 4D/RCS

- The 4D/RCS architecture is particularly well suited to support adaptability and flexibility in an unstructured, dynamic, tactical environment
  - It has situational awareness, and it can perform as a deliberative or reactive control system, depending on the situation
- The 4D/RCS is modular and hierarchically structured with multiple sensory feedback loops closed at every level
  - This permits rapid response to changes in the environment within the context of high-level goals and objectives



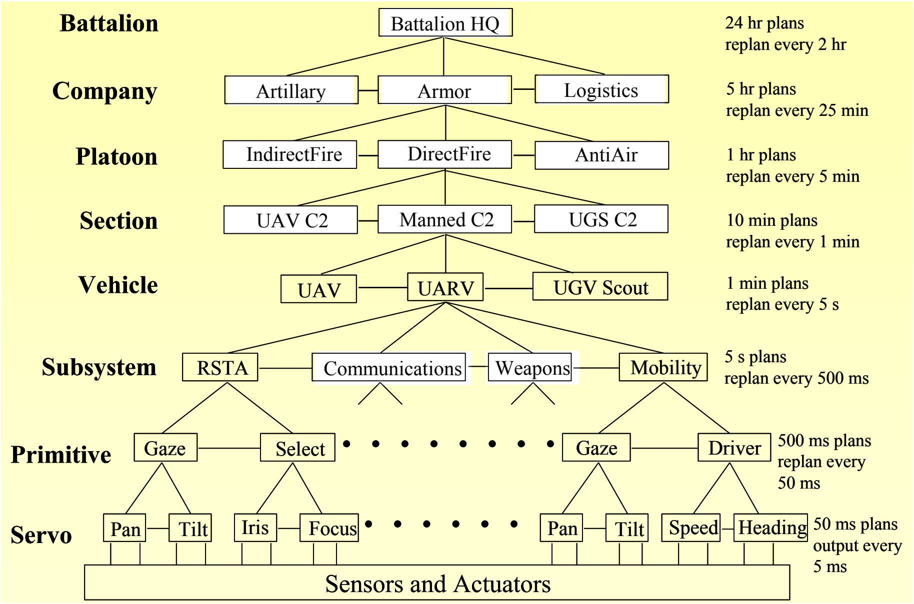
AUTONOMOUS INTELLIGENT CONTROL: 4D/RCS

- At the lowest (Servo) level, the 4D/RCS closes actuator feedback control loops within milliseconds
- At successively higher levels, the 4D/RCS architecture responds to more complex situations with both reactive behaviors and real-time re-planning



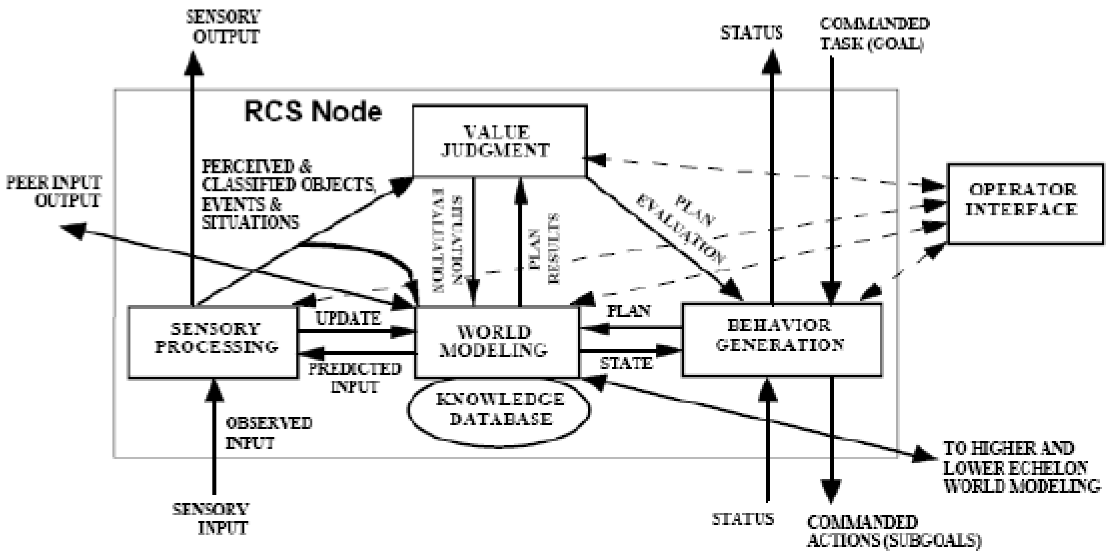
AUTONOMOUS INTELLIGENT CONTROL: 4D/RCS

- For example, at the second (Primitive) level, the 4D/RCS reacts to inertial accelerations and potentially catastrophic movements within hundredths of a second
- At the third (Subsystem) level, the 4D/RCS reacts within tenths of a second to perceived objects, obstacles, and threats in the environment
- At the fourth (Vehicle) level, the 4D/RCS reacts quickly and appropriately to perceived situations in its immediate environment, such as aiming and firing weapons, taking cover, or maneuvering to optimize visibility to a target
- At the fifth (Section) level, the 4D/RCS collaborates with other vehicles to maintain tactical formation or to conduct coordinated actions
- At the sixth (System of Systems) level, which has not yet been implemented, the 4D/RCS serves as an overarching intelligent control and decision system for (all or part of) a manifold of distributed unmanned and manned platforms, unattended sensors and weapons, and control centers



AUTONOMOUS INTELLIGENT CONTROL: 4D/RCS

- At each level the 4D/RCS combines perceived information from sensors with a priori knowledge in the context of operational orders, changing priorities, and rules of engagement provided by a human commander
- At each level, plans are constantly recomputed and reevaluated at a range and resolution in space and time that is appropriate to the duties and responsibilities assigned to that level
- At each level, reactive behaviors are integrated with real-time planning to enable sensor data to modify and revise plans in real-time so that behavior is appropriate to overall goals in a dynamic and uncertain environment
  - This enables reactive behavior that is both rapid and sophisticated

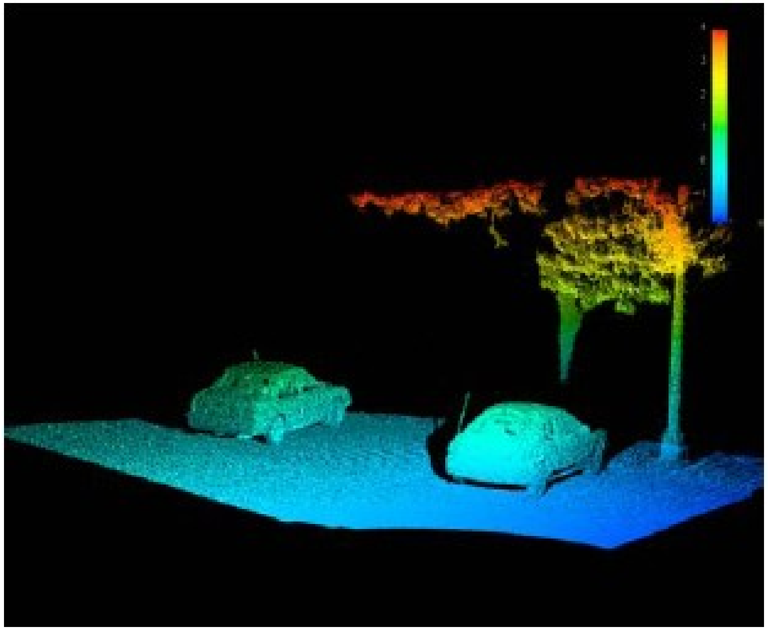


AUTONOMOUS INTELLIGENT CONTROL: 4D/RCS

- At the section level and above, the 4D/RCS supports collaboration between multiple heterogeneous manned and unmanned vehicles (including combinations of air, sea, and ground vehicles) in coordinated tactical behaviors
- The 4D/RCS also permits dynamic reconfiguration of the chain of command, so that vehicles can be reassigned and operational units can be reconfigured on the fly as required to respond to tactical situations

AUTONOMOUS INTELLIGENT CONTROL: 4D/RCS

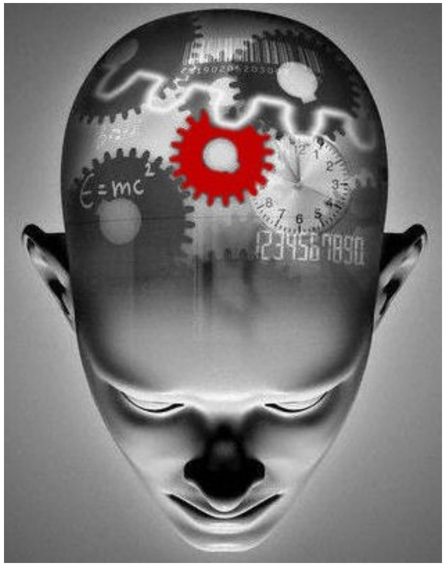
- The 4D/RCS methodology maintains a layered partitioning of tasks with levels of abstraction, sensing, task responsibility, execution authority, and knowledge representation
  - Each layer encapsulates the problem domain at one level of abstraction so all aspects of the task at this one layer can be analyzed and understood
- The 4D/RCS architecture to be readily adapted to new tactical situations
  - The modular nature of the 4D/RCS enables modules to incorporate new rules from an instructor or employ learning techniques



AUTONOMOUS INTELLIGENT CONTROL: 4D/RCS

"All processes of mind have computational equivalents"
---- James Albus

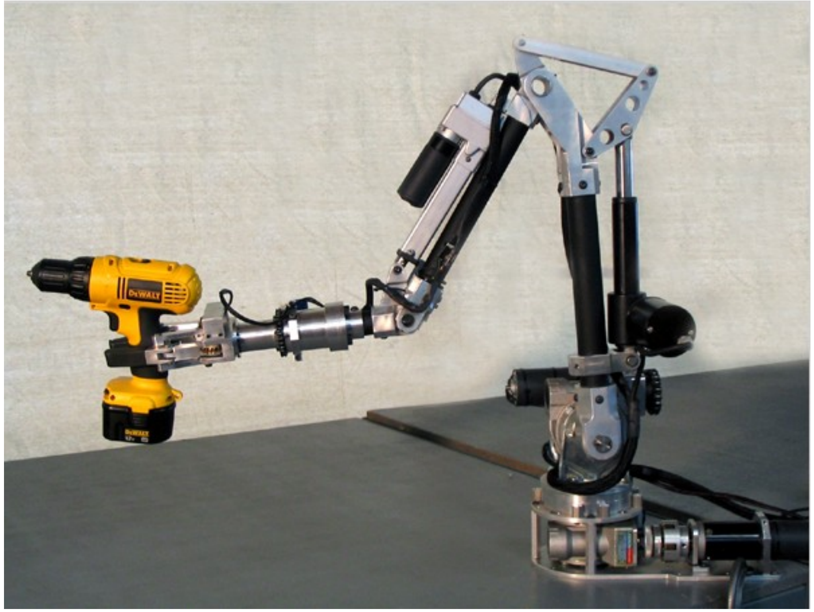
Imagination = visualization, modeling, and simulation
Thought = analysis of what is imagined
Reason = logic applied to thinking
Emotion = value judgment, evaluation of good and bad
Feeling = experience of sensory input
Perception = transformation of sensation into knowledge
Knowledge = organized information
Communication = transfer of knowledge
Intelligence = ability to acquire and use knowledge
Intuition = built in knowledge
Awareness = knowledge of the world situation
Consciousness = include self in world model



We are evolving the 4D/RCS towards machine cognition for ubiquitous applications

HARVESTING VEGETATION: ROBOTIC ARM AND END EFFECTOR

- One tool for harvesting vegetation is a robotic arm and end effector
- Robotic arm and end effector will be attached to the robotic mobility platform, either directly or affixed to a platform towed behind the vehicle
  - It will have sufficient degrees-of-freedom, extend sufficiently from the platform, and have a sufficient payload to reach and lift appropriate materials in its vicinity
  - The end effector will consist of a hand or gripper with sufficient degrees-of-freedom to grasp and operate a cutting tool (e.g., a circular saw) to demonstrate an ability to prepare biomass for ingestion, and to grasp and manipulate vegetation for ingestion



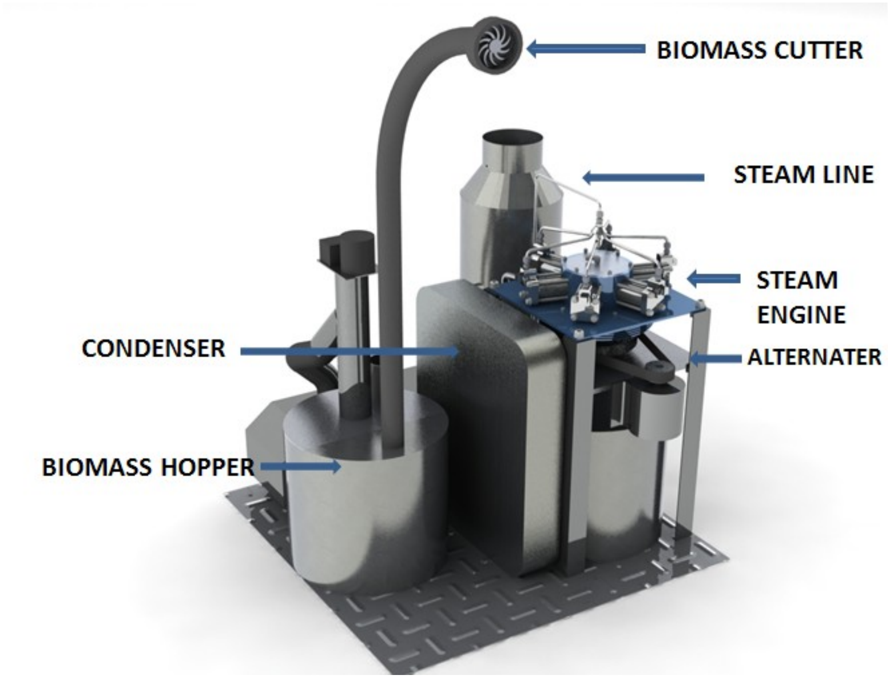
Elbit Arm With 6 Degrees Of Freedom

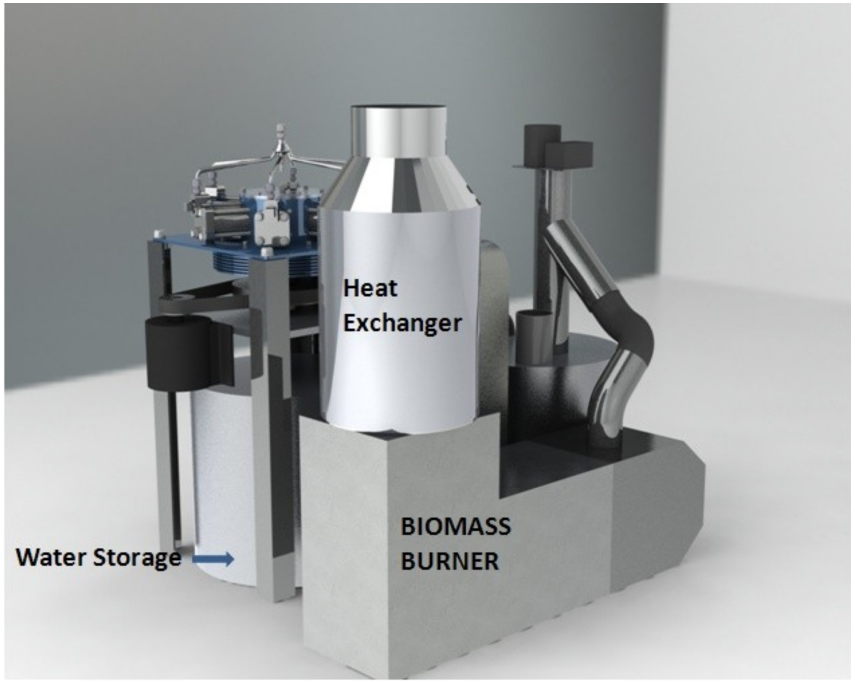
HARVESTING VEGETATION: ROBOTIC ARM AND END EFFECTOR

- Other potential tools for harvesting vegetation include:
  - A mowing system, similar to a commercial brush mower, able to mow and mulch grass, bushes, and tree saplings three inches in diameter
  - A flexible, tubular system, similar to a large vacuum cleaner hose or elephant’s trunk, with a cutting tool embedded in the front end able to cut and mulch grass, brush, and wood and inhale the cuttings into the biomass hopper
    - A robotic arm in the form of an elephant’s trunk was developed at least one university (Rice): it has 32 degrees of freedom in 16 links, with 4 sections having 2 controllable degrees of freedom each

HYBRID EXTERNAL COMBUSTION ENGINE

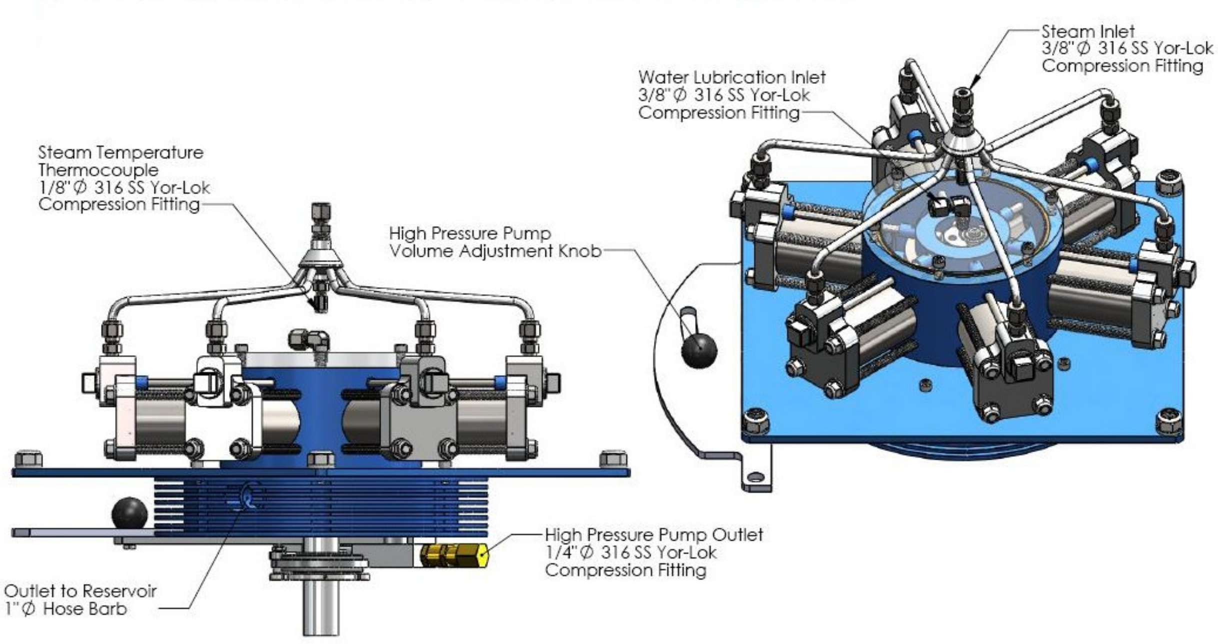
- Source of power for EATR™: new hybrid external combustion engine system from Cyclone Power Technologies Inc.: Biomass combustion chamber subsystem; Rankine cycle steam engine subsystem; battery pack subsystem
- Hybrid external combustion engine is very quiet, reliable, efficient, and fuel-flexible compared with the internal combustion engine



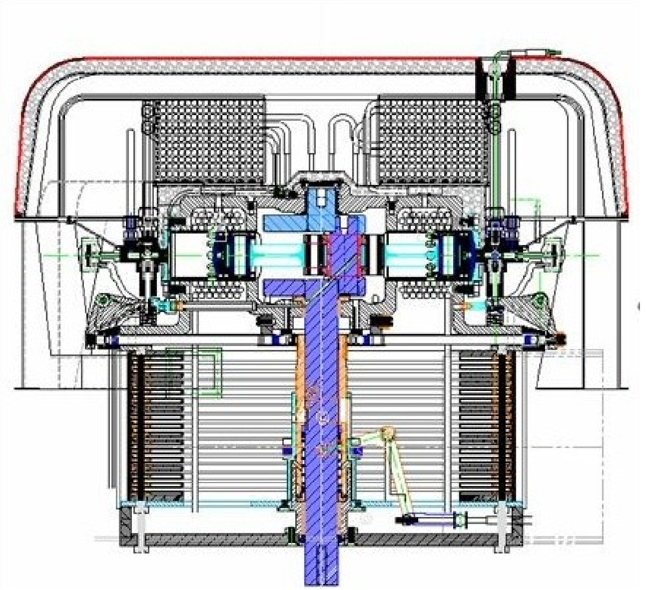


HYBRID EXTERNAL COMBUSTION ENGINE

- Integrated with a biomass combustion chamber to provide heat energy for the engine (can also use supplemental fuel, such as propane)
- Engine will provide electric current for a rechargeable battery pack, which will power the sensors, processors and controls, and the robotic arm/end effector (battery ensures continuous energy output despite intermittent biomass energy intake)
- Engine does not provide mobility power for vehicle in proof-of-concept phase, but will for EATR™ prototype



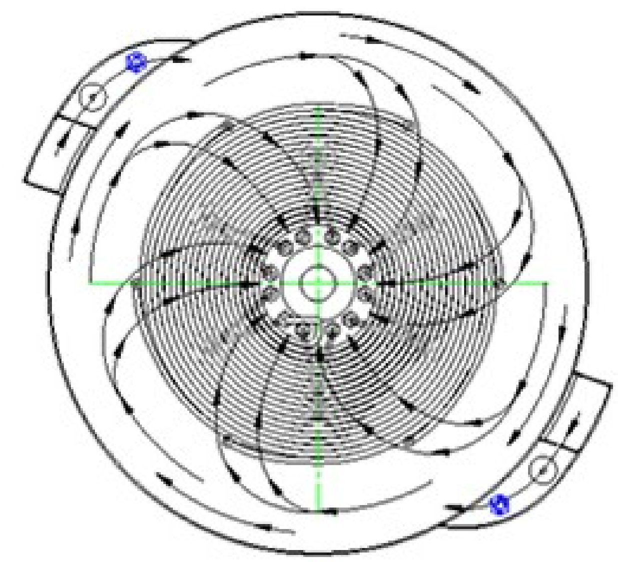
HYBRID EXTERNAL COMBUSTION ENGINE

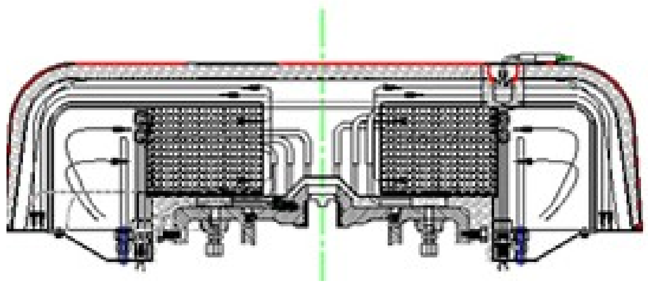


- Unlike internal combustion engines, the Cyclone engine uses an external combustion chamber to heat a separate working fluid (de-ionized water) which expands to create mechanical energy by moving pistons or a turbine (i.e., Rankine cycle steam engine)
- Combustion is external so engine can run on any fuel (solid, liquid, or gaseous)
  - Biomass, agricultural waste, coal, municipal trash, kerosene, ethanol, diesel, gasoline, heavy fuel, chicken fat, palm oil, cottonseed oil, algae oil, hydrogen, propane, etc. – individually or in combination
- A 100 Hp vehicle engine has been developed; more powerful engines are being developed

HYBRID EXTERNAL COMBUSTION ENGINE

- **Cyclone engine is environmentally friendly because combustion is continuous and more easily regulated for temperature, oxidizers, and fuel amount**
  - **Lower combustion temperatures and pressures create less toxic and exotic exhaust gases**
  - **Uniquely configured combustion chamber creates a rotating flow that facilitates complete air and fuel mixing, and complete combustion, so there are virtually no emissions**
  - **Less heat released (hundreds of degrees lower than internal combustion exhaust)**
  - **Does not need: catalytic converter, radiator, transmission, oil pump or lubricating oil (water lubricated)**
  - **Decreased engine size and weight, increased efficiency and reliability**





HYBRID EXTERNAL COMBUSTION ENGINE

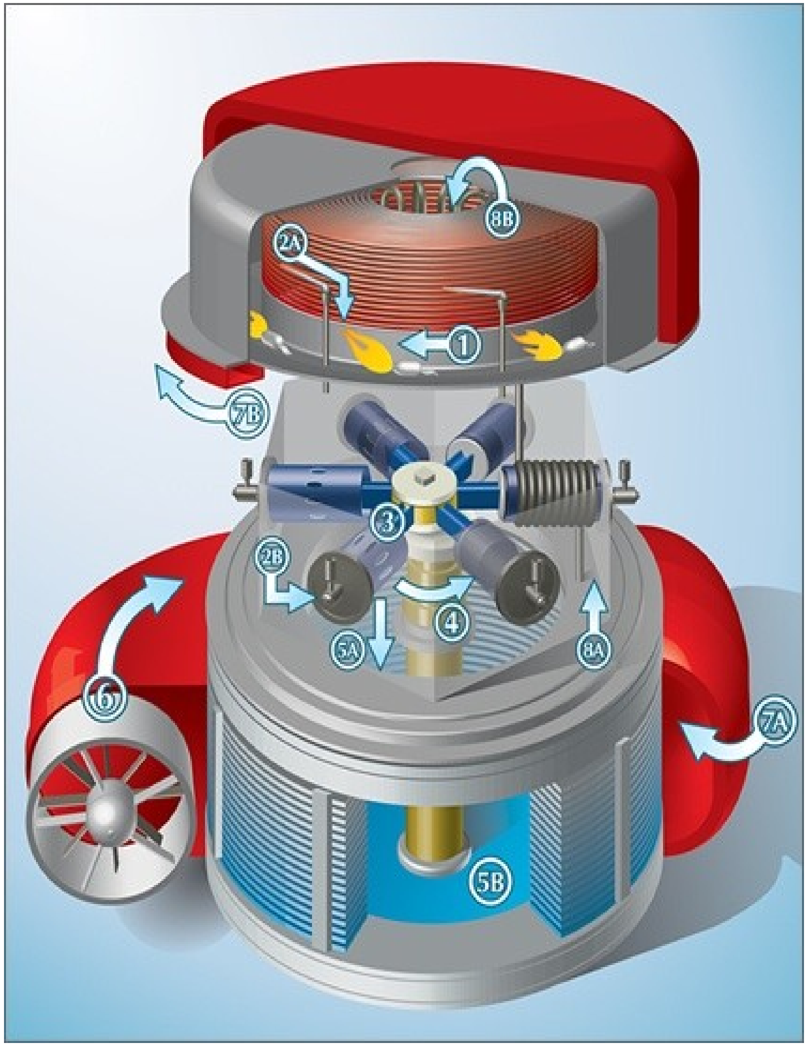
- **HEAT PROCESS**

(1) Fuel is atomized and injected into the patented centrifugal combustion chamber where a spark ignites the fuel-air mixture into a flame that spins around the heat coils. Thermocouples control the duration of combustion to keep the heat in the combustion chamber at a constant temperature.

(2) (2A) Water contained in the coils becomes super-heated steam (up to 1200°F) which is piped to the cylinders, **(2B)** where it enters through a valve system (not pictured).

- **MECHANICAL PROCESS**

(3) Steam enters the six radial-configured cylinders under pressures up to 3200 psi to push the pistons in sequence. No motor oil is used – water is both the working fluid and engine lubricant. Because of valve design, engine starts without the need of a starter motor.



HYBRID EXTERNAL COMBUSTION ENGINE

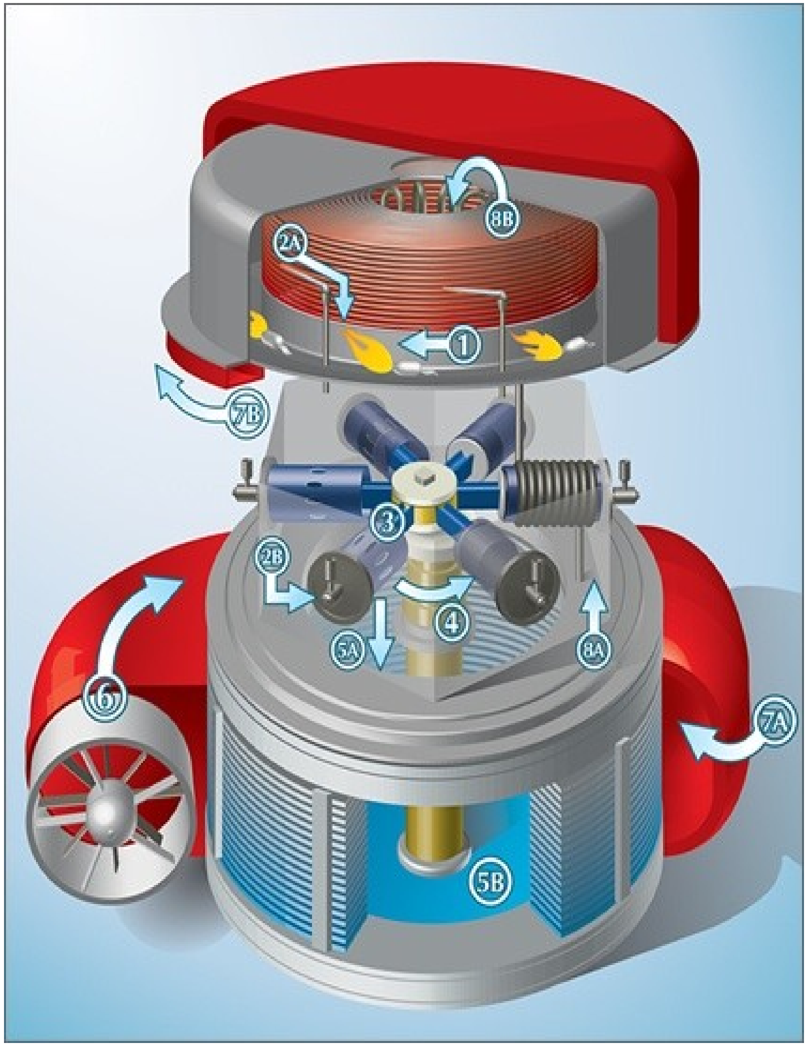
- **MECHANICAL PROCESS (CONT.)**

(4) The rotating action of the pistons connected through a patent-pending spider bearing (not pictured) turns the crank shaft. Note, because the greatest amount of torque occurs at the first rotation, the shaft can be directly connected to a drive train without a transmission.

- **COOLING PROCESS**

(5) **(5A)** Steam escapes the cylinders through exhaust ports and enters the patent-pending condensing unit where it turns back into water, and **(5B)** collects in a sealed pan at the bottom of the condenser. Note, this is a closed-loop system – the water does not need to be replaced or topped-off.

(6) Blowers spin fresh air around the condenser to speed the cooling process.

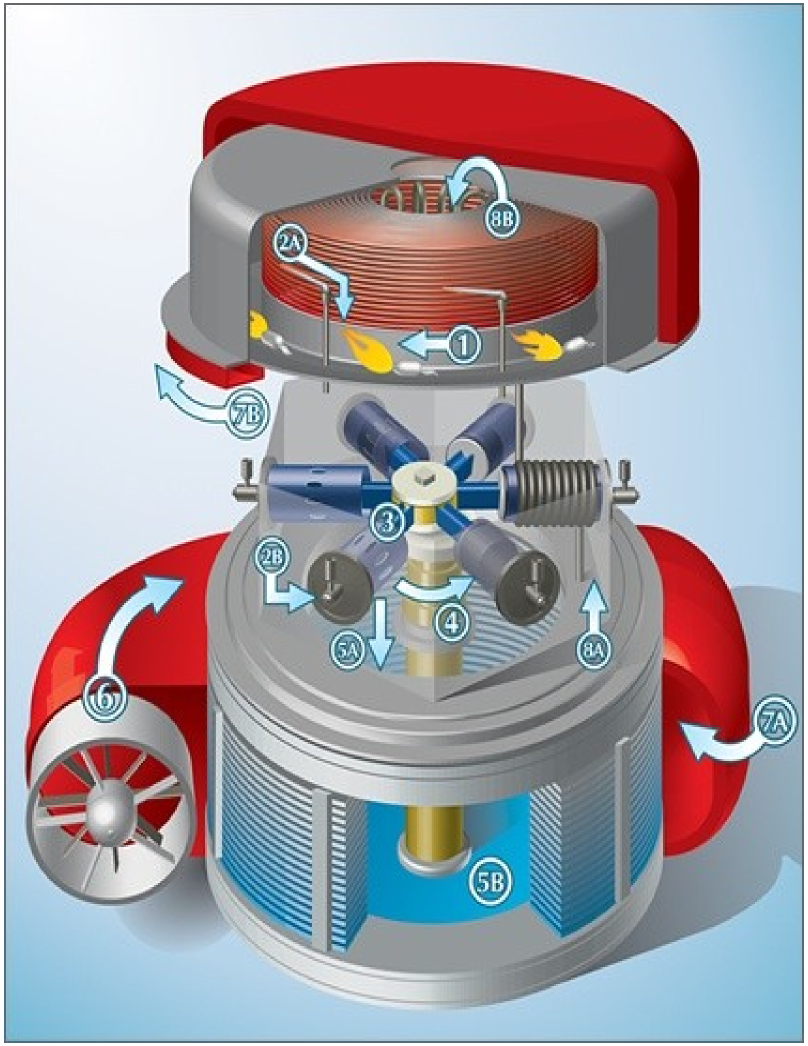


HYBRID EXTERNAL COMBUSTION ENGINE

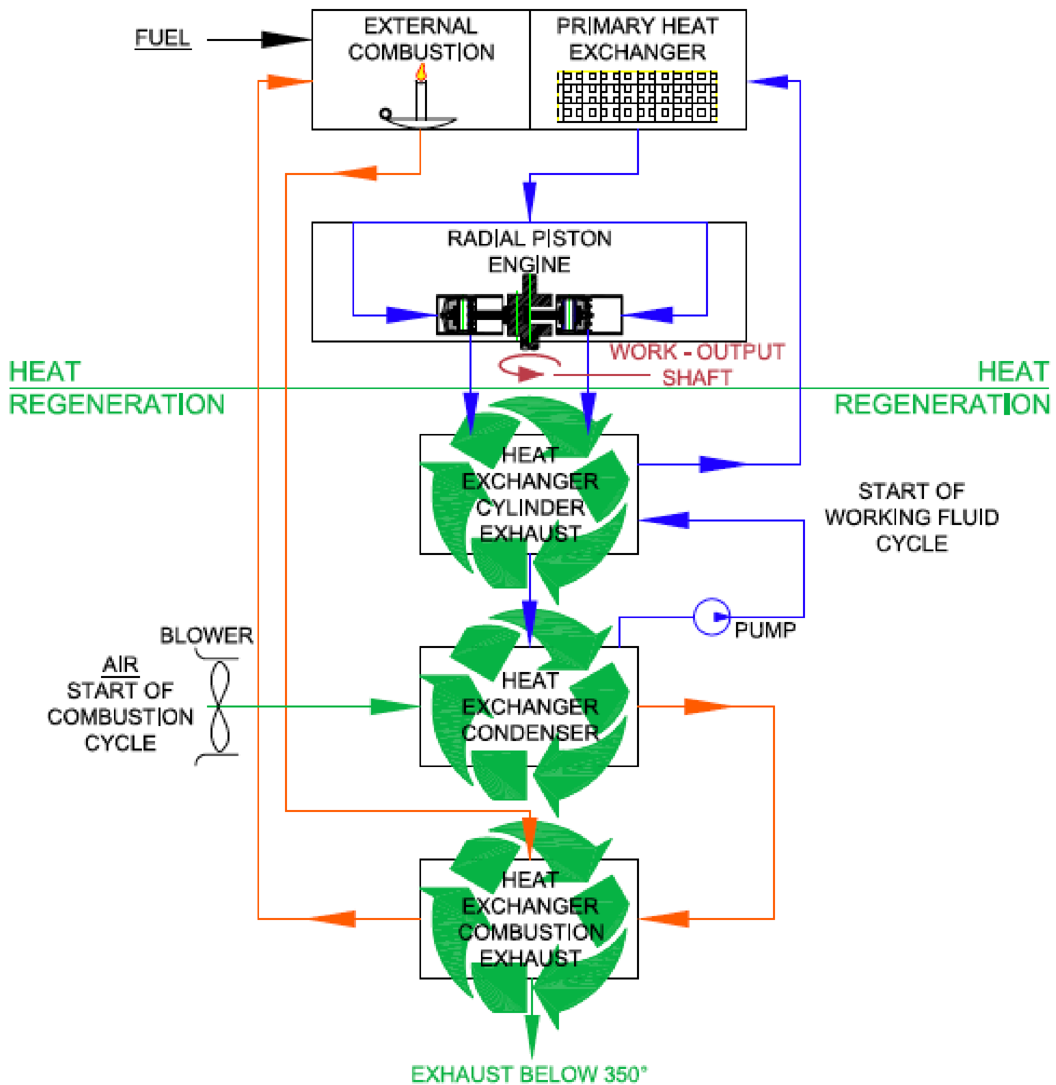
➢ **REGENERATIVE PROCESS**

(7) (7A) Air which has been pre-heated from the condensing unit, (7B) continues up to a second heat exchanger located in the exhaust port of the combustion chamber, further pre-heating the air used for combustion while also cooling the exhaust fumes (to about 320°F).

(8) (8A) A high pressure pump (not pictured) pipes water from the collecting pan to the heat coils via heat exchangers surrounding each of the cylinders (only one pictured), and then (8B) to the center of the coils to start the heat cycle again.



CYCLONE ENGINE CYCLE SCHEMATIC

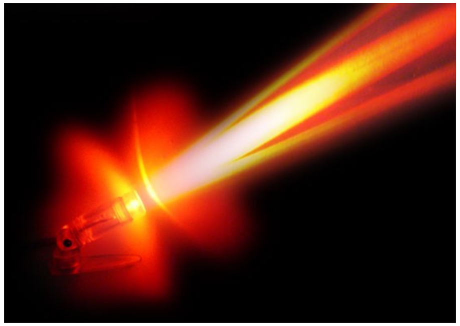


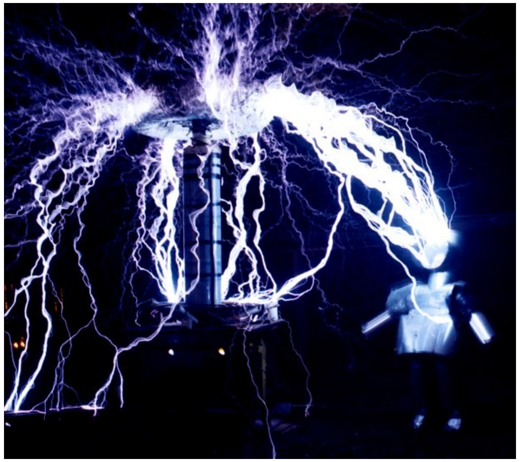
Patented, U.S. Patent No. 7,080,512 - Other Patents Pending, U.S. and Foreign.

EATR™ ENERGETICS: FEASIBILITY

- We performed a Rough Order of Magnitude (ROM) feasibility analysis of prospective energy sources and expenditures of the EATR™
  - A complete operational analysis will be performed during the Phase II Enhancement, along with technology risk reduction, experimental prototype design, and operational concept development
- The ROM energetics analysis showed that prospective EATR missions, such as long-range, long-endurance reconnaissance, surveillance, and target acquisition (RSTA), or serving as a pack-mule or mobile energy source, are energetically feasible

EATR™ ENERGETICS: ENERGY

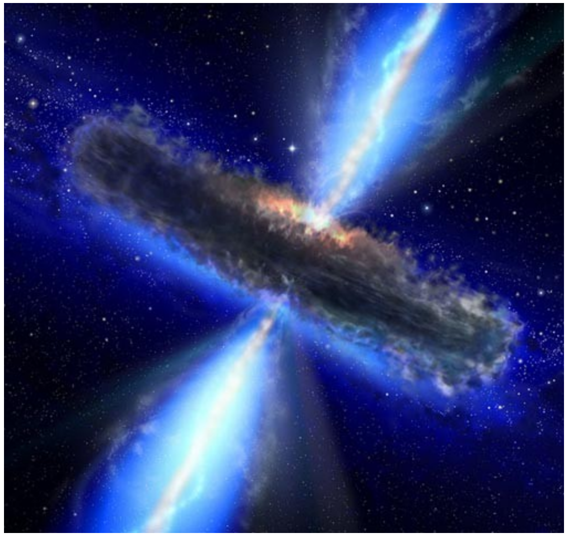


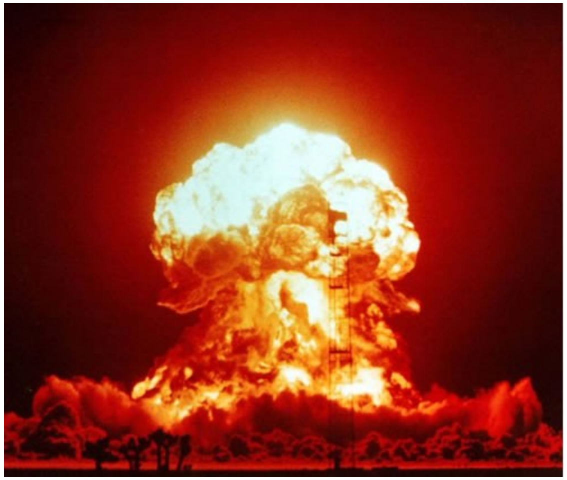


- There are many forms of energy, including: kinetic, potential, thermal, gravitational, sound, elastic, light, and electromagnetic; all forms of energy are equivalent and can be converted from one form into another
- There are many units of energy, but the current canonical unit of measurement for energy is the International System of Units (SI) unit of energy, the joule; other units of energy include the kilowatt-hour (kWh), the British thermal unit (Btu), and the horsepower-hour, which are larger units of energy than the joule, where the conversions are:
  - 1 kWh = 3,600,000 joules (exactly)
  - 1 Btu = 1,055 joules (approximately)
  - 1 kWh = 3,413 Btu (approximately)
  - 1 BTU = 0.00029 kWh (approximately
  - 1 kWh = 1.34 horsepower-hour (approximately)

EATR™ ENERGETICS: POWER

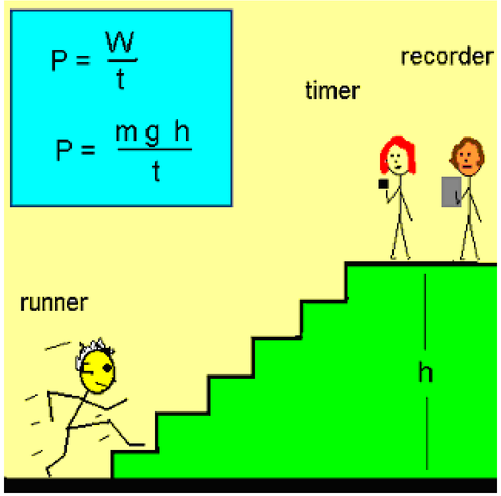
- In physics, power (P) is the rate at which work is performed or energy is transmitted, or the amount of energy required or expended for a given unit of time; as a rate of change of work done or the energy of a subsystem, power is:
  - P = Work/time
- The average power (often simply called "power" when the context makes it clear) is the average amount of work done or energy transferred per unit time; the instantaneous power is then the limiting value of the average power as the time interval Δt approaches zero
- Units of power are units of energy divided by time, where the SI unit of power is the watt (W), which equals one joule per second
  - There are non-SI units of power still in use, including the horsepower (hp)





EATR™ ENERGETICS: POWER

- **An incandescent light bulb typically uses 40-100 W; a person climbing a flight of stairs generates about 200 watts; an athlete produces 500 watts; a 30 hp automobile engine produces 25kW while cruising**
  - **One unit of horsepower is equivalent to 33,000 foot-pounds per minute, or the power required to lift 550 pounds one foot in one second, and is equivalent to about 746 watts**
  - **The kilowatt (kW) equals one thousand watts; a kilowatt-hour is the energy expended during an hour by a power output of 1 kW (or about 1.34 horsepower)**
  - **1 W = 1 joule/second = 1 j/s (exactly)**
  - **1 hp = 746 W (approximately)**
  - **1 hp = 0.746 kW (approximately)**
  - **1 kW = 1.34 hp (approximately)**



EATR™ ENERGETICS: OPERATIONAL ENVIRONMENT

- **The operational environment determines the availability of vegetation for the EATR™ energy supply (aside from auxiliary energy supplies), and it might include the vegetative spectrum from lush forests and crops to deserts, where conditions may be harsh but ample vegetation is still often available**

EATR™ ENERGETICS: OPERATIONAL ENVIRONMENT

- **Even in a harsh environment such as Afghanistan there is a variety of suitable vegetation which is sufficiently abundant**




EATR™ ENERGETICS: ENERGY CONTENT OF VEGETATION

- There are many different values for the energy content of vegetation as fuel, including a variation among the type (species) and state (seasoned, green, and freshly-cut)
  - Example: Hickory wood has about twice the energy per unit volume as Balsam Fir wood
  - Data is available on the energy content of wood for dozens of species of trees and other vegetation
- Maximum energy extraction: about 2.5 kWh/lb (8,660 Btu/lb) for perfectly dry vegetation with 0% moisture content in an atmosphere of pure oxygen
  - Unrealistic for practical applications

EATR™ ENERGETICS: ENERGY CONTENT OF VEGETATION

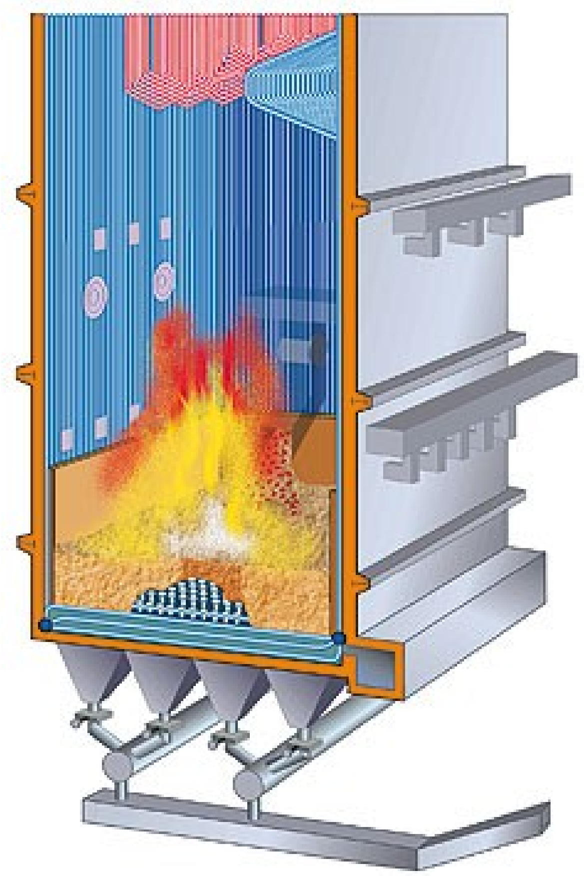
- **Vegetation other than wood can be used as a source of energy by EATR™, including grass, and leaves**
  - **As with wood, different species of grass and leaves have different energy contents, e.g., leaves from white chestnut and red oak trees have higher energy than leaves from maple trees**
- **In general, grass, leaves, and wood contain about the same amount of energy per unit weight**

EATR™ ENERGETICS: ENERGY CONTENT OF VEGETATION

- Summarizing the approximate energy content of vegetation (wood, grass, and leaves) and approximate conversions for the energy content of gasoline and coal:
  - Seasoned (Dry) vegetation = 2kWh/lb
  - Green vegetation = 0.9 kWh/lb
  - Fresh-cut vegetation = 0.6 kWh/lb
  - 1 gallon of gasoline = 18 lb (seasoned vegetation)
  - 1 gallon of gasoline = 40 lb (green vegetation)
  - 1 gallon of gasoline = 60 lb (freshly cut vegetation)
  - 1 lb coal = 1.4 lb (seasoned vegetation) = 0.078 gallons of gasoline

EATR™ ENERGETICS: FLUIDIZED BED COMBUSTION

- Freshly-cut and green vegetation, with higher moisture content, are not as easy for combustion as seasoned (drier) vegetation
  - Freshly-cut or green vegetation can be dried in a hopper with engine exhaust heat or used in fluidized bed combustion (FBC)
- FBC, in conjunction with an auxiliary fuel source, can be used to extract energy from vegetation with higher moisture content
  - FBC, used in power plants, involves the suspension of solid fuels (such as the green vegetation) on upward-blowing jets of air during the combustion process, resulting in a turbulent mixing of gas and solids
  - FBC provides more effective chemical reactions and heat transfer and allows the use of fuels which are otherwise difficult to burn



EATR™ ENERGETICS: ENERGY CONSUMPTION

- EATR™ mobility energy
  - A vehicle, such as a robotic HMMWV, getting about 12 mpg of gasoline could travel 100 miles burning 150 lb of dry vegetation (wood, leaves, or grass), assuming similar engine efficiencies and environmental effects
    - The Cyclone external combustion engine is generally more efficient than an internal combustion of equivalent power (more than 30% thermal efficiency vs. about 25-30% for automotive internal combustion engine)
  - The Cyclone external combustion engine can provide electricity to a battery pack to drive the vehicle or directly drive the vehicle – or do both, like a hybrid car
    - If a robotic vehicle were to achieve 50 mpg, then it could travel 100 miles on about 36 lb of dry vegetation or 77 lb of green vegetation or 125 lb of freshly cut vegetation

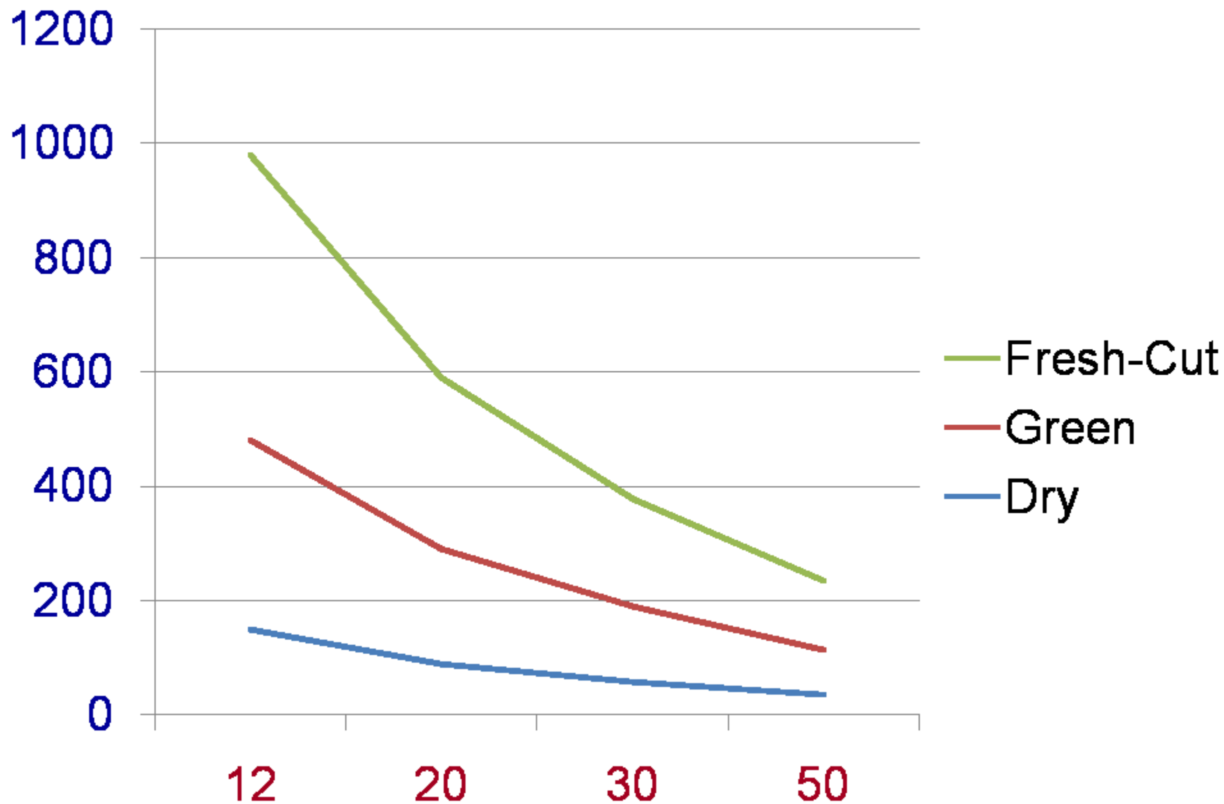
EATR™ ENERGETICS: ENERGY CONSUMPTION

- **EATR™ Mobility Energy: The Table shows examples of the weight of vegetation needed for vehicle mobility only (not including other mission functions), given a range of gas-equivalent mileage, where the EATR™ travels 100 miles**

Equivalent Gas Mileage (mpg)	Equiv. Gasoline Consumed (gal)	Dry Vegetation Weight (lb)	Green Vegetation Weight (lb)	Fresh Cut Vegetation Weight (lb)
12	8.3	150	330	500
20	5.0	90	200	300
25	4.0	72	160	240
30	3.3	59	130	190
50	2.0	36	79	120

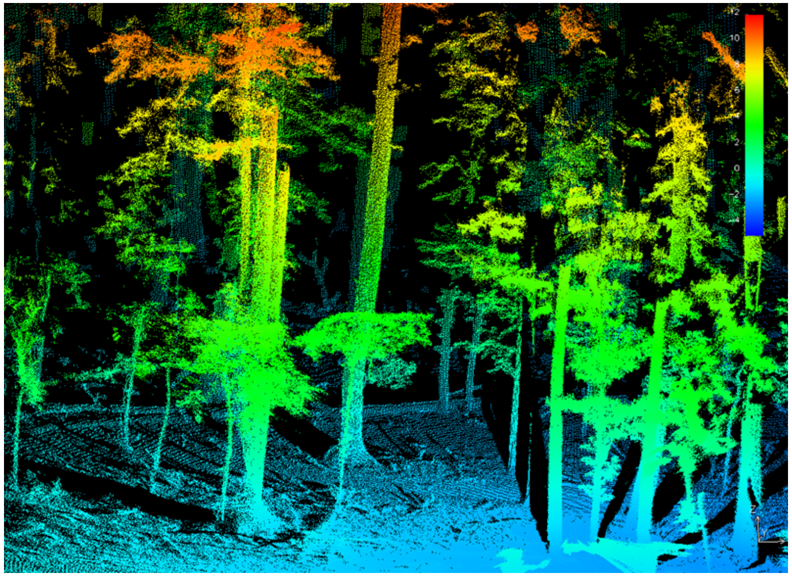
EATR™ ENERGETICS: ENERGY CONSUMPTION

- EATR™ Mobility Energy: The graph's y-axis shows the weight (lb) of vegetation needed for the EATR™ to travel 100 miles if the vehicle had the gas mileage (mpg) equivalent shown on the x-axis, for dry, green, and fresh-cut vegetation



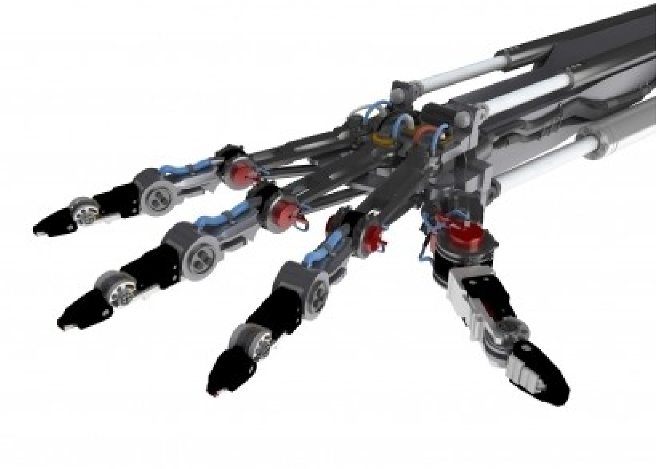
EATR™ ENERGETICS: ENERGY CONSUMPTION

- EATR™ non-mobility energy
  - In addition to energy needed for the mobility of the platform, all of the EATR™ subsystems require energy: sensors, processors, communications, robotic arm or harvester, and other payloads
  - Relatively little energy is required for housekeeping (or standby), where the processors and other subsystems are in a standby mode
  - A modest amount of energy is required for a reconnaissance, surveillance, and target acquisition (RSTA) mission when the platform is in an overwatch position and is stationary for a long time
  - As with animal herbivores, foraging would require the expenditure of energy as the EATR™ seeks and consumes vegetation: mobility, sensing, processing, manipulation, and consumption of vegetation



EATR™ ENERGETICS: ENERGY CONSUMPTION

- EATR™ non-mobility energy
  - Estimated power requirements for the EATR vehicle subsystems are:
    - Sensors (ladar, hyper-spectral camera, stereo digital camera, GPS/INS, strain gage, pan/tilt, acoustic): 100 W
    - Processors: 100 W
    - Robotic arm and end effector (while lifting): 200 W
    - Chipper/Shredder: 1,000 W = 1 kW
    - Brush mower: 10,000 W = 10 kW
  - The chipper/shredder and brush mower (if used) can consume significant power, but have relatively short duty cycles
  - A harvesting system (robotic arm, brush mower, etc.) could ingest 150 lb of vegetation within 15 minutes or so (even a single small swallow of only 15 pounds would provide sufficient energy to perform many missions



EATR™ ENERGETICS: ENERGY CONSUMPTION

- The table below summarizes what EATR™ would accomplish, approximately, with 150 pounds of dry or green vegetation, where vehicle 1 is a relatively low-mileage vehicle like a HMMWV, the equivalent of 12 mpg, while vehicle 2 is a relatively high-mileage vehicle, the equivalent of 50 mpg; standby and stationary operations assumes 25% for heat energy to electricity conversion

Vegetation State	Distance (miles) Vehicle 1	Distance (miles) Vehicle 2	Standby Ops. (hours)	Stationary Ops. (RSTA) (hours)
Dry (2kWh/lb)	100	400	1,000	100
Green (1kWh/lb)	45	180	450	45

- The table below summarizes what EATR™ would accomplish, approximately, with only 15 pounds of vegetation (10% of all in the above table)

Vegetation State	Distance (miles) Vehicle 1	Distance (miles) Vehicle 2	Standby Ops. (hours)	Stationary Ops. (RSTA) (hours)
Dry (2kWh/lb)	10	40	100	10
Green (1kWh/lb)	4.5	18	45	4.5

EATR™: SUMMARY ENERGY BUDGET

- Example: 15 lbs of dry vegetation could provide sufficient energy for
  - About 10-40 miles of driving, depending on the vehicle
  - About 100 hours of standby
  - About 10 hours for a stationary RSTA mission (depending on power draw and duty cycle) before needing to forage, process and generate/store power again
- About 150 lbs of vegetation could provide sufficient energy for 100 miles of driving (for a low-mileage vehicle)

EATR™AS A MOBILE GENERATOR

- **The military needs portable electricity: in one mission, the EATR™ can serve primarily as a mobile (or stationary) generator of electricity, providing energy for a multitude of applications**
  - **Depending on the application and energy to be generated, the system might be considerably larger than for purely combat missions**
  - **As a generator, EATR™ could either obtain its own sources of energy by autonomously foraging for vegetation or other combustible material – or vegetation could be brought to the EATR by human or robotic vegetation transporters**

EATR™ AS A MOBILE GENERATOR

- **There are a number of applications for EATR™ as a source of electrical energy, where it could provide:**
  - **Energy for the multitude of rechargeable batteries carried by soldiers**
  - **Electricity for mobile command and control centers**
  - **Energy for swarms of smaller, electrically-powered robots for combat missions (e.g., reconnaissance, surveillance, and target acquisition; tactical defense or offense)**
  - **Energy for civil-type applications (e.g., waste dump cleanup; civil reconstruction & services)**
  - **Energy for regular or emergency backup power for remote military or civil sites or unattended sensor arrays, in conjunction with solar and wind energy**
  - **Energy for Directed Energy Weapons (e.g., microwave or laser DEW)**

EATR™AS A MOBILE GENERATOR

- As an electrical generator, EATR™ would use combustion of vegetation as its primary source of energy, but could also use many other conventional and unconventional auxiliary fuels
  - Such as gasoline, Diesel, heavy fuel, kerosene, propane, natural gas, coal, paper, algae, solar, and cooking oil
- For example, the energy content of vegetation gasoline, and coal:
  - Dry vegetation = 2 kWh/lb
  - Green vegetation = 0.9 kWh/lb
  - Fresh-cut vegetation = 0.6 kWh/lb
  - 1 gallon of gasoline = 36 kWh
  - 1 gallon of gasoline = 18 lb (seasoned vegetation)
  - 1 gallon of gasoline = 40 lb (green vegetation)
  - 1 gallon of gasoline = 60 lb (fresh cut vegetation)
  - 1 lb coal = 1.4 lb dry vegetation = 0.078 gallons of gasoline

EATR™ AS A MOBILE GENERATOR

- By 2015-2020, each soldier will require at least 20W of power the advanced combat suit
  - With integrated sensors, processors, communications, weapons, environmental comfort, health-monitoring, and self-protection (not including powered exoskeletons)
- Worst-case scenario: soldier requires 20W for 24 hours = 480 Wh (0.5 kWh rounded)
  - A single AA battery provides about 4 Wh; 0.5 kWh is equivalent to 125 AA batteries per day per soldier
- Army unit sizes vary, but assume a US Army company = 200 soldiers and an Army battalion = 1,000 soldiers
  - Worst-case scenario: every soldier drawing 20W 24 hours/day; then a company requires 100 kWh/day and battalion 500 kWh/day
  - Assume in normal operations the energy demand would be half: 50 kWh/day for the company and 250 kWh/day for the battalion

EATR™ AS A MOBILE GENERATOR

- **Assuming an EATR™ efficiency of 25% for heat to electrical conversion, stored in a battery pack**
  - **The daily weight of dry vegetation (double for green vegetation) to generate the daily energy needed by US Army soldiers, companies, and battalions, assuming 20 W/soldier/day for 24 hours/day (worst-case) and 12 hours/day (nominal case), is:**
    - **Per soldier (max): 1 lb/day**
    - **Per soldier (nominal): 0.5 lb/day**
    - **Per Company (max): 200 lb/day**
    - **Per Company (nominal): 100 lb/day**
    - **Per Battalion (max): 1,000 lb/day**
    - **Per Battalion (nominal): 500 lb/day**

EATR™ AS A MOBILE GENERATOR

- Even for worst case scenarios sufficient vegetation should be readily available for soldiers
  - With auxiliary energy sources available for those cases where vegetation is either unavailable or cannot be gathered
- A Command and Control Center, with electronics and air conditioning (a major consumer of electricity) might require 20kW for 24 hours/day, or 480 kWh/day – round up to 500 kWh/day – the same as a battalion's energy requirements for all of its (1,000) soldiers, each with advanced soldier systems
  - The Command and Control Center would then need 1,000 lb of vegetation per day, assuming an energy conversion efficiency of 25%

EATR™ AS A MOBILE GENERATOR

- Examples energy content of standard bundles of vegetation of hay and wood
  - Single bale of hay (as produced by standard farm equipment) exceeds 1,000 lb and could provide sufficient daily energy for the entire exemplar Command and Control Center
  - Volume and weight of a cord of wood varies depending on the type of wood and moisture content
    - From about 70 ft^3 to 90 ft^3, and from about 2,000 lb to 4,000 lb (for dry wood at about 12% moisture content) and from about 3,000 lb to 7,000 lb (for green wood at about 50% moisture content)
  - Half a cord of wood per day could provide sufficient daily energy for the entire exemplar Command and Control Center

EATR™: COMMERCIALIZATION OPPORTUNITY

- Commercialization of the EATR™ is focused on:
  - Developing a prototype EATR™ for military applications and civil applications including agriculture, forestry, and homeland security
  - Evolving the NIST 4D/RCS autonomous intelligent control system for a wide variety of applications, including:
    - Unmanned air, ground, and water vehicles; robotic swarms and cognitive collectives; driverless cars; distributed intelligence; ubiquitous intelligence and intelligent infrastructures; control of complex systems of systems; decision tools for decision makers

EATR™: COMMERCIALIZATION OPPORTUNITY

- We are able to fast-track the Phase III commercialization (for military and civil applications) of our technology because DARPA will match dollar-for-dollar additional funding from companies or other government agencies
  - Therefore, we are interested in teaming with organizations (government or industry) which will invest in the project in exchange for sharing in the intellectual property and commercialization of our transformational technology

EATR™: COMMERCIALIZATION OPPORTUNITY

- There are more than a dozen scientists and engineers working on the EATR™ project
- The University of Maryland Intelligent Systems Laboratory is our subcontractor
- Elbit Systems of America signed on as our first Teaming Partner, Boeing our second, and the US Forest Service will be our third
- We have plans for additional Teaming Partners during the Phase III Commercialization: DARPA will match funds dollar for dollar for 100% leveraging
- NIST is our subcontractor, transferring the 4D/RCS autonomous intelligent control system to the EATR™ Project

RTI

UNIVERSITY OF MARYLAND

CTSM
Technology for Intelligent Decisions

I S L
Intelligent Systems Laboratory

Elbit Systems of America

BOEING

NIST

FOREST SERVICE
U S
DEPARTMENT OF AGRICULTURE