MILITARY ROBOTICS: MALIGNANT MACHINES OR THE PATH TO PEACE?

Presented By:

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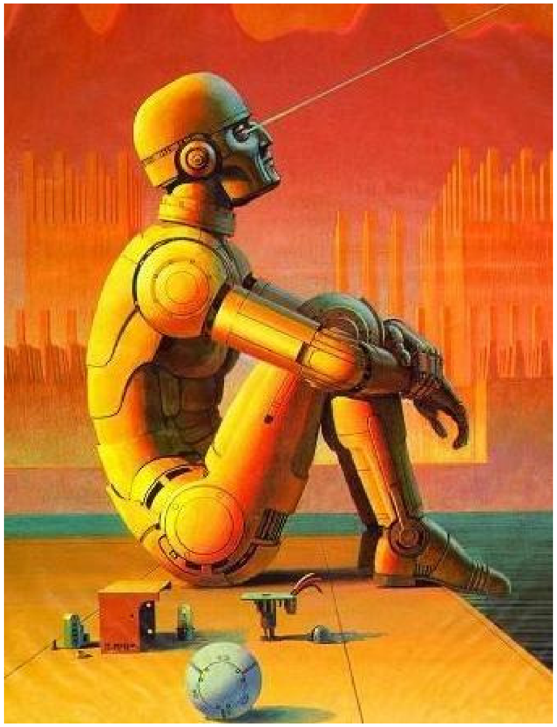
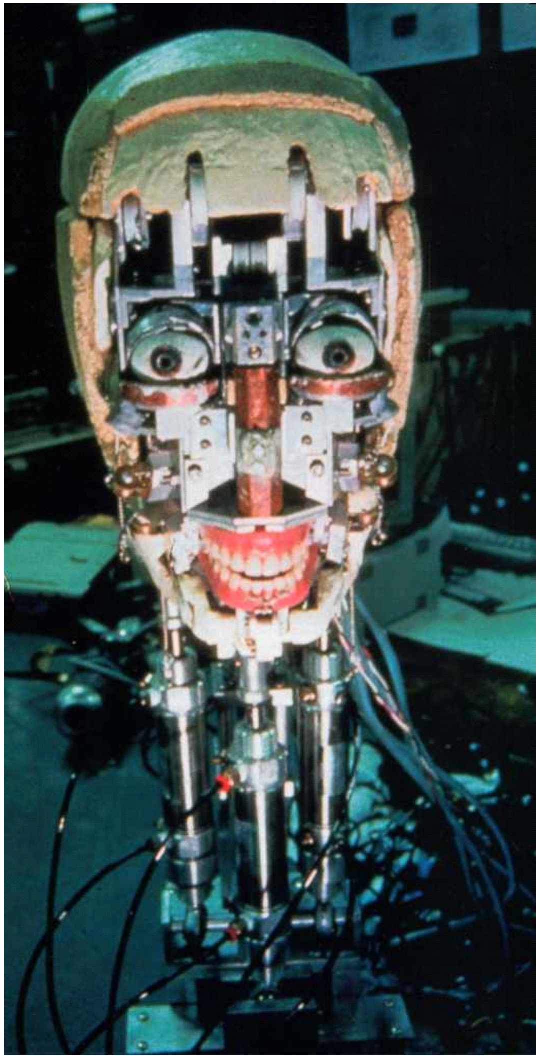


September 2007

AN OVERVIEW OF MILITARY ROBOTICS

- A brief history of military robotics
- Types of military robots
- Intelligence and autonomy
- Current programs and the Future Combat System
- State of the technology
- Potential impacts on tactics, strategy, doctrine
- Military robotics for homeland security
- Humanoid, legged, and chimera robots
- Commercialization of military robotics
- Forecast to the 22nd century – impacts on the military and society

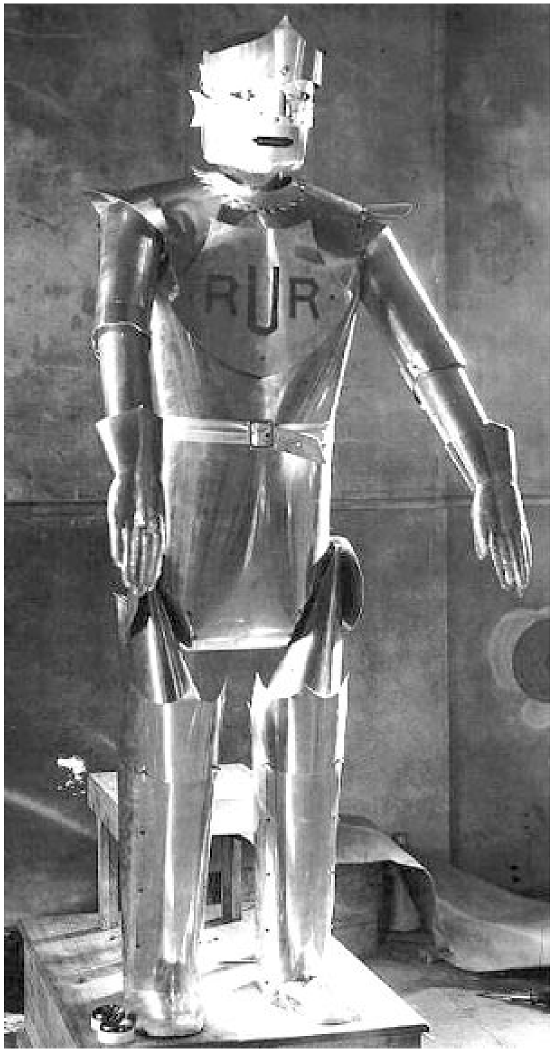


WHAT IS A ROBOT?

- Neologism derived from Czech noun "robota" meaning "labor"
  - Contrary to the popular opinion, not originated by (but first popularized by) Karel Capek, the author of RUR
  - Originated by Josef Capek, Karel's older brother (a painter and writer)
- "Robot" first appeared in Karel Capek's play *RUR*, published in 1920
  - Some claim that "robot" was first used in Josef Capek's short story *Opilec* (the *Drunkard*) published in the collection *Lelio* in 1917, but the word used in *Opilec* is "automat"
  - Robots revolt against their human masters – a cautionary lesson now as then

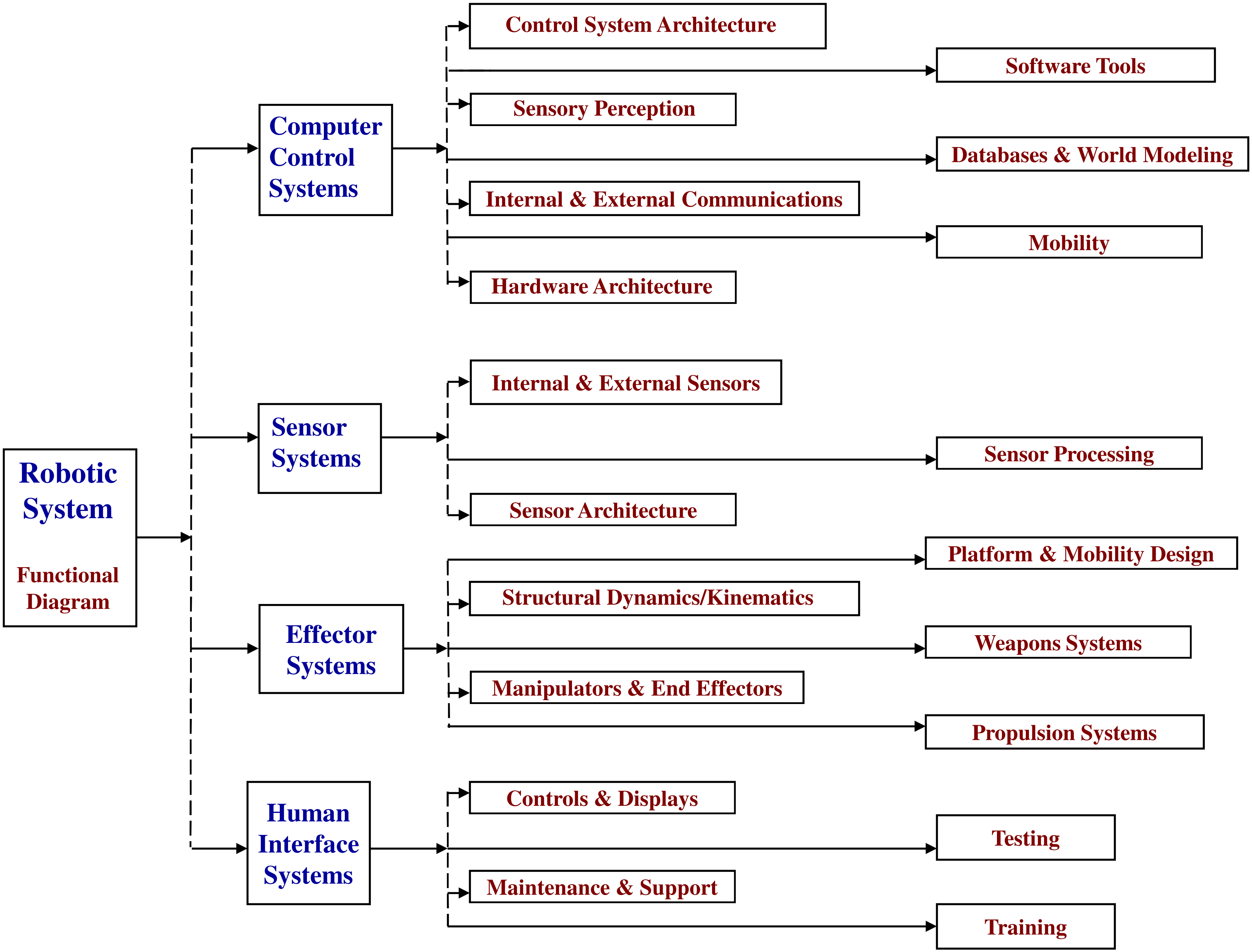
WHAT IS A ROBOT?

- Many taxonomies
  - Control taxonomy
    - Pre-programmed (automatons)
    - Remotely-controlled (telerobots)
    - Supervised autonomous
    - Autonomous
  - Operational medium taxonomy
    - Space
    - Air
    - Ground
    - Sea
    - Hybrid
  - Functional taxonomy
    - Military
    - Industrial
    - Household
    - Commercial
  - Etc.



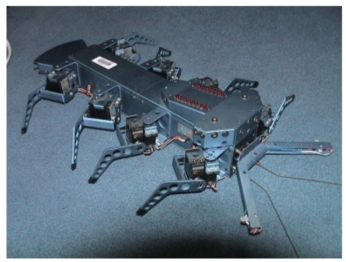
WHAT IS A ROBOT?

- The emerging robot is a machine with sensors, processors, and effectors able to perceive the environment, make appropriate decisions, and act upon the environment
  - Various sensors: active and passive optical and ladar vision, acoustic, ultrasonic, RF, microwave, touch, etc.
  - Various effectors: propellers, wheels, tracks, legs, hybrids
  - Various control system architectures: deliberative, reactive, hybrid
  - Various command, control, and communications systems: cable, fiber optic, RF, laser, acoustic
  - Various human/machine interfaces: displays, telepresence, virtual reality
- Military unmanned vehicles are robots
  - Air, ground, water

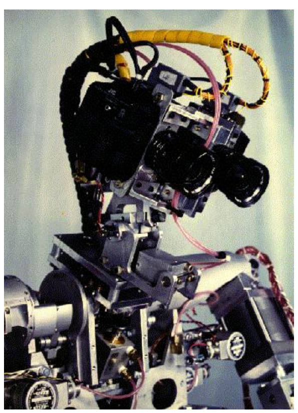

Robotic System
Functional Diagram
Computer Control Systems
Control System Architecture
Software Tools
Sensory Perception
Databases & World Modeling
Internal & External Communications
Mobility
Hardware Architecture
Sensor Systems
Internal & External Sensors
Sensor Processing
Sensor Architecture
Effector Systems
Platform & Mobility Design
Structural Dynamics/Kinematics
Weapons Systems
Manipulators & End Effectors
Propulsion Systems
Human Interface Systems
Controls & Displays
Testing
Maintenance & Support
Training

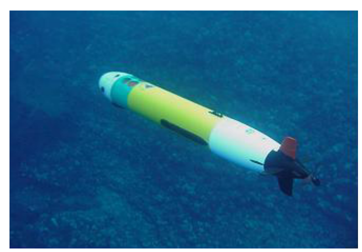
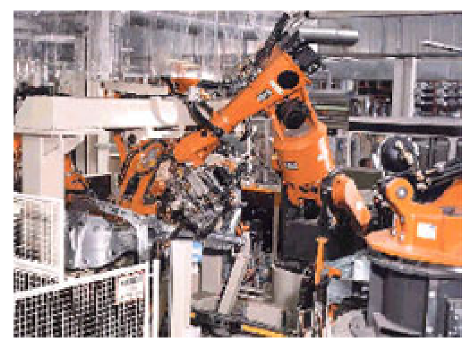
A POTPOURRI OF ROBOTS





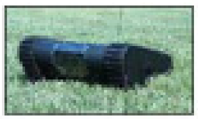
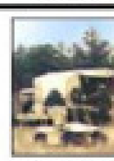
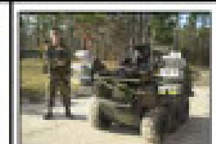
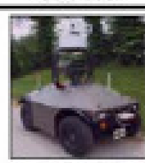
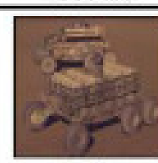
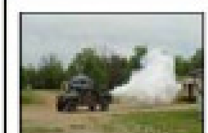
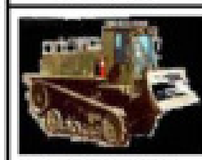


A POTPOURRI OF ROBOTS

- **There are many taxonomies that have been used for robotic air, ground, and water vehicles: based on size, endurance, mission, user, C3 link, propulsion, mobility, altitude, level of autonomy, etc., etc.**

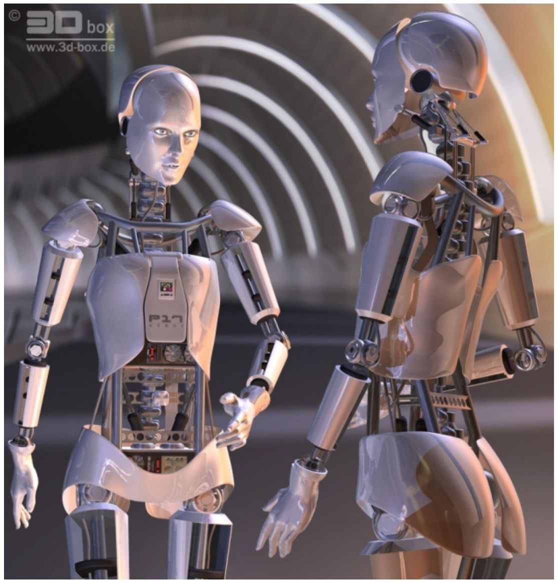
Summary of JRP Weight Classes

Small (Light) 31 to 400 lbs	 MATILDA 40 lbs	 PackBot 40 lbs	 ODIS 40 lbs	 TALON 80 lbs	 T3 110 lbs	 EOD MTRS 145 lbs
Small (Medium) 401 to 2500 lbs	 RONS 600 lbs	 SARGE 650 lbs	 REDCAR 1000 lbs	 GLADIATOR 1600 lbs	 Mini-Flail 2500 lbs	
Small (Heavy) 2501 to 20K lbs	 MDARS 2640 lbs	 DEMO III XUV 3000 lbs	 MULE 5000 lbs	 ARTS 8100 lbs	 RCSS 11,220 lbs	 Smoke HMMWV-CRS 11,500 lbs
Large Over 30K lbs	 DEUCE-CRS 18 tons	 D7G-CRS 28 tons	 A-AOE 34 tons	 Panther-CRS 40 tons	 Abrams Panther-CRS 43 tons	

*No systems currently exist in the Micro (<8 lbs), Miniature (8-30 lbs), or Medium (20K-30K lbs) classes.

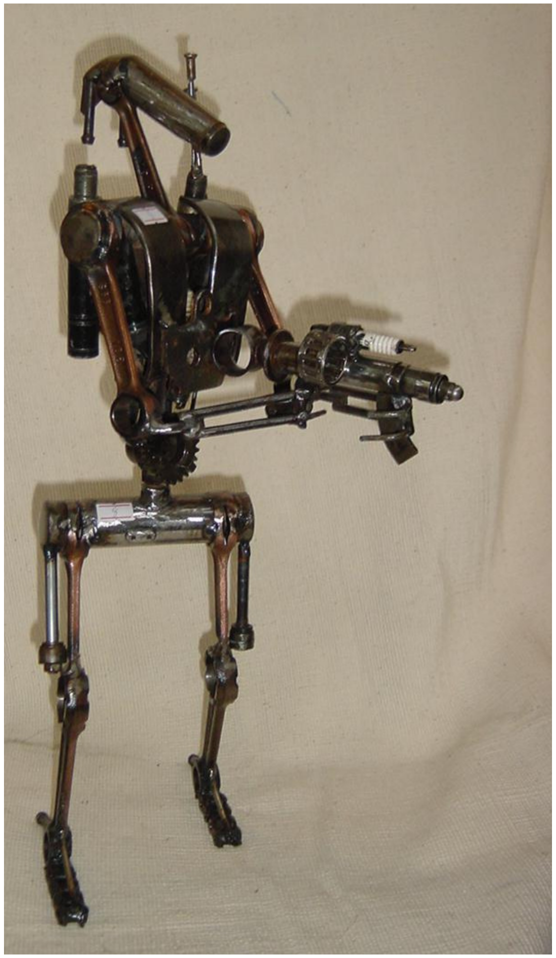
RATIONALE FOR ROBOTS

- Three Hs: hot, heavy, hazardous
- Three Ds: dull, dirty dangerous
- Increasing lethality of warfare
  - Less acceptance of casualties and POWs
  - High attrition of expensive, not easily replaced, systems
  - Televised & Internet war
- Personnel costs & changing demographics
- Changing geopolitical climate & doctrine
- Proliferation of weapons of mass destruction (CBR)
  - Render large areas toxic, uninhabitable
  - Protective garments limit manned efficiency and effectiveness



RATIONALE FOR ROBOTS

- No need to encase and protect humans in vehicles: smaller, lighter, less expensive
- Expendable: suicide missions
- More survivable: small signature
- More maneuverable: faster, higher acceleration
- Faster response time: pre-positioning
- Riskier maneuvers and tactics
- Fearless and aggressive: not deterred by near misses
- No need for sleep or rest
- Fewer personnel can supervise more systems
- Advancing, emerging technology: US strength and decreasing cost
- Disruptive, transformative technology
- Equivalent of ESP



RATIONALE FOR ROBOTS

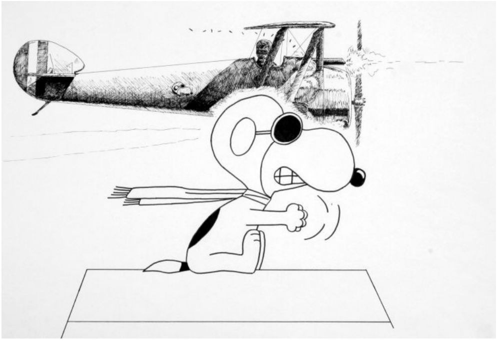
Congress has mandated that one-third of all combat vehicles will be robots by 2015

RATIONALE FOR ROBOTS

- In this presentation we are focusing on robotic ground vehicles
  - Also known as unmanned ground vehicles (UGV)
  - But will include, from time to time, to air and sea robotic vehicles

Advantages Of Robotic Air Vehicles

- They don't need crew rest
- They don't hog all the seats at the officer's club during happy hour
- You don't have to call them by some dumb nickname
- It doesn't bother them that they don't know their parents
- They don't have egos greater than all outdoors
- They don't embarrass you at social functions by molesting the opposite sex and playing aircraft carrier on a beer-soaked table
- They don't throw up on your wife's new dress
- They don't need $100 sunglasses to hide their bloodshot eyes
- They don't need no stinkin' leather flight jacket



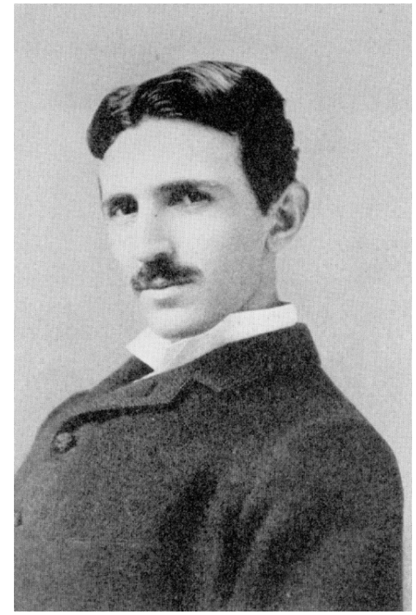
Advantages Of Robotic Ground Vehicles

The Army recently had a road test for its new **autonomous intelligent Robotic Ground Vehicle.** The program manager, briefing the General, was somewhat disappointed.

"The robot was doing fine," he said, "autonomously driving itself along the road, staying in its lane, and avoiding obstacles. But after a few miles **it ran over a skunk** which was crossing the road, and then a little later **it ran over a lawyer** who was out jogging."

"But, General," said the program manager, "the test wasn't a total failure – it left ***skid marks*** in front of the ***skunk***."

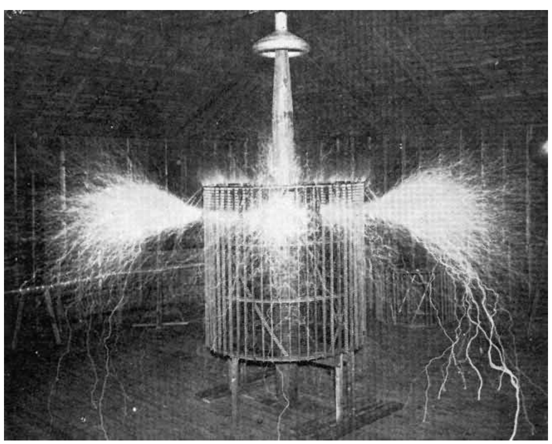
A BRIEF HISTORY OF MILITARY ROBOTICS

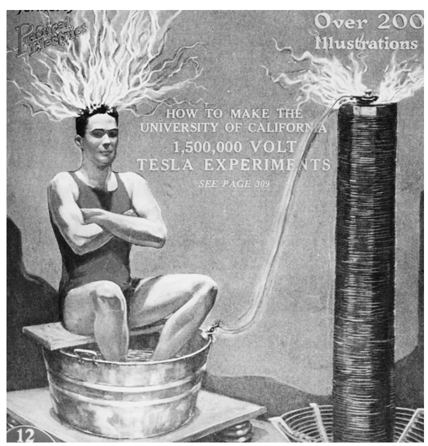


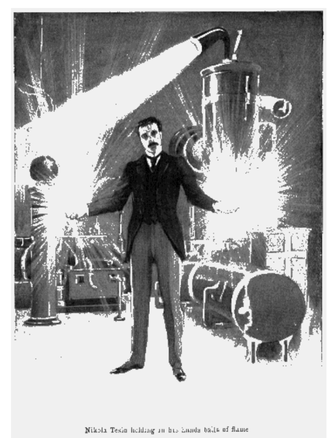
"Those who cannot remember the past are condemned to repeat it." **-- Santayana**

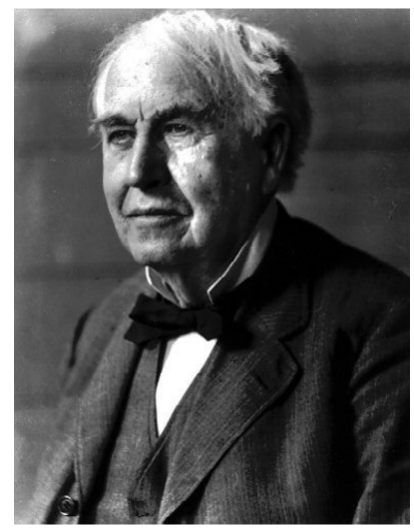
"History is bunk." **-- Henry Ford**

- **Ancient History (Before 1980)**
  - **Dawn of robotic vehicles: late 1800s when American researchers such as Thomas Edison and Nikola Tesla, while pioneering early radio technology, were also experimenting with radio-controlled devices**



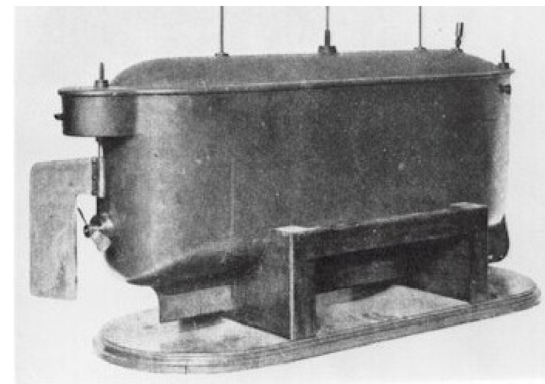


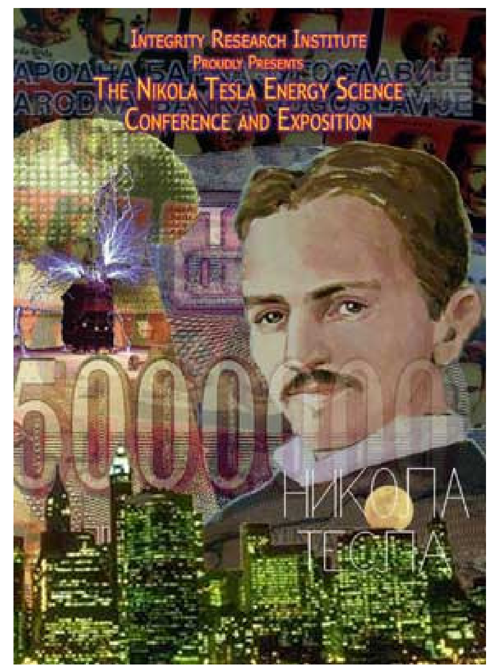




A BRIEF HISTORY OF MILITARY ROBOTICS

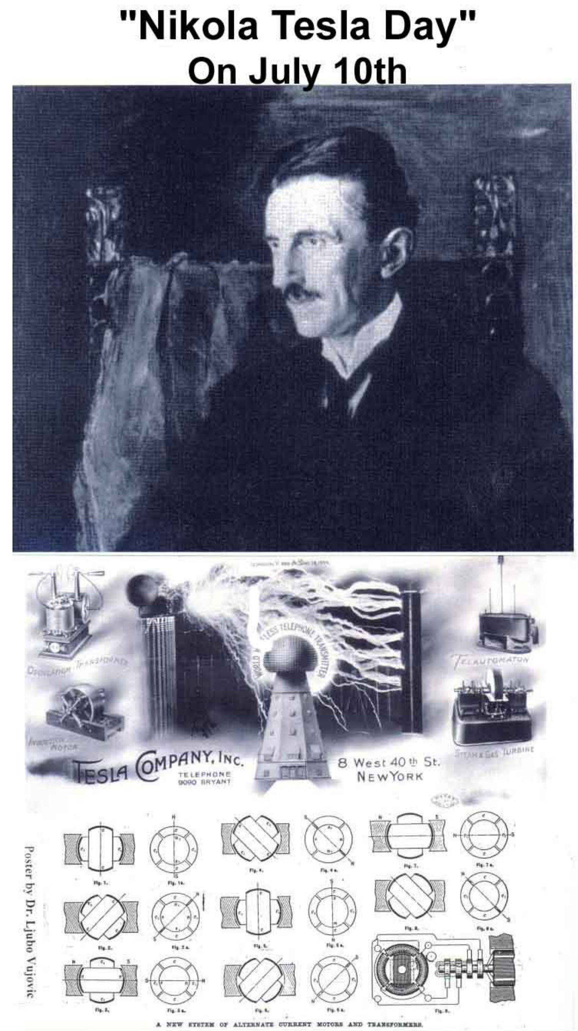
- **In 1898 Tesla demonstrated long-wave wireless communication and the remote control of vehicles at Madison Square Garden**
  - **Tesla named his invention *teleautomatics***
  - **Also conceived of a system to prevent the control signals from being jammed by using coordinated tuning devices that responded only to a combination of several radio waves at different frequencies**
  - **In 1900 Tesla prophesied the advent of autonomous, intelligent robotic vehicles, writing that such a vehicle "will be able to follow a course laid out or to obey orders given far in advance; it will be capable of distinguishing between what it ought to do and of making experiences … of recording impressions which will definitely affect its subsequent actions"**





A BRIEF HISTORY OF MILITARY ROBOTICS

- **Telsa's 19th century vision had to be tempered with the real world of bureaucrats and funding: he said shortly after patenting his device:**
  - **"I called an official in Washington, with a view of offering the invention to the government, and he burst out in laughter upon telling him what I had accomplished"**
  - **"Nobody thought then that there was the faintest prospect of perfecting such a device"**

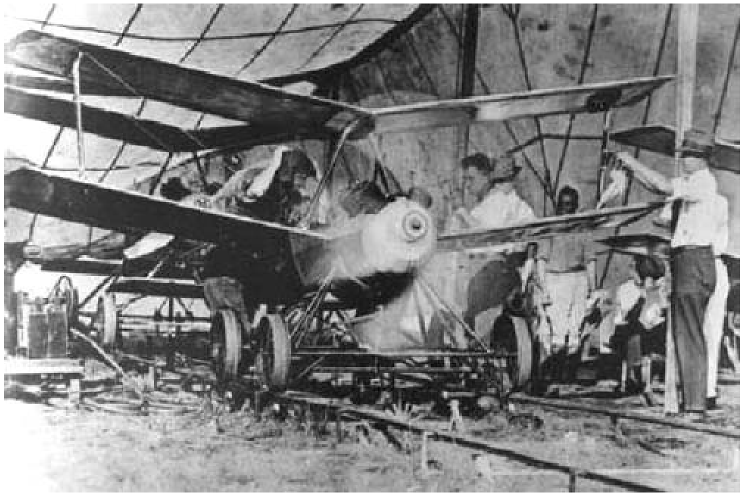


A BRIEF HISTORY OF MILITARY ROBOTICS

- By World War I there was a growing appreciation of automated vehicles
  - Unmanned aircraft, such as
    - Kettering"Bug" (an "aerial torpedo")
    - Automated Navy N-9 Curtis Seaplane
    - Note: In 1890s, Samuel Langley (of the Smithsonian) flew unmanned aircraft ("aerodromes") and nearly was the first to demonstrate a manned aircraft
  - Unmanned ground vehicles, such as
    - "Electric Dog" three-wheeled cart
    - "Land torpedo" – a modified car
  - Unmanned water vehicles, such as
    - German unmanned motor boats

A BRIEF HISTORY OF MILITARY ROBOTICS

- Kettering "Bug" (an "aerial torpedo")
  - 530-lb (238 kg biplane designed to carry a 180-lb (52 kg) bomb a distance of 40 miles (64 km) at 55 mph (88kph)
  - Designed from scratch as unmanned air vehicle
  - 1918 flight tests – fourth flight successful
  - War ended soon after
- Automated Navy N-9 Curtis Seaplane
  - Flown by pre-set gyroscope for direction, aneroid barometer for altitude
  - At estimated distance, engine stopped, mechanism removed bolts
  - Fuselage filled with explosives descended on target
  - 1919 flight test – flew 1,000 yards



A BRIEF HISTORY OF MILITARY ROBOTICS

- **WWI "Electric Dog" three-wheeled cart: 1915**
  - **Three-wheeled cart improvised from a child's tricycle**
  - **Controlled and activated by beams of searchlight acting on selenium cells**
  - **Demonstrated how shining a light could remotely drive the vehicle**
    - **When the light shined on the right cell, the steering wheel turned to the right; on the left, it turned left**
    - **The Electric Dog would follow the light of a lantern at night, thus trailing behind a person carrying the light**
    - **The four circuits controlling the vehicle were connected for forward, reverse, and right and left turns**
  - **This technology successfully demonstrated the simultaneous and independent operation of control circuits**
    - **Was explored further in the 1920s by the U.S. Naval Research Laboratory**

A BRIEF HISTORY OF MILITARY ROBOTICS

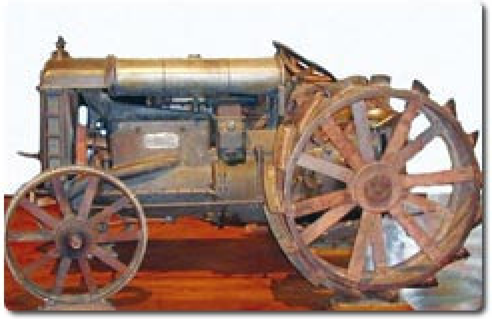
- “Land torpedo” – a modified car: 1915
  - A cheap, unmanned vehicle that could carry either a high explosive mine, shrapnel, missile, or a combination payload
  - It could also be equipped with caterpillar wheels and a wire cutter, enabling the vehicle to cross over shell craters and through entanglements, into the enemy’s trenches, where it would be exploded
  - Vital parts would be armored to enhance survivability
  - Prototype was ordinary, small gasoline-powered automobile converted into a “land torpedo”
  - Designed to carry about 1,000 pounds (454 kg) of explosives mounted on crutch-like frames
  - Wire cables led from electric ignition coils to the vehicle

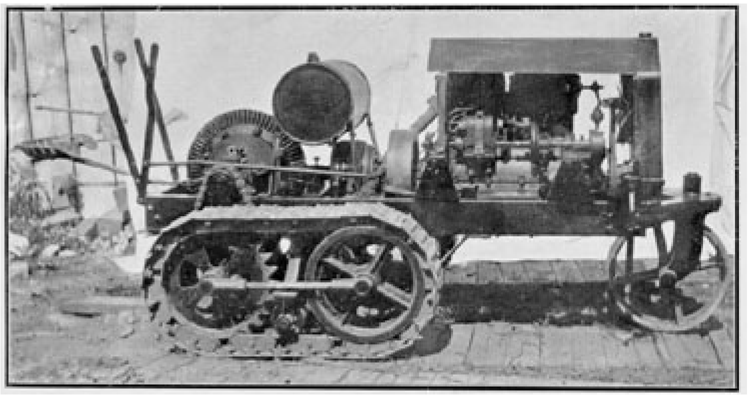
A BRIEF HISTORY OF MILITARY ROBOTICS

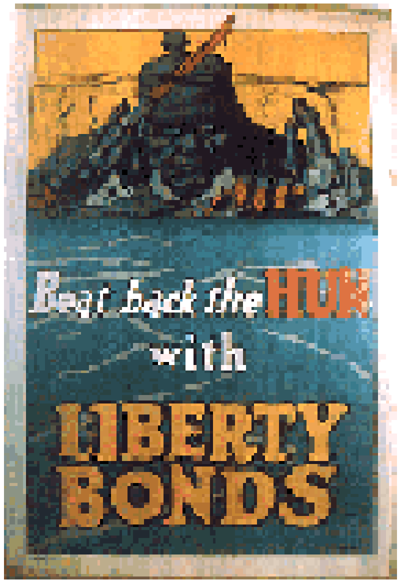
- WWI Land Torpedo operational concept
  - Inexpensive used cars could be converted into cost-effective weapons platforms
  - From shipping points in Europe, the men of the Land Torpedo Corps could manually drive the converted automobiles directly to the World War I front (relieving the railroads of transporting the vehicles)
  - On reaching the front, the crew would mount explosive charges on the vehicle, set and lock the steering gears, and open a clutch from the rear of the vehicle
  - Land torpedo would attack the enemy at speeds up to 60 mph (96 kph)

A BRIEF HISTORY OF MILITARY ROBOTICS

- **In 1918, the Caterpillar Tractor Company designed and developed a remotely controlled demolitions carrier, called the Land Torpedo, partly based on the earlier concept**
  - **Battery-powered and teleoperated via cable**
  - **Completed too late for combat in WWI**





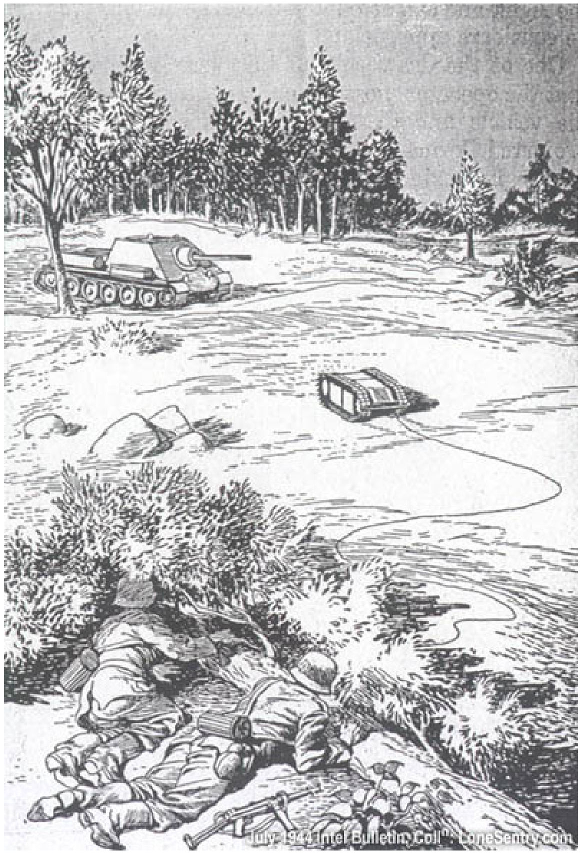


A BRIEF HISTORY OF MILITARY ROBOTICS

- A patented a Land Torpedo concept was featured in the September 1917 issue of *Popular Science Monthly*
  - An inexpensive way to obliterate breastworks and barbed wire entanglements, and blast the enemy from entrenched positions
  - Vehicle was basically a car frame with front a rear axels, spiked wheels for traction, and a container for several hundred pounds of high explosives (which would destroy everything within a radius of 200 feet)
  - Gas, steam, compressed air, or a battery would propel it
  - Control was via cable

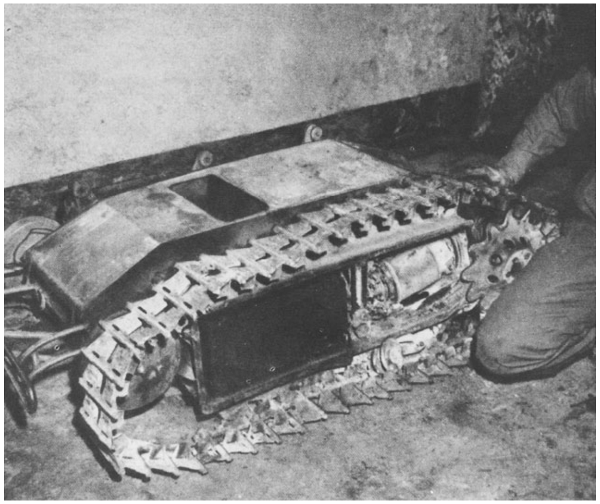
A BRIEF HISTORY OF MILITARY ROBOTICS

- Between WWI and WWII, there were concepts and developmental systems for unmanned air and ground vehicles
  - The Germans used the Electric Dog technology in World War II to develop an inexpensive telerobotic vehicle for mine clearing
  - In 1939, the Borgward Company of Brener developed a full-tracked, remotely controlled vehicle (the BI)
    - It had a hull made of concrete and a four-cylinder engine, and it towed a steel-roller mine-clearing device
    - Fifty BIs were delivered by 1940
    - A hundred units of an improved version with a six-cylinder engine, the BII, were produced



A BRIEF HISTORY OF MILITARY ROBOTICS

- The BII was followed by the BIV Demolition Vehicle, which went into mass production in 1942, with about 500 built during the war
  - It weighed over 8,000 pounds (3,660 kg) and incorporated the chassis of a tracked load carrier
  - It carried a large explosive charge container hooked to its front, and an onboard driver would manually drive the vehicle until he considered driving to be unsafe, at which point he dismounted and the BIV continued its mission under radio control
  - Upon reaching the target, the vehicle would release its charge with a delay ignition device, and then back away to a safe distance before the charge was initiated
  - However, the delay mechanism often failed, resulting in the destruction of the vehicle along with the target



Goliath

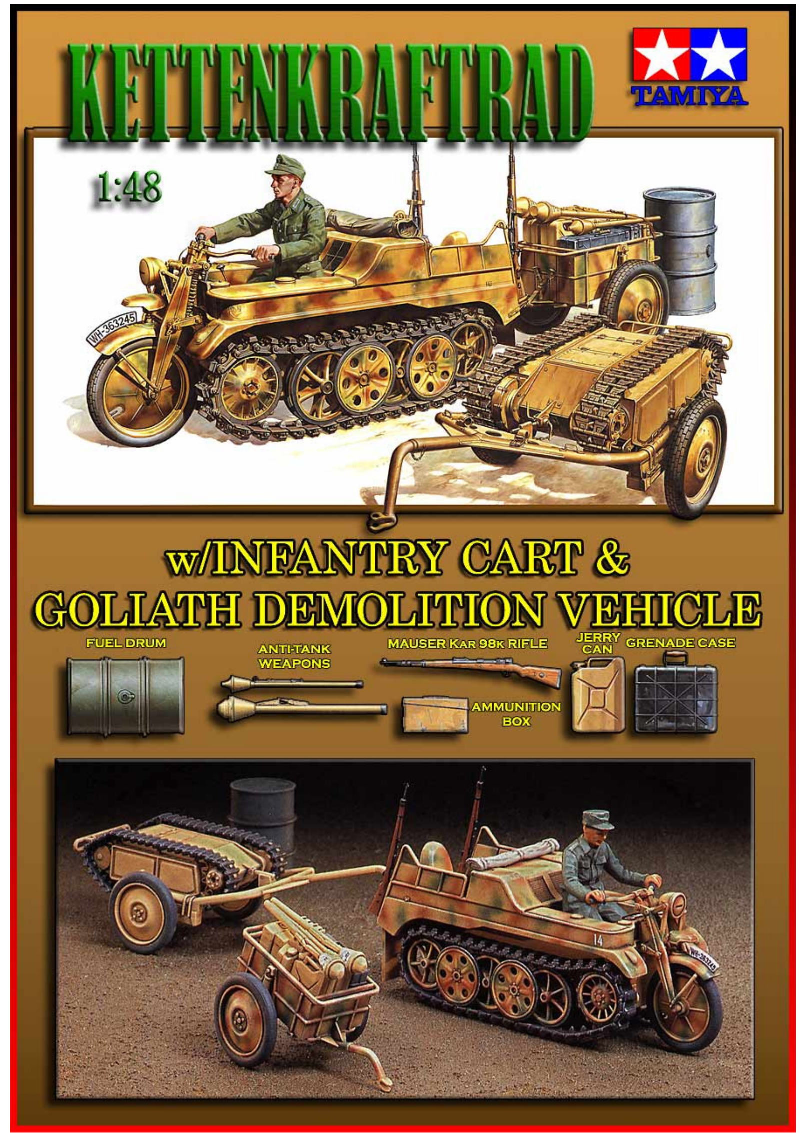
(Next Chart)

A BRIEF HISTORY OF MILITARY ROBOTICS

- **In 1940 Borgward developed a remotely controlled tracked vehicle smaller than the B-series vehicles, ironically named the *Goliath* Demolition Vehicle**
  - **Designed to carry a demolition charge to a fortified target such as a pillbox and sacrifice itself while destroying the target**
  - **It was 59 inches (1.5.m) long, 33 inches (84 cm) wide, and 22 inches (56 cm) high and could carry a 132-lb (60 kg) explosive charge**
  - **A drum situated at the rear of the vehicle dispensed 0.9 miles (1.4 km) of a three-cord cable: two strands were used to transmit steering signals; a third strand transmitted a firing signal**
  - **The operator controlled the vehicle through a handheld box that had switches and batteries to regulate the relays in the vehicle**

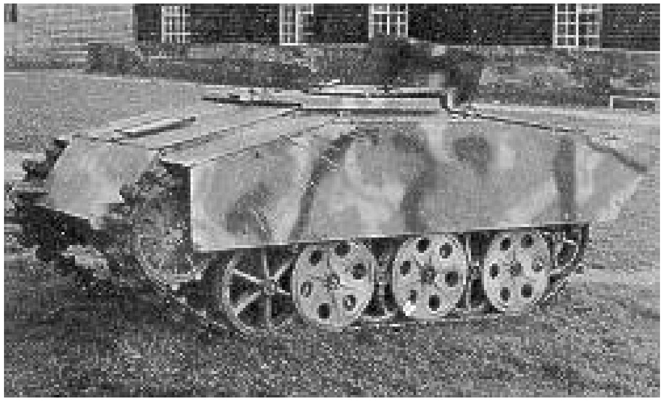
A BRIEF HISTORY OF MILITARY ROBOTICS

- More than 2,500 of the electric-powered Goliaths were produced for demolition and mine clearing tasks
- A slightly larger version could deliver a 220 lb (100 kg) explosive charge and over 4,500 were built and deployed primarily as an anti-tank vehicle



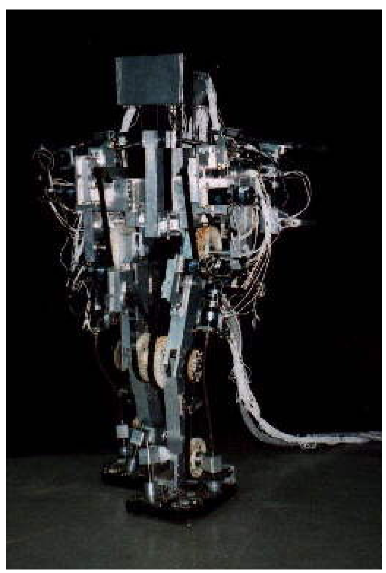
A BRIEF HISTORY OF MILITARY ROBOTICS

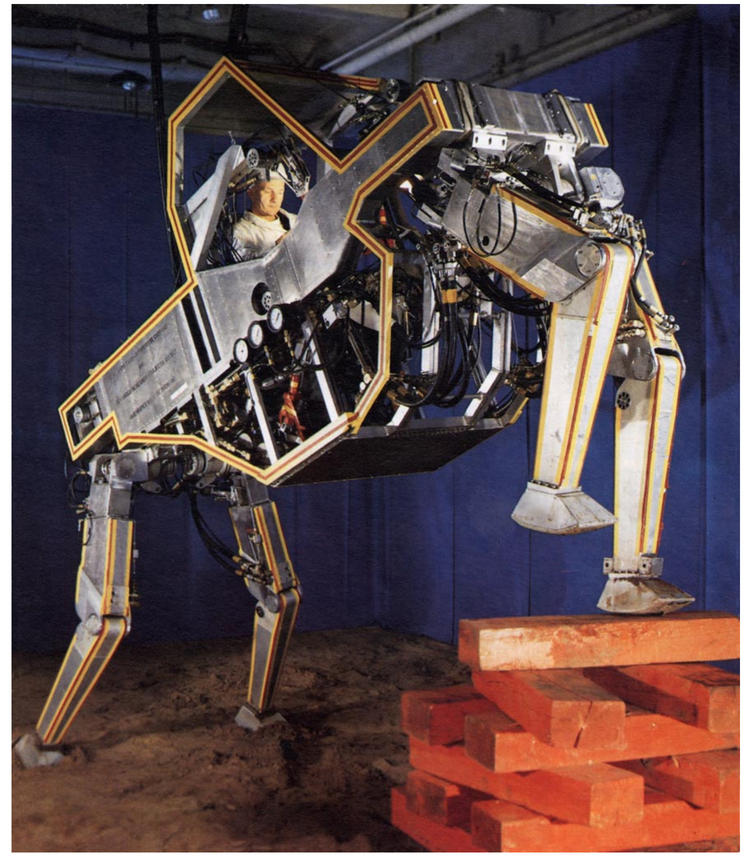
- In 1944 the telerobotic *Springer* was built by NSU Werke AG using components from a motorcycle half-track tractor, the *Kettenkrad*
  - Springers were lightly armored and carried a larger payload than Goliath; an attempt was made to convert them into fighting vehicles as the war ended
- In contrast to the small remotely controlled demolitions vehicles, Krupp of Esser built a gigantic articulated armored mine-clearing vehicle weighing 130 metric tons (130,000 kg) called the *Raeumer S*.
  - Only one was built and tested because it did not perform well on rugged terrain
  - A smaller, 40-ton (36,300 kg) version was designed by Alkett and Krupp but never built



A BRIEF HISTORY OF MILITARY ROBOTICS

- **The British were also active in developing robotic land vehicles in the 1940s**
  - **W.H. Allen and Co. designed a four-legged, 100-ton (90,800 kg) walking tank that could operate on uneven terrain**
  - **A prototype was built and tested, but the project was cancelled**





GE Walking Machine

A BRIEF HISTORY OF MILITARY ROBOTICS

- During WWII, unmanned air vehicles were developed by the U.S. and Germany
- Damaged B-17 and B-24 bombers were converted into bomb-laden UAVs
  - A pilot would fly the aircraft conventionally until it reached the coast of England
  - The pilot would bail out and while still over land
  - The aircraft would cross the English Channel to Germany under remote guidance
  - Joseph Kennedy was killed in such a remotely-controlled bomber when it exploded over England before he could bail out

A BRIEF HISTORY OF MILITARY ROBOTICS

- **After years of dormancy, the U.S. military began developing a new generation of robotic ground vehicles in the mid-1980s**
- **Robot Defense Systems of Thornton, Colorado, built its *Programmable Robot with Logical Enemy Response* (*PROWLER*)**
  - **This six-wheeled, semi-autonomous, telerobotic, all-terrain vehicle could carry a 2,000 lb (908 kg) payload at a speed of 17 mph (17 kph)**
  - **The Defense Advanced Research Projects Agency (DARPA) and the U.S. Army's Ninth Infantry Division awarded contracts for field demonstrations, including the firing of tandem-mounted 9mm machine guns from the vehicle's turret, and the launching of rockets**
  - **The PROWLER demonstrated the ability to sight and fire on an armored target via remote control**

A BRIEF HISTORY OF MILITARY ROBOTICS

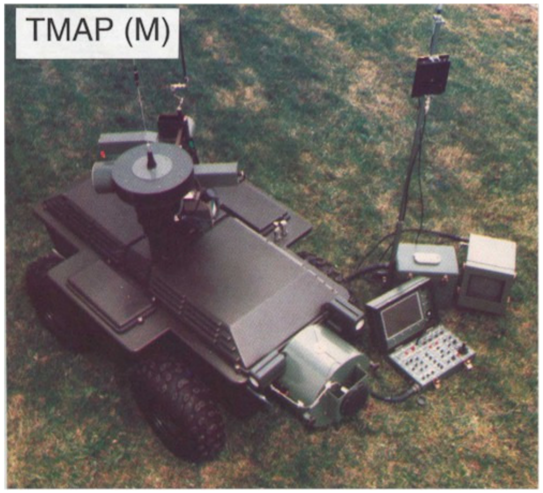
- **In the 1980s, the U.S. Marine Corps (USMC), Army, and DARPA funded the development of telerobotic and autonomous vehicle prototypes**
- **Both the Marine Corps *Ground Surveillance Robot*, developed by the Naval Ocean Systems Center, and the Army Tank Automotive Command's (TACOM) *Advanced Ground Vehicle* used the M-113 armored personnel carrier as the basic platform**
  - **It was equipped with sensors, processors, and servo-control**
- **The *Autonomous Land Vehicle*, sponsored by DARPA, used an 8-wheeled platform developed by Martin Marietta Denver Aerospace to demonstrate the integration of robotic technologies with artificial intelligence in a fully autonomous (albeit with limited ability) platform**

A BRIEF HISTORY OF MILITARY ROBOTICS

- In the mid-1980s, TACOM developed the *Robotic Obstacle Breaching and Assault Tank* (*ROBAT*) – a modified telerobotic M-60 tank
- Program was canceled before production because of technical and budget problems

A BRIEF HISTORY OF MILITARY ROBOTICS

- **Also in 1980s, Army awarded contracts to Grumman Electronic Systems and Martin Marietta to develop competing proof of principle prototypes for an anti-armor *Teleoperated Mobile Anti-armor Platform* (*TMAP*) – never went into production**
  - **Congressional language in 1987 restricted the use of funds to acquire and evaluate new weapons mounted on robots**
  - **A congressional staff member believed the TMAP platforms were too small and underpowered to serve as anti-tank weapons; an urban legend spread that congress forbid the development and use of robots as weapons platforms**
  - **The TMAP mission and acronym was changed to *Tactical Multipurpose Automated Platform*, and it was mainly exercised in the reconnaissance role**
  - **TMAP, linked to the control station with fiber optic cable, was used in a number of field exercises and demonstrations**

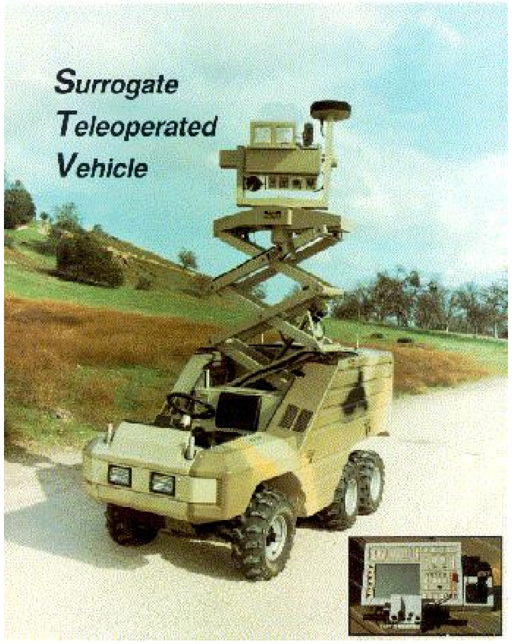


A BRIEF HISTORY OF MILITARY ROBOTICS

- **During mid to late 1980s, USMC Program Management Office for Ground Air Telerobotic Systems (GATERS) developed the *Tele-Operated Vehicle* (TOV)**
  - **Operator wore a helmet-mounted display system to create a sense of telepresence (i.e., an illusion of being immersed in the remote environment)**
  - **A fast-attack vehicle (similar to a dune buggy) was modified into the TOV test vehicle**
  - **Later replaced with the larger *High Mobility Multipurpose Wheeled Vehicle* (HMMWV) that was, like its predecessor, controlled over a fiber optic link to the remote control station**

A BRIEF HISTORY OF MILITARY ROBOTICS

- **In response to a 1988 congressional mandate requiring DoD to "advance joint robotics programs or joint development efforts," DoD, Army, and USMC consolidated the robotic ground vehicle development into an Unmanned Ground Vehicle Joint Program Office (UGV JPO)**
- **After testing of the TMAP and TOV were completed, development began on a *Surrogate Teleoperated Vehicle* (STV), and Robotic Systems Technology built 14 STVs**
- **The purpose of the STV was to help service users to develop and validate UGV employment concepts that were to shape the development and acquisition of the *Tactical Unmanned Ground Vehicle* (TUGV) in the 1990s**



A BRIEF HISTORY OF MILITARY ROBOTICS

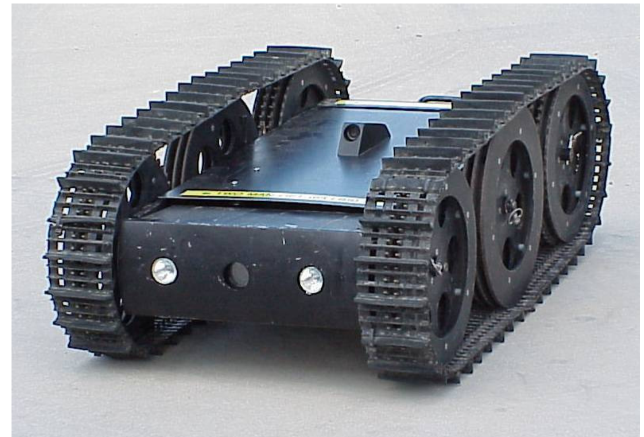
- **During Desert Storm (or the Persian Gulf War, 1990-1991)**
  - **Some Security Explosive Ordnance Disposal (SEOD) UGVs were sent to Saudi Arabia**
    - **The U.S. Navy had bought 72 of the vehicles in 1989 from the Standard Manufacturing Company**
  - **Also, 20 telerobotic kits, built by Kaman Sciences Corp., were sent to the Persian Gulf to convert M-60 tanks to telerobots for mine clearing operations**
    - **The kits were rapidly used to convert the tanks into unmanned minefield breaching systems, but the ground war was over before the systems could be deployed**
  - **The Army and Marines in the Gulf requested a hundred UGVs that could not be sent because they were still under development**
  - **After the war, a number of EOD robots were used to clear minefields and remove unexploded ordnance (there are many brands of EOD telerobots built by many companies in many countries)**

A BRIEF HISTORY OF MILITARY ROBOTICS

- By the early 1990s, there were a number of DOD UGV platform and supporting technology development programs
  - The U.S. Army Laboratory Command was a sponsor of the *UGV Technology Enhancement and Exploitation Demonstration I*, which focused on near-term teleoperation and teleassistance technologies and supervised robotics for navigation, reconnaissance, surveillance, and target acquisition (RSTA)
  - The project culminated in a technology demonstration to the user community called Demo I
  - Demo II followed this, the result of *UGV Technology Enhancement and Exploitation Demonstration II*, which was geared toward demonstrating multiple vehicles operating cooperatively under supervised autonomy
  - The platforms for Demos II and I varied, but were mostly modified HMMWVs

A BRIEF HISTORY OF MILITARY ROBOTICS

- A few robotic platforms were used in Bosnia and Kosovo (e.g., the *Standardized Robotic System* (SRS)
  - A kit for converting conventional combat vehicles into teleoperated, semi-autonomous vehicles for mine-proofing and other hazardous operations)
- EOD robots and small robots for sensing used in Afghanistan and Iraq
- The DOD OSD Joint Robotics Program is developing a number of robotic platforms
- The *Future Combat System* (FCS) program is developing a family of robotic and manned ground vehicles to ultimately replace major battlefield weapons systems (e.g., tanks, artillery, and air defense artillery)
- But combat land robots are still mostly developmental and behind UAVs in user acceptance and widespread deployment



HISTORICAL LESSONS LEARNED: A CAUTIONARY TALE

- **Lessons from a number of sources, including:**
  - **SPAWAR Technical Report 1869, by Blackburn, Laird, and Everett, Nov. 2001**
  - ***Lessons Learned in Group Robotic Command and Control*, by P. Drewes, SAIC, 2000**
- **May the *Powers-That-Be* who manage unmanned vehicle programs (especially the Future Combat System) take these lessons to heart – or risk dire consequences from the ghost of the ill-fated *Aquila***

POIGNANT PROVERBS

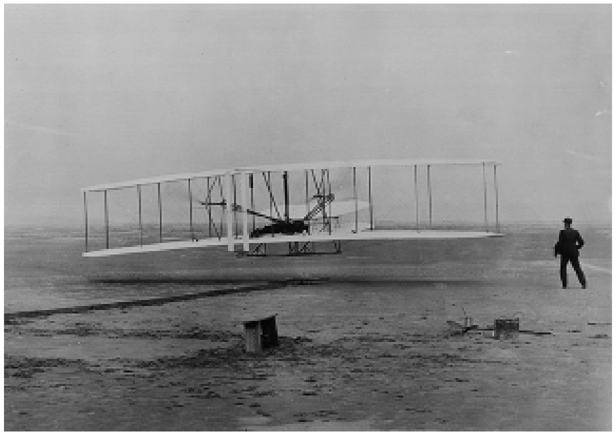
- Experience is the hardest kind of teacher: it gives you the test first and the lesson afterward
- More people would learn from their mistakes if they weren't so busy denying that they made them
- Man must sit in chair with mouth open for very long time before roast duck fly in
- Never ascribe to malice what can perfectly well be explained by stupidity
- If fortune turns against you, even jelly breaks your tooth
- Better be wise by the misfortunes of others than by your own
- If you don't know where you're going, you'll end up somewhere else
- A danger foreseen is half avoided
- You can only predict things after they've happened

EARLY LESSONS LEARNED

- Over the decades since WWI, UAVs received far more developmental support than UGVs (although small compared with most weapons systems)
- Then during the 1970s, the Aquila Remotely Piloted Vehicle (RPV) program alone swallowed over $1 billion (in pre-inflation dollars) and vanished with barely a trace
  - In general, the development of UAVs was an unmitigated tribulation
  - There has never been a comprehensive, definitive analysis of the ordeal of developing UAVs to determine why this is so

EARLY LESSONS LEARNED

- There are a number of reasonable explanations for the turmoil and the glacial introduction of operational unmanned systems
  - Now garnering sufficient funding and critical mass to attract swarms of the 3Cs: contractors, consultants, and congressmen
- May be a natural consequence of the development of any new complicated technology
  - New technologies are typically worse than the ones they are replacing
  - Disruptive innovations, in contrast, usually don't attempt to bring better products to established customers in existing markets
  - Rather, they disrupt and redefine the competition by initially introducing products and services that are not as good as currently available products
  - But disruptive (transformational) technologies offer other benefits
  - Examples: manned aircraft or the automobile; television (initial introduction, color, and HDTV)



EARLY LESSONS LEARNED

- Many robotic vehicle developmental problems shared by other kinds of military systems, including:
  - "Gold-plating," where performance or reliability standards are gradually increased throughout the development program regardless of cost
  - Expendability becomes permanence and off-the-shelf becomes special-purpose; every subsystem is designed for the worst-case, super-technologically sophisticated foe
  - "Requirements creep," where the system is expected to perform more and more missions, to carry more sensors or weapons, to operate in more hostile and extreme environments, and to meet the needs of all of the services under all conditions

EARLY LESSONS LEARNED

- Until recently, military robotics programs suffered from being a consequence of **technology-push** rather than **demand-pull**
- A sequence of historical events, benefiting from actual combat use, elevated UAVs into demand-pull arena
  - Sufficient demand to allow programs to survive Congressional evil eye despite any programmatic debacles
- Support from top is essential for new technology systems to survive long and tedious procurement process into actual successful deployment

EARLY LESSONS LEARNED

- For many years, UAVs (and RPVs before them) suffered from the white scarf mentality (pro-pilot bias) on the part of U.S. Air Force
- Psychosocial phenomenon can be generalized to the *reason for existence* or *self-actualization* mentality – e.g., pilots fly airplanes
  - In the Air Force, pilots become generals
  - In the Army, tank drivers become generals
  - In the Navy, submarine drivers become admirals
- It was easier to accept UAVs in the Army, Navy, and Marine Corps (and wherein there were enthusiastic supporters) than in the Air Force

EARLY LESSONS LEARNED

- Air Force eventually accommodated to UAVs (as previously with intercontinental ballistic missiles)
  - Because it was threatened with other services' infringement on traditional Air Force missions
- Related to this source of developmental problems is inter-service rivalry
  - Vested interests and rice bowls interfere with the rational development and application of new systems
- After years of inter-service bickering and duplication of effort, Congress mandated a coherent, joint program office for UAVs
  - Then after years of failing expectations and program failures, joint effort devolved back to the individual services

EARLY LESSONS LEARNED

- **Promising new ways of doing business, such as the Advanced Concept Technology Demonstration (ACTD), went astray**
  - **Place systems in the hands of operational users as quickly as possible for demonstration and evaluation by eliminating conventional bureaucratic procurement processes**
  - **After overcoming the usual inertia and resistance, the process worked well with one UAV development program (*Predator*), and then became corrupt and failed with another program (*Outrider*)**
  - **House National Security Committee: because of Outrider, "In the future, the conferees will look less favorably on ACTD programs…"**
  - **Good intentions still require sufficient oversight (or as President Reagan said in a different context, "Trust but verify")**
  - **Example: cost of each *Global Hawk*, in production, is several hundred percent greater than the cost mandated at the start of the program**

EARLY LESSONS LEARNED

- Lack of rules and regulations stifled development of civil and commercial versions of UAVs
  - And therefore squelched spin-on applications to the military and the development of commercial-off-the-shelf (COTS) technology
  - Can do same with UGVs (e.g., autonomous cars)
- Federal Aviation Administration (FAA) still contemplating UAV flight rules for U.S. civil airspace, having initiated the process in 1992
  - No viable civil/commercial UAV industry can be established until reasonable rules are in place

EARLY LESSONS LEARNED

- Lack of **doctrine, strategy, and tactics** (just now being addressed) for many years prevented full flowering of UAVs in the U.S. military
- There are still issues relating to suitable missions for UAVs and integration of UAVs with manned aircraft and other assets and forces, including robotic ground and sea vehicles
- Major technology issue (starting to be addressed): robotic systems being open, interoperable, and common

EARLY LESSONS LEARNED

- Rational resistance to the introduction of *any* new technology in the military
  - Lack of user confidence because of unfamiliarity with performance of the technology and its advantages
- UAVs instilled confidence in users after multitude of recent successful real-world combat engagements: Lebanon to Bosnia to Kosovo to Afghanistan to Iraq
- Many users and commands now have favorable experiences with UAVs and there is a large constituency demanding UAVs

EARLY LESSONS LEARNED

- Historically, the experience in Vietnam with RPVs was misunderstood because of
  - Secrecy of the missions (and lack of widespread knowledge of mission successes)
  - Limited field tests with insignificant data collections
  - Improper measurement techniques
  - Lack of public relations
- Successful use of RPVs during the Vietnam War was therefore underrated and unappreciated
  - Reliability and effectiveness were better than the perception on the part of the services
  - It took decades for UAVs to recover from Vietnam misperceptions

EARLY LESSONS LEARNED

- Now missions are carefully recorded and analyzed
- Successes are publicized
- In each theater of UAV operation
  - Tables are kept detailing the UAV platform, operation dates for that platform, total flights, total flight hours, total flights in a combat zone, total flight hours in a combat zone, and percent returned
  - Other statistics include: number of mishaps in a given year, number of flight hours and sorties, percent sorties loss, and percent sorties accident
  - Failures are better understood in context (e.g., it is better to have the enemy's heavy air defense shoot down a UAV than a manned aircraft)

EARLY LESSONS LEARNED SUMMARY

To summarize the lessons to be learned from the UAV development and operations and applied to the development of future UAVs or UGVs:

- Initial goal
  - Develop and demonstrate the simplest, least expensive robotic system that will be uniquely useful to the user
  - Get it into inventory (preferably into actual combat) as soon as possible
- Vanquish without mercy any attempt at gold plating or requirements creep
- Do not deviate from the prototype and its defined missions, functional requirements, and engineering design until it has been successfully demonstrated to the user's joy and satisfaction, after which reasonable product improvements may be made on a planned schedule

EARLY LESSONS LEARNED SUMMARY

- Focus on the systems being open, interoperable, and common wherever it makes sense
- Gather a critical mass of stakeholders from industry and government, and especially marshal requirements for the technology from users and enthusiastic support from the top command levels

EARLY LESSONS LEARNED SUMMARY

- Establish a clear and compelling rationale for robotic systems in the Army of the 21st century - especially the benefits to the users - and promulgate it to all who feel their jobs, careers, or self-esteem are threatened by the technology
- Coordinate the development of Unmanned Vehicles among all of the services (and share technology where appropriate) to alleviate rivalry
- Develop doctrine, strategy, and tactics for using the new technology in integrated operations with manned and unmanned platforms, in all relevant missions

EARLY LESSONS LEARNED SUMMARY

- At all stages of development and demonstration, the overriding objective must be to **instill confidence** in the user
  - Keep detailed records of combat operations and publicize the successes (while promptly correcting the source of failures)
- The DoD should encourage **technology transfer** for widespread **civil and commercial** applications (e.g., agriculture, automotive, construction, air transport) for robotic systems to broaden the technology base and allow commercialization to enable faster, better, cheaper systems for military missions

EARLY LESSONS LEARNED SUMMARY

- Cost and size escalation
  - Gold-plating
  - Requirements creep
- Technology-push vs. demand-pull
- Politico-psycho-social phenomena
  - Inter-service rivalry
  - Vested interests and rice bowls
  - Ego
  - Fear of change and new technology
- Lack of rules and regulations
- Lack of doctrine, strategy, and tactics
- Technology issues
  - Efficacy
  - Reliability
  - Lack of open, interoperable, and common systems
  - Lack of user confidence

ROBOT LESSONS LEARNED

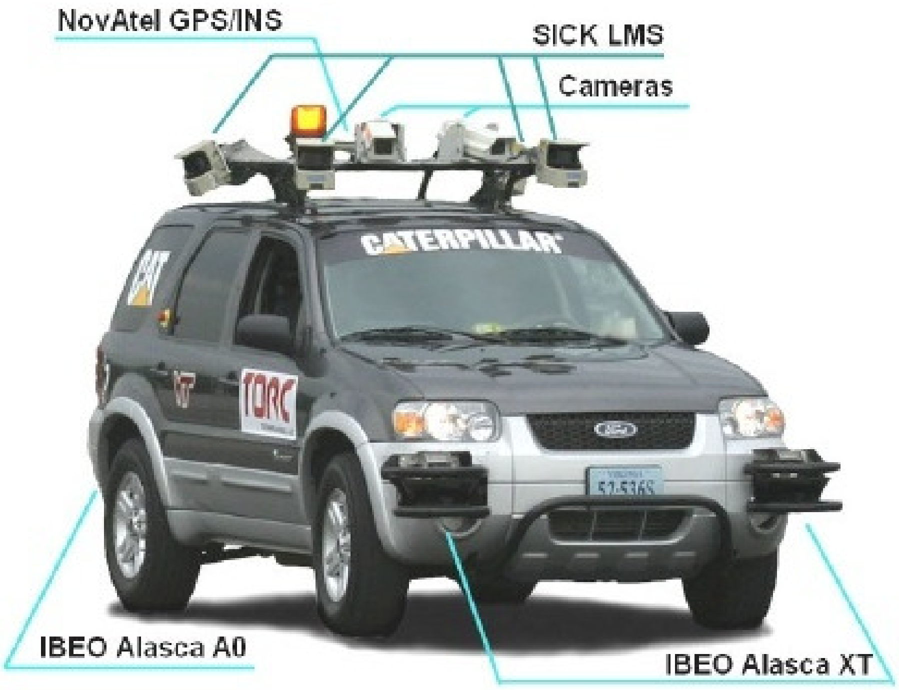
- Some UGV lessons learned were compiled by SPAWAR from more than 50 experts in the UGV community
  - Based on direct experience with robotic systems (e.g., with Explosive Ordnance Disposal (EOD) and Mine Counter-Measures (MCM) robots)
- Other "lessons" are actually expert opinions, based on contemplation about robotic systems, on how UGVs should be developed and deployed
  - Insufficient combat experience with UGVs for substantial lessons learned as yet

ROBOT LESSONS LEARNED: TOP TEN

- (1) Uncertainty promotes success
  - Robot behavior should not be deterministic and predictable to the enemy
  - Robot must be able to deal with environmental and adversarial uncertainty
- (2) Many simple cooperating UGVs are generally superior to one complex UGV
  - Single complex UGV is limited in time and space – generally suitable for single complex mission and not generally expendable
  - Large numbers of simple robots (e.g., insects) can perform complex missions through collective behavior
  - Inherently flexible, robust, survivable, and expendable
  - But cognitive behavior in a collective or swarm of simple robots has yet to be achieved

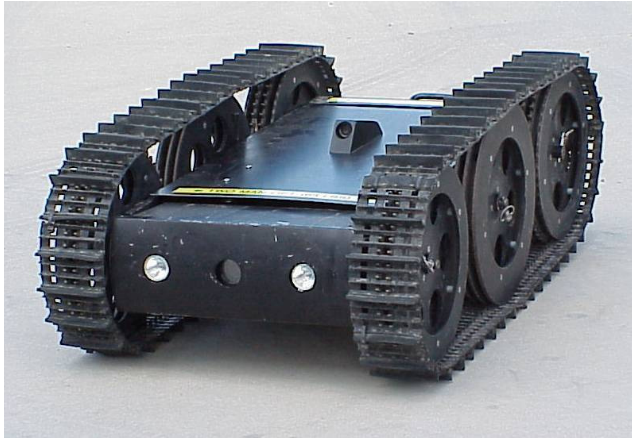
ROBOT LESSONS LEARNED: TOP TEN

- **(3) Understanding between user and developer is critical**
  - **Developer must understand the application**
  - **User must understand the developer's proposed solution to his problem**
  - **Misunderstanding leads to useless products**



ROBOT LESSONS LEARNED: TOP TEN

- (4) New technology forces changes in operations
  - Military tends to view technology as an enabler of operations - but historically it has been a transformer of operations
  - New technology, such as robotic ground vehicles, will alter tactics, strategy, and doctrine, just as tanks did at the turn of the 20th century
  - But as was the case for armored vehicles, it is likely to take many years to learn how to use the new robotic technology
  - New military technology also engenders countermeasures and counter-countermeasures, ad infinitum, and the military must keep control of the evolution of the technology and counter the countermeasures in a continuing process

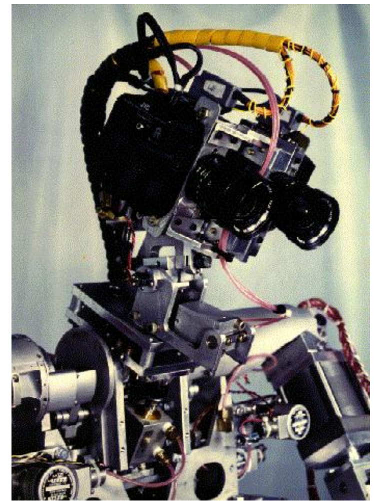


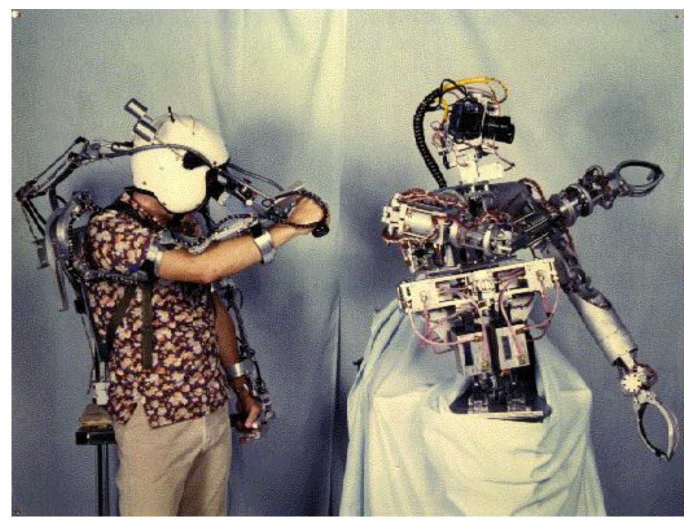
ROBOT LESSONS LEARNED: TOP TEN

- (5) Understanding the technology is cost-effective
  - Program office must have – and maintain – a comprehensive understanding of the core and supporting technologies to facilitate long-range planning and development of useful products
- (6) Simpler solutions provide better foundations
  - A simple solution is a process that meets a few of the system requirements without sacrificing or violating other requirements
  - A complicated solution is a process that meets some of the requirements, while integrating badly with more traditional solutions to the remaining requirements
  - Nature enforces this process in evolution with natural selection

ROBOT LESSONS LEARNED: TOP TEN

- (7) Integration is not easy
  - Difficult to integrate new technology, such as robotic vehicles, into an existing organizational and operational framework, such as that of the military
  - Mundane aspects of the technology, such as logistics, maintenance, and training, must also be designed and developed
  - Difficult to integrate new subsystems and components into the evolving technology
  - Important to design robotic vehicles to be modular with adaptable interfaces, to be open, interoperable, and common
- (8) Communications are not dependable
  - Environmental conditions for ground vehicles add to inherent difficulties with battlefield communications – autonomy is very important



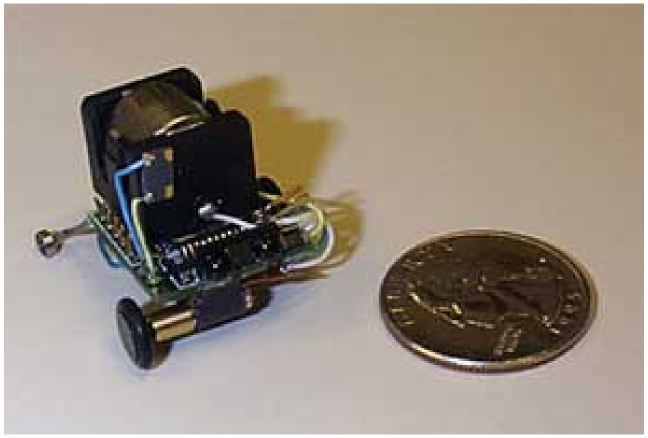


ROBOT LESSONS LEARNED: TOP TEN

- (9) Automatic processes are not autonomy
  - Automatic processes, like those of a washing machine, are easy to implement in a robot
  - But autonomy implies a suitable level of intelligence (and situational awareness) which allows the robot to survive and perform its mission in an uncertain, hostile, and adversarial environment
  - Intelligent autonomy is not (currently) simple to implement in a robot, but currently achievable autonomy is sufficient for portions of some missions – or the entirety of certain missions

ROBOT LESSONS LEARNED: TOP TEN

- (10) The road from teleoperation to autonomy does not exist – you cannot get there from here
  - A purely teleoperated control system has a fundamentally different form and function compared with a fully autonomous control system; it will not transform
  - An appropriate autonomous control system architecture can serve as a framework for the spectrum of teleoperation through semi-autonomy and supervised autonomy to full autonomy
  - Autonomy should be designed into the robotic vehicle at the start, not pure teleoperation which cannot later evolve into autonomy



ROBOT LESSONS LEARNED

- It is cheaper to build a mine than a countermine robot; and it is faster to build a new mine than new countermeasure robots
- Intelligent group behavior will not emerge spontaneously from a collection of simple swarm robots
- Random search patterns are inefficient; the environment is not random, which tends to defeat random search patterns
- Smaller and cheaper is better – as long as it accomplishes the mission
- Smaller robots require refueling more frequently than larger robots (as is the case with mice and dinosaurs)
- Smaller robots lack sustaining energy and must be placed closer to the mission area than larger robots
- Good designs can suffer from bad production

ROBOT LESSONS LEARNED

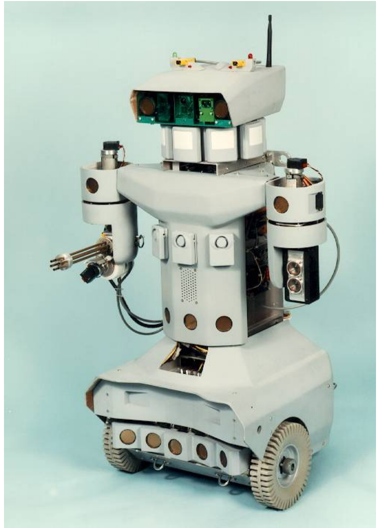
- Nothing substitutes for fundamentally reliable equipment
- In a new system, it is hard to get everything to work at once
- Don't waste time talking about architecture – talk about more reliable components
- Another definition of *reliable* is *survivable*
- Sacrifice elegant solutions for KISS
- The total systems solution should as much advantage of the human operator (or supervisor) as possible
- A simple solution is an adequate solution
- A robot may be of any degree of internal complexity as long as its demands on the user are simple

ROBOT LESSONS LEARNED

- The system must be designed to accommodate rapidly evolving technologies (especially through modularity)
- The system must be developed interactively with the user, especially where the operational environment is not well understood) – and, as much as possible, developed in the operational environment
- Multi-robot collaboration is difficult because of poor communications
- Computing is not an issue, but poor communications will increase the computing load
- On robotic vehicles, tracks and wheels are generally more useful than legs
- Be ruthless about the vehicle's hotel load; keep it a small fraction of the power budget
- Adaptive processes reduce energy requirements

ROBOT LESSONS LEARNED

- **Organisms are focused on energy requirements:**
  - **(1) much of an organisms system is devoted to the acquisition and consumption of energy**
  - **(2) organisms conserve energy through rest, sleep and suspended animation**
  - **(3) organisms short on energy feed upon themselves (e.g., stored fat, then structural carbohydrates, then structural proteins)**
  - **Robotic vehicles could be designed with a similar ability to seek and consume energy, extracting and storing energy from the environment and using its structural elements as energy sources in emergencies**



ROBOT LESSONS LEARNED

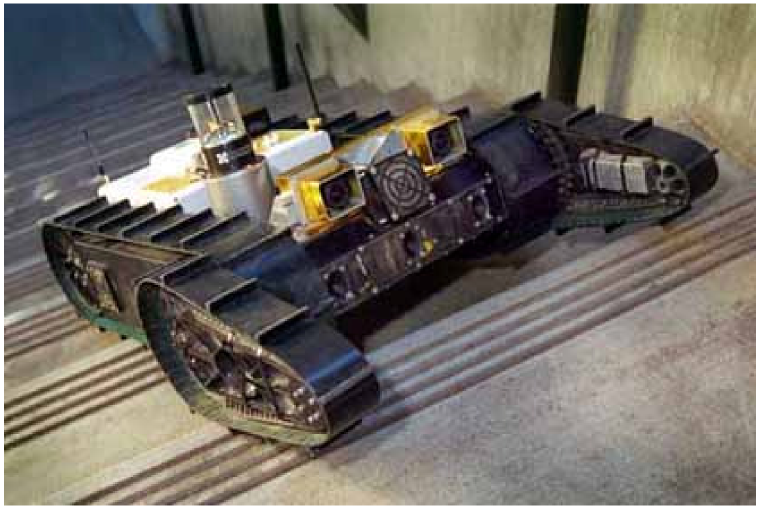
- Teleoperated robotic vehicles are better than no robotic vehicles; but supervised autonomy is better than teleoperation
- Supervised autonomous vehicle commanders are generally overtaxed
- Soldiers may prefer an autonomous system when under fire, but a teleoperated system when at leisure
- With new technology, you don't know what you don't know

ROBOT LESSONS LEARNED

- Reactive or randomly behaving robots cannot be stealthy or interact well with humans in the operational environment
- Limited communications bandwidth requires greater onboard processing ability
- Automated target recognition is still primitive and leads to unacceptably high false alarm rates, inundating human operators
- It is difficult for robotic vehicles to detect negative obstacles (e.g., holes)
- Robotic vehicle operators (supervisors) should have: motion video (instead of just still imagery); the ability to see what the robots are viewing; vehicle health and operability status indicators; optional grid lines on graphics; depth perception displays

ROBOT LESSONS LEARNED

- An autonomous robotic control system should integrate *knowledge-based* as well as *behaviorist* approaches, and *deliberative* as well as *reactive* behaviors
- Computing power keeps increasing exponentially, but remains far short of human capabilities
- Incremental growth of computing power suggests an incremental approach to developing robot intelligence – but robots with intelligence significantly less than that of humans can still perform useful functions and missions
- Evolutionary computing is a promising tool for developing intelligent robots



ROBOT LESSONS LEARNED

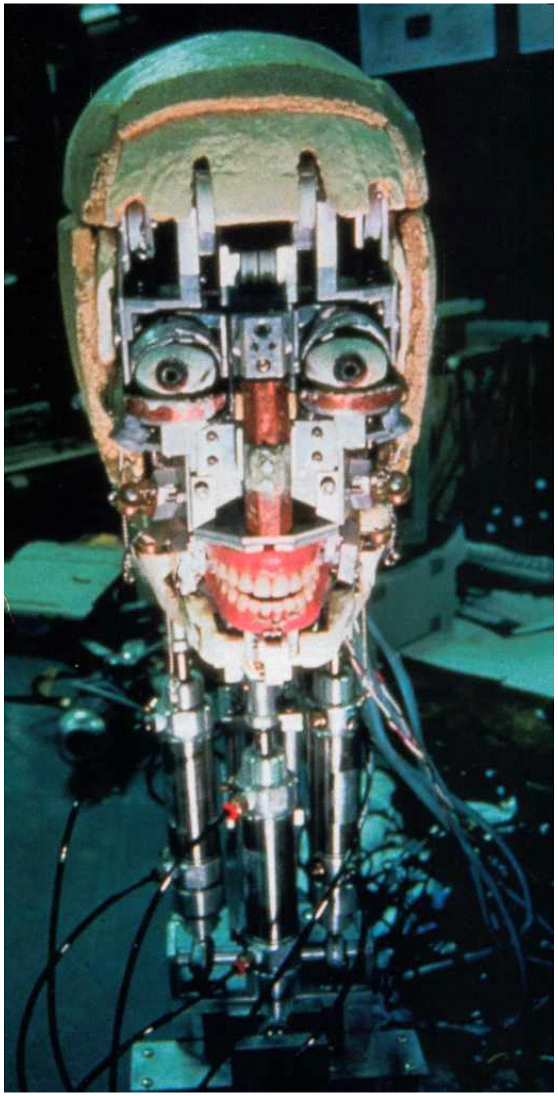
- A robotic vehicle must be able to:
  - Take care of itself
  - Automatically recover and escape
  - Recharge or refuel quickly
  - Automatically reacquire lost communications
  - Discourage abuse or careless handling
  - Determine geo-position
  - Negotiate obstacles
- The robot's architecture should be task-oriented, not designed around the human operator

ROBOT LESSONS LEARNED

- Robot developers must understand the operational constraints – the new technology must fit the operational infrastructure
- Robots on the battlefield will likely change the operational environment
- Most of the robots in academia are too constrained to be applicable on the battlefield
- Maintainability should be at the user level; Modular components should be replaceable by soldiers in the field
- The viability of the robotic vehicle contractor is important for long-term logistics support
- R&D contracts should be for "best effort" at a firm fixed price (FFP)

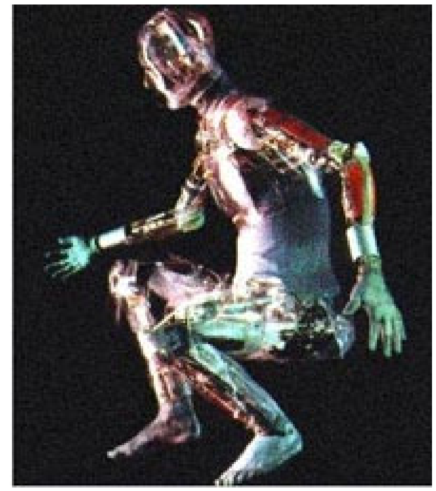
ROBOT LESSONS LEARNED

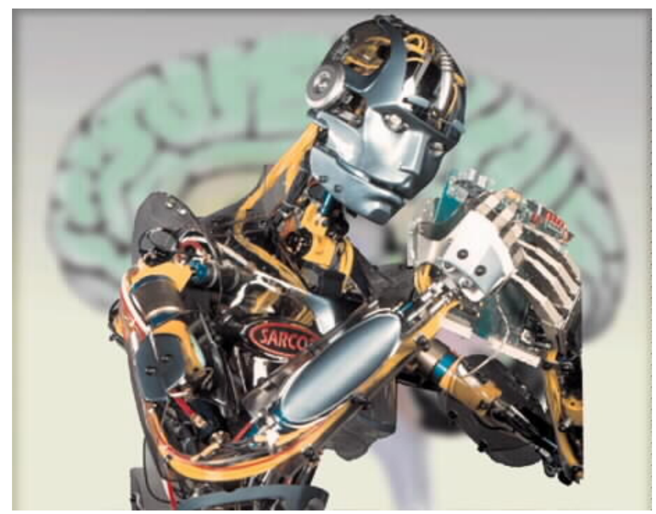
- A commercial base for robotic vehicles would stimulate robot development and provide needed competition
- The same contractor should be used, where possible, for the R&D and production phases
- The contractor needs appropriate autonomy – but too much autonomy leads to projects being late and over budget
- A key metric of the robotic vehicle is affordability
- The human/machine interface should be tested in high-stress situations
- Robots should be able to ask for help from operators



ROBOT LESSONS LEARNED

- Specialized, but cheaper, robots may be preferable to "Swiss Army Knife" robots that do many things (or, in the Aesop fable's terms, the hedgehog who knows one big thing may be more survivable than the fox who knows many little things)
- Software should be modularized, as well as hardware; in addition to simpler repairs and maintenance, modularization permits upgrade-ability by parts
- Keep existing projects from over-reaching while building a well-developed technology baseline – and adapt existing technology wherever possible
- Define suitable metrics and submetrics for specific applications and missions
- To control life cycle costs, include consideration of intermediate and depot level repair





ROBOT LESSONS LEARNED

- Early UGV programs had identified difficulties:
  - Poor communication and feedback among all parties, especially users
  - Inadequate understanding of required operational capabilities, coupled with lack of appreciation of technology deficiencies
  - No workable long-term robotic plan
  - No baseline assessment of technology capabilities and deficiencies
  - Failure by project managers in initial planning stages to have a working knowledge of the technology and actively employ available resources
  - Inadequate early research and development efforts prior to initiating advanced development
  - Failure to meet design goals due to existence of technology gaps unidentified early in the process

ROBOT LESSONS LEARNED

- **Example Early Problems in the MDARS (Mobile Detection, Assessment, and Response System) project:**
  - **Initial lack of a bona fide application and validated payback**
  - **Ignorance on the part of the project manager and/or developing organization as to what the user really wanted**
  - **Lack of awareness by the user about what near-term technology could and could not support**
  - **Overlooked or under-estimated systems integration efforts**
  - **Constantly changing goals and objectives, sometimes as a result of turnover in the program office**
  - **Insufficient funding or requirements creep**

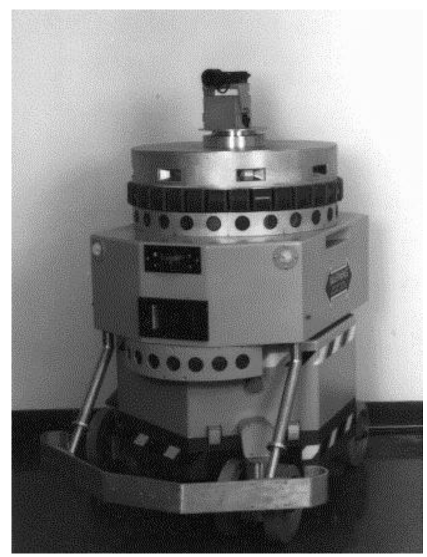
MDARS-E Prototype Platform with Gunpod

ROBOT LESSONS LEARNED

- Example Early Problems in MDARS (Continued):
  - Premature attempts to apply off-the-shelf components without fully understanding the system needs
  - “System shock” from too abrupt a transition from the pristine laboratory to the harsh environment
  - Insufficient documentation to support program transitions from R&D phases to production

ROBOT LESSONS LEARNED

- Example Early Problems in MDARS (Continued):
  - Projects with greatest likelihood of success were relatively small and highly focused in terms of their stated objectives
  - The bigger the performing organization, the lower the chance of success – especially true of large corporations that entered the program from other fields and had no robotics experience



ROBOT LESSONS LEARNED

- Example Early Problems in MDARS (Continued):
  - Program managers did not appreciate the issues associated with a software intensive program
    - Treated software as if it were magic and expected unrealistic end results without understanding the process
    - Little understanding of the costs of software development, much less maintenance
    - Resulted in spaghetti code that could not be maintained or upgraded

ROBOT LESSONS LEARNED

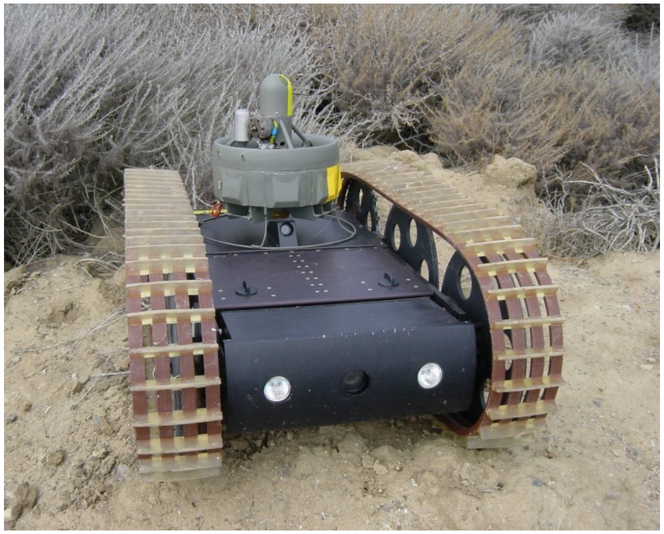
- **Example Early Problems in MDARS (Continued):**
  - **The greater the number of active players and organizations, the less the likelihood of meaningful developmental results – problems associated with the effective coordination of a large group of geographically dispersed organizations overshadow any prospective synergy**
  - **It is easier to demonstrate technical feasibility than value added**

ROBOT LESSONS LEARNED

- Prevent politics from over-riding sound technical judgment
- Avoid the “not-invented-here” syndrome – take advantage of all lessons learned elsewhere
- Be willing to eat your young – abandon (or upgrade) any approach or technology that is superseded by something better
- Start with an objective in mind, and then work backward
- Avoid up-front assumptions (e.g., robotic wheels are preferable to legs)
- When defining the program, write the concept of operations (CONOPS) first, and then invite industry to comment
- A concept of operations should consider all weather and day/night conditions

ROBOT LESSONS LEARNED

- Project managers should wait until the operations requirements document (ORD) is complete before beginning to develop a final system (otherwise, resources will be wasted)
- Keep the user involved at all times – involve a neutral third party if another perspective is needed
- Expectations tend to exceed system capabilities in early demonstrations
- Inadequately trained operators are a major problem
- Significant resources are needed for debugging and preparing demonstrations
- The success of a demonstration is often dependent on the state of the developer/demonstrator (e.g., coordination, team management, and training)

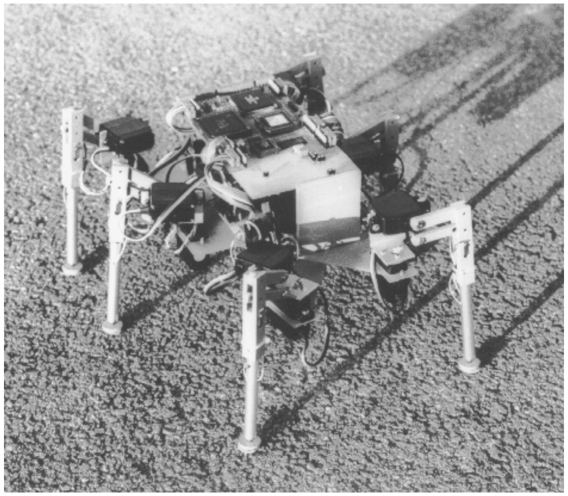


ROBOT LESSONS LEARNED

- Urge is to attempt too much in demonstrations – restrain overly ambitious objectives
- Plan for bad weather in operational testing
- Modeling and simulation provide valuable insights into potential system performance and methods of employment; allocate M&S resources early in project
- Modeling and simulation may substitute for unavailable prototypes
- Users tend to be impatient and expect more than can be delivered
- Environmental requirements should be dealt with early in the project; otherwise, the cost will be much higher to do so after the design is completed
- Avoid "war stories" (anecdotes) as the basis for requirements

ROBOT LESSONS LEARNED

- Problems defining system requirements:
  - All requirements may not be necessary (e.g., excessive temperature range)
  - Sufficient input from soldiers, on a regular basis, on human factors (e.g., interfaces)
  - Peacetime restrictions on radio frequencies, nationally and globally, which may interfere with training
  - Need early consensus on hardening requirements
- The robot must be useful and worth its price
- Expect and allow for requirements creep
- When managing schedule and performance goals, it is better to achieve the goals and let the schedule slip

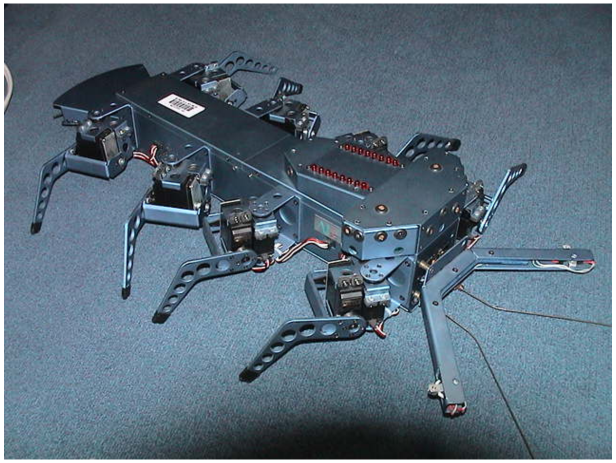


ROBOT LESSONS LEARNED

- Contractor should make two prototypes because the engineering prototype will generally be modified during operational testing
- A successful prototype depends heavily on the contractor who does the work (care must be taken in the selection of the contractor)
- In selecting a contractor:
  - The same contractor should be able to do both the R&D and production
  - The contractor should have suitable facilities available for field tests
  - The contractor should have a quality assurance plan
  - The contractor should have a suitable software engineering standard
  - The contractor should have sufficient resources and be economically viable

ROBOT LESSONS LEARNED

- Low-risk, but useful, robotic applications should be used to introduce users to the technology
- Do not claim that robotics will reduce people – it will make them more effective
- Identify a champion and nurture support from the top
- Look ahead to future issues in the event that current objectives are accomplished
- Apply the appropriate sensors for the type of required control
- For robust operation, use fusion of redundant sensors
- Don't depend on single sensor technology – sensors lie
- If the environment changes, check each sensor for adverse effects



ROBOT LESSONS LEARNED

- Cooperative behavior among robots can be achieved without explicit communications
- Avoid breakable buttons, switches, etc. for the control center – touch screen interfaces are more rugged
- Make the control system as plug and play as possible
- Avoid elaborate and complex control centers
- Robot control strategies must expect the unexpected – prepare for uncertainty
- A major research question is how to handle mixed initiative control (i.e., where the human operator and autonomous control system are attempting to direct the vehicle simultaneously)
- Too much is spent on vehicles and not enough on control

ROBOT LESSONS LEARNED

- Moving a robot from one environment to another can create unanticipated problems from:
  - Hardware and software errors not manifested in the previous environment
  - Sensor modes or algorithms tuned too tightly to specific characteristics of the previous environment
  - Subtle interactions between limitations in multiple hardware and software components
- Robustness can be assured only by exhaustively exercising operational capabilities in a number of diverse environments
- Ideally, there should be a basis for the robot's perception and performance not entirely dependent on a specified world model

ROBOT LESSONS LEARNED

- Display interface information that is meaningful to human controllers of the robotic vehicle (not just to its developer technicians), preferably in graphic format
- The interface should indicate what action is expected from the operator, along with pop-up explanations in clear language
- The robotic system's state should be monitored automatically, proactively, and defensively
- Understand the users: their job, education, training, and experience
- Respect the users' concerns and expectations
- Design the system such that it is difficult for the user to make inappropriate inputs to the system

ROBOT LESSONS LEARNED

- In an attack momentum is everything: the robot must keep up – or it will get left behind
- Hierarchical control will always be needed for dynamic mission planning
- The four areas in UGV development that cause the most stress in system design are: mobility, communications, power, and navigation
- For robot collectives or swarms, it is difficult to:
  - Coordinate many small vehicles
  - Scale control strategies to large numbers of vehicles
  - Provide useful behavior through cooperative action
  - Coordinate multiple robots by multiple operators
  - Communicate among many vehicles and operators, especially because of bandwidth problems

ROBOT LESSONS LEARNED

- It is necessary to define metrics and benchmarks to assess and quantify mobile robot autonomy
- Robotic learning is still primitive
- It is still difficult for robotic vehicles to operate in unpredictable environments
- It is expensive and impractical to specifically program robotic vehicles to respond appropriately to novel tasks and environments
- Very small untethered robots are not ready for tactical operations

ROBOT LESSONS LEARNED

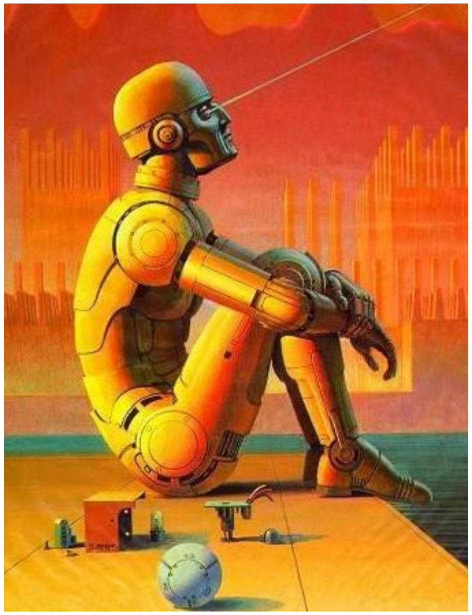
- Challenges to FCS robotic vehicle objectives are:
  - Autonomous mobility
  - Tactically intelligent behaviors
  - Robust adaptive perceptual capabilities
  - Intelligent, adaptive vehicle behaviors
  - Modular, non-intrusive soldier/robot interface
- FCS has insufficiently considered the necessity of evolution
- The robotics ambition of the FCS is comparable to the proverbial creation of man from the Euphrates mud

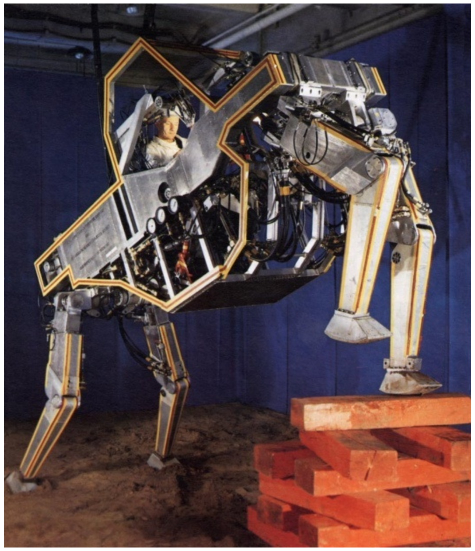
ROBOT LESSONS LEARNED

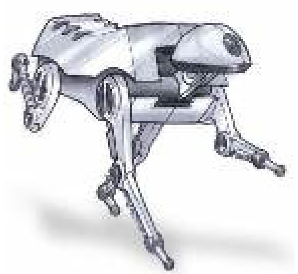
- Robot power requires higher energy densities
- Need to determine what is relevant for information displays
- Robotic sensors need higher resolution and range, with lower size, weight, and power
- Integrators must pay close attention to component experts
- Need complete descriptions of interfaces for software and hardware integration
- Component developers must comply with software interface standards (or fixing interfaces can take as much time as writing component code)
- The system integrator should provide a development and debugging environment for the developers

ROBOT LESSONS LEARNED

- Do not depend on manufacturer specifications for products; products must be characterized in the environments where they will be used
- Plan alternatives for high-risk items
- Have a backup plan for everything
- Keep exact records of all steps during integration, debugging, and troubleshooting
- Semi Automated Forces environments provide a robust testing arena for robotic behaviors
- When debugging, make only one change at a time

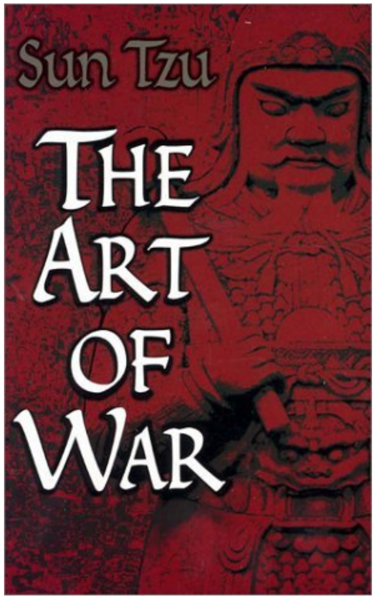






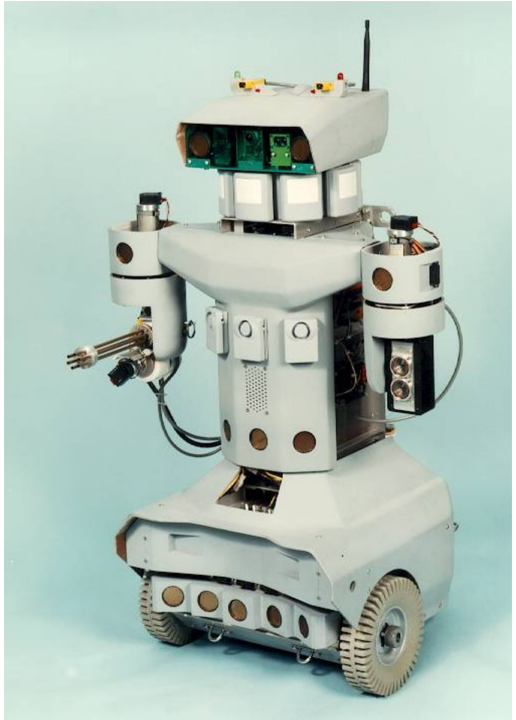
MILITARY ROBOTICS AND THE ANCIENT WISDOM OF SUN TZU

- ***Sun Tzu On The Art Of War*** **– oldest extant military treatise (2400 years old)**
- **Each example aphorism from Sun Tzu (in italics) is followed by an explanation of how the utility of military robotic forces satisfies the maxim**



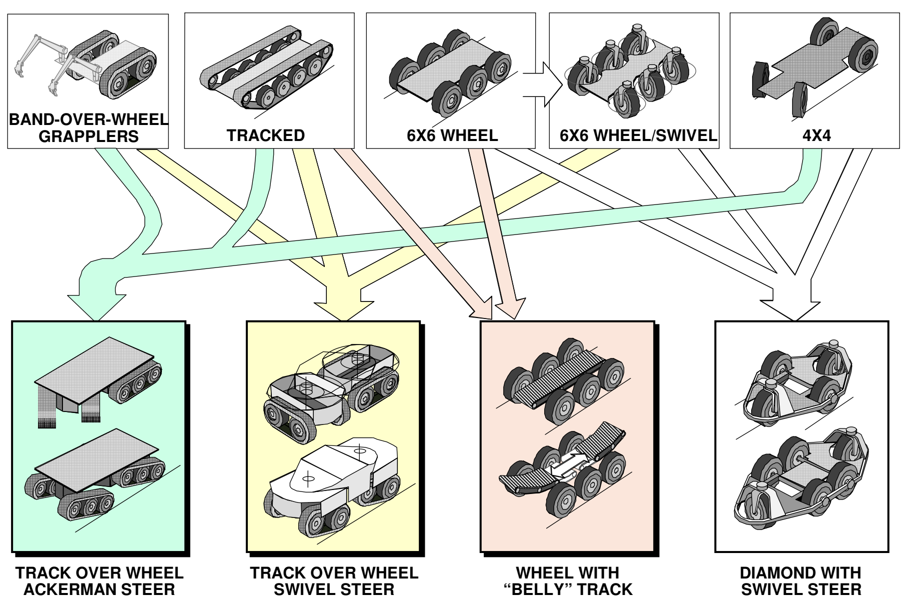
MILITARY ROBOTICS AND THE ANCIENT WISDOM OF SUN TZU

- *The art of war is vital to the state*
  - **Military technology must advance to meet new threats**
- *As circumstances are favorable, one should modify one's plans*
  - **Robots will be flexible, adaptable, resilient; reconfigurable and transportable**
- *All warfare is based on deception*
  - **Robotic systems can take many forms; be stealthy or intentionally noisy; cloak themselves and deceive the enemy physically, electronically, and behaviorally**



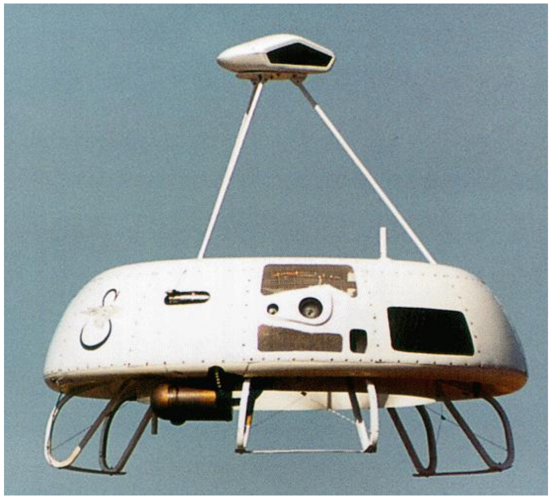
MILITARY ROBOTICS AND THE ANCIENT WISDOM OF SUN TZU

- *If he is taking his ease, give him no rest. If his forces are united, separate them*
  - **Robotic systems are tireless**
  - **They will implacable and remorselessly hound the enemy**
  - **With stealth and micro-robots they can infiltrate enemy forces and cause them to scatter**



MILITARY ROBOTICS AND THE ANCIENT WISDOM OF SUN TZU

- ***Attack him where he is unprepared, appear where you are not expected***
  - **With a profusion of linked sensors in space, in the air, on the ground – unattended and mobile – the robotic system of systems will more easily determine where the enemy is unprepared**
  - **And robotic systems can better appear where not expected (e.g., more stealthy, travel without rest)**

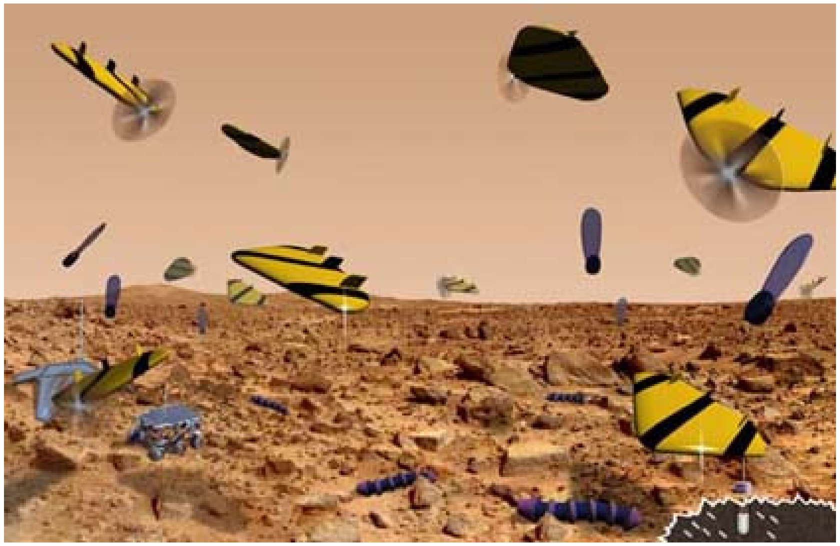


MILITARY ROBOTICS AND THE ANCIENT WISDOM OF SUN TZU

- ***Though an obstinate fight may be made by a small force, in the end it must be captured by the larger force***
  - **A robotic force can put up an "obstinate fight" if it will contribute to the mission – and not be concerned about being captured**
- ***Hold out baits to the enemy. Feign disorder and crush him***
  - **Robotic systems, being expendable, can be used as bait to lure the enemy into the killing zone**

MILITARY ROBOTICS AND THE ANCIENT WISDOM OF SUN TZU

- ***Hence that general is skillful in attack whose opponent does not know what to defend; and he is skillful in defense whose opponent does not know what to attack***
  - **The "shape-shifting" nature of the agile robotic collective, reconfiguring into forces with different elements and abilities, will leave the enemy with an inability to know what to best defend or attack**

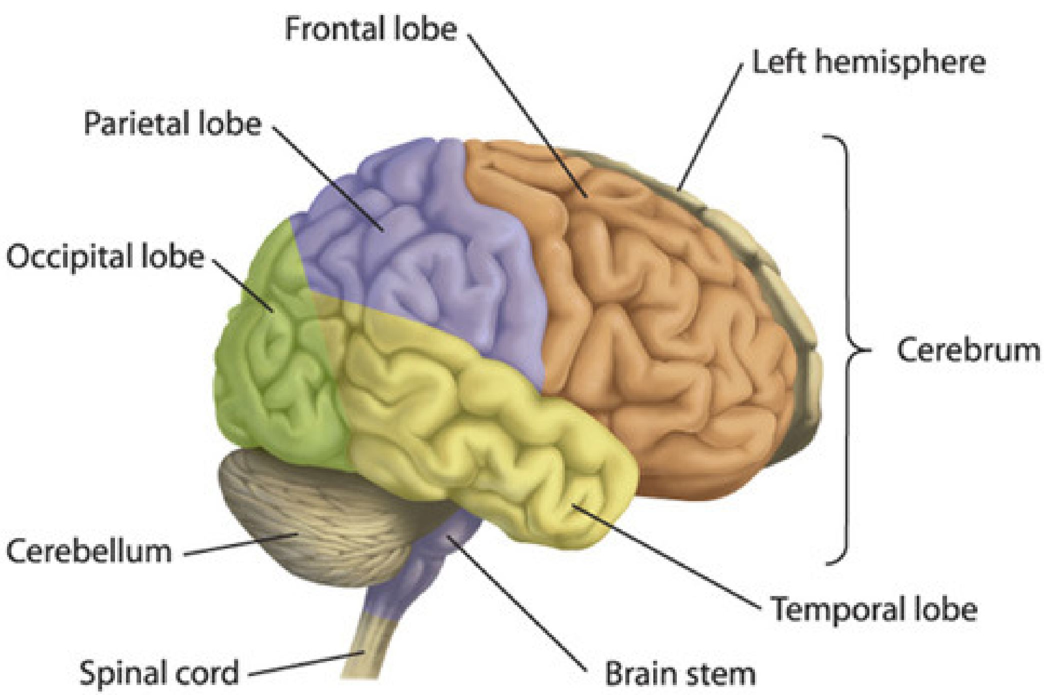


MILITARY ROBOTICS AND THE ANCIENT WISDOM OF SUN TZU

- ***Do not repeat the tactics which have gained you one victory, but let your methods be regulated by the infinite variety of circumstances***
  - **The tactics for combat robotics (which must yet be developed) can be far more varied than for conventional systems**
  - **Prospective tactics can be tested in near-real time by distributed interactive simulators embedded within the systems**

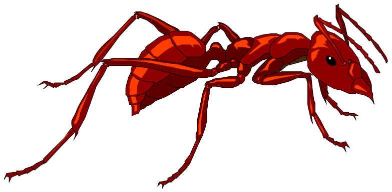
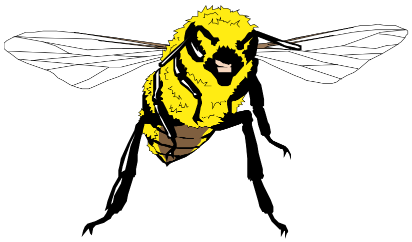
INTELLIGENCE AND AUTONOMY

- **The question is not how smart a military robot should be, but how dumb can it be and still do its job?**



WHAT IS INTELLIGENCE?

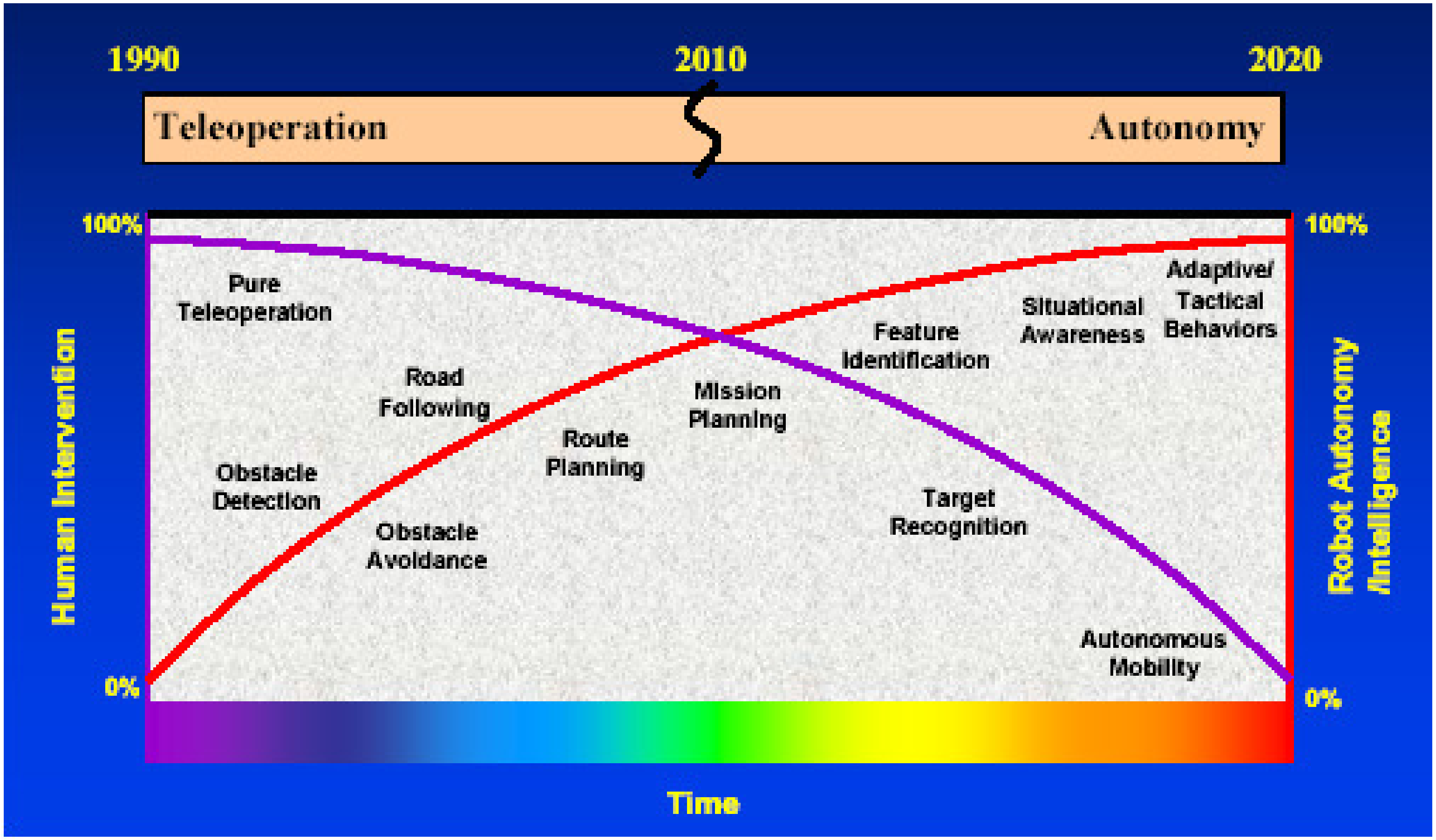
- **Pragmatic definition of intelligence: "an *intelligent system* is a system with the ability to act *appropriately* (or make an appropriate choice or decision) in an uncertain environment."**
  - **An *appropriate* action (or choice) is that which maximizes the probability of successfully achieving the *mission goals* (or the *purpose* of the system)**
- **Intelligence need not be at the *human* level**
  - ***Appropriate* intelligence: ability of vehicle to perform as a skilled human driver would under a variety of conditions**
  - **Desired level of vehicle intelligence: depends on the user's requirements and technical, operational, and economical feasibility of achieving the desired level of intelligence**

WHAT IS INTELLIGENCE?

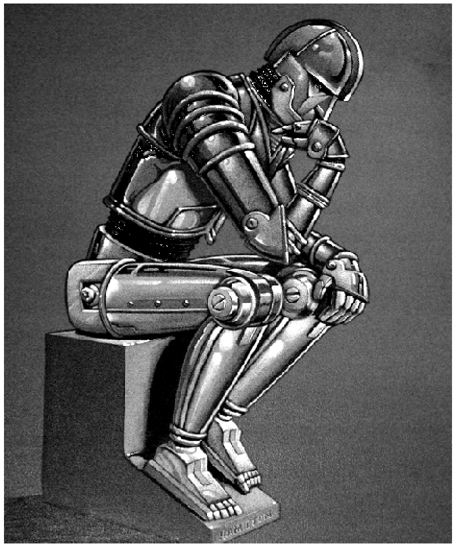
- **Three useful corollary definitions of intelligence:**
  - **Reactive intelligence (adaptation)**
    - **Based on an autonomic sense-act modality**
    - **Ability of the system to make an appropriate choice in response to an immediate environmental stimulus (i.e., a threat or opportunity)**
    - **Example: it is raining and the system is getting wet, so it seeks shelter**
  - **Predictive intelligence (learning)**
    - **Based on memory**
    - **Ability to make an appropriate choice for events that have not yet occurred but which are based on prior events**
    - **Example: it is very cloudy and the system infers that it will likely rain soon, so it decides to seek shelter before it rains**
  - **Creative intelligence (invention)**
    - **Based on learning and the ability to cognitively model and simulate**
    - **Ability to make appropriate choices about events which have not yet been experienced**
    - **Example, it takes too much time and energy for the system to seek shelter every time it rains or threatens to rain, so it invent an umbrella to shield it from the rain (the system can imagine that the umbrella, which never before existed, will protect it from the rain)**

AUTONOMOUS INTELLIGENCE: DOD GOAL



WHAT IS LEARNING?

- **Learning:** the acquisition of knowledge, skill, ability, or understanding by study, instruction, or experience, as evidenced by achieving growing success (improved behavior), with respect to suitable metrics, in a ***fixed*** environment
  - Learning takes place when the system's behavior *increases the efficiency* with which data, information, and knowledge is processed so that desirable states are reached, errors avoided, or a portion of the system's environment is controlled

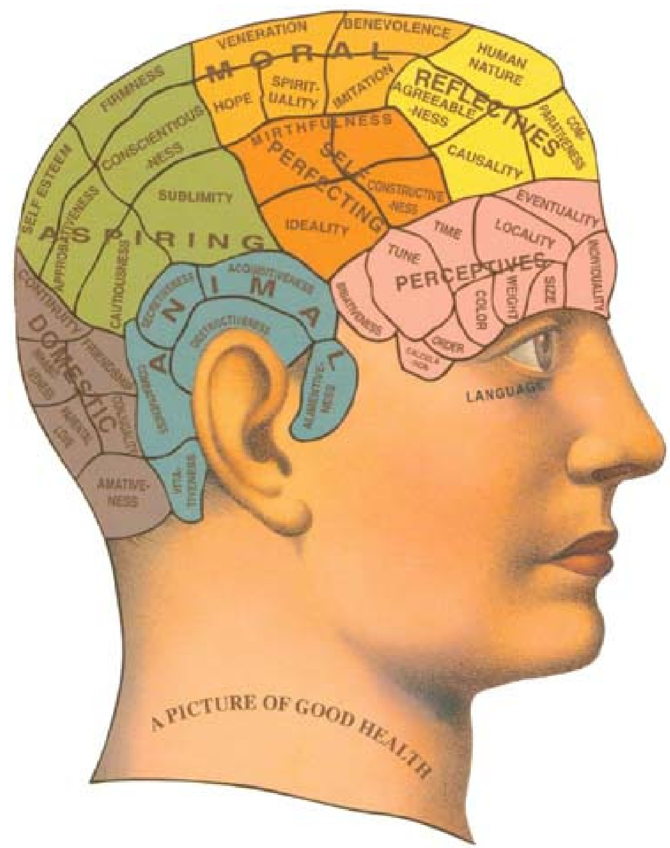


WHAT IS ADAPTATION?

- **Adaptation: A change in behavior (or structure) in response to a *changed* environment**
  - **Able to maintain critical or essential variables within physical (or physiological) limits (e.g., homeostasis)**
  - **Where the changed behavior (or structure) increases the probability that the system can achieve its function or purpose (e.g., maintain homeostasis) by adjusting to the new or changed environment**

Learning – fixed environment

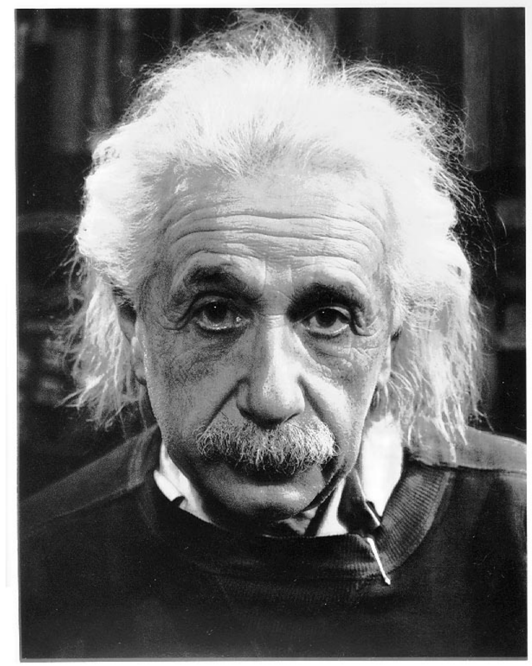
Adaptation – changed environment



WHAT IS WISDOM?

- **Many projects to develop machine learning and intelligence – but none yet for machine wisdom**
- **The original meaning of the word *philosophy* is "love of (or search for) *wisdom*"**
  - **A perception of the relativity and relationships among things**
  - **An awareness of wholeness that does not lose sight of particularity or concreteness, or of the intricacies of interrelationships**
  - **The ability to filter the inessential from the essential**
  - **The ability to recognize that which is significant amongst the detail (to see the forest as well as the trees)**

Knowledge involves aggregating facts; wisdom lies in disaggregating facts



"Things should be made as simple as possible, but not any simpler."
- Albert Einstein

Where is the
WISDOM
We have Lost in
KNOWLEDGE
?

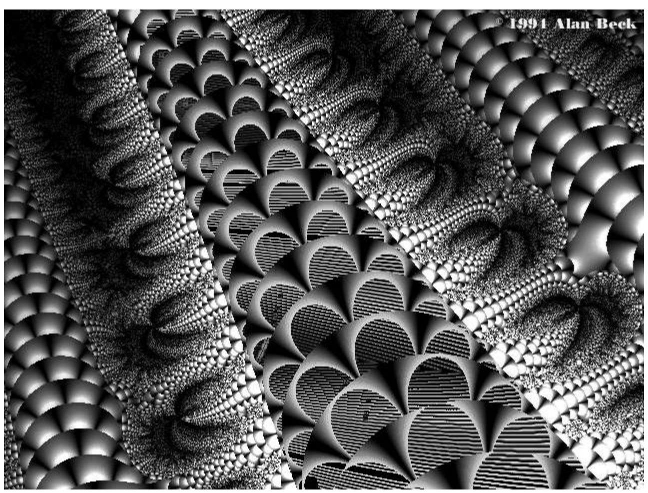
WHAT IS AUTONOMY?

- Still being defined
- ALFUS (Autonomy Levels For Unmanned Systems) Working Group
  - Managed by the Army Research Lab (ARL) and the National Institute of Standards and Technology (NIST)
  - Since 2003, meets at various U.S. locations

autonomy levels

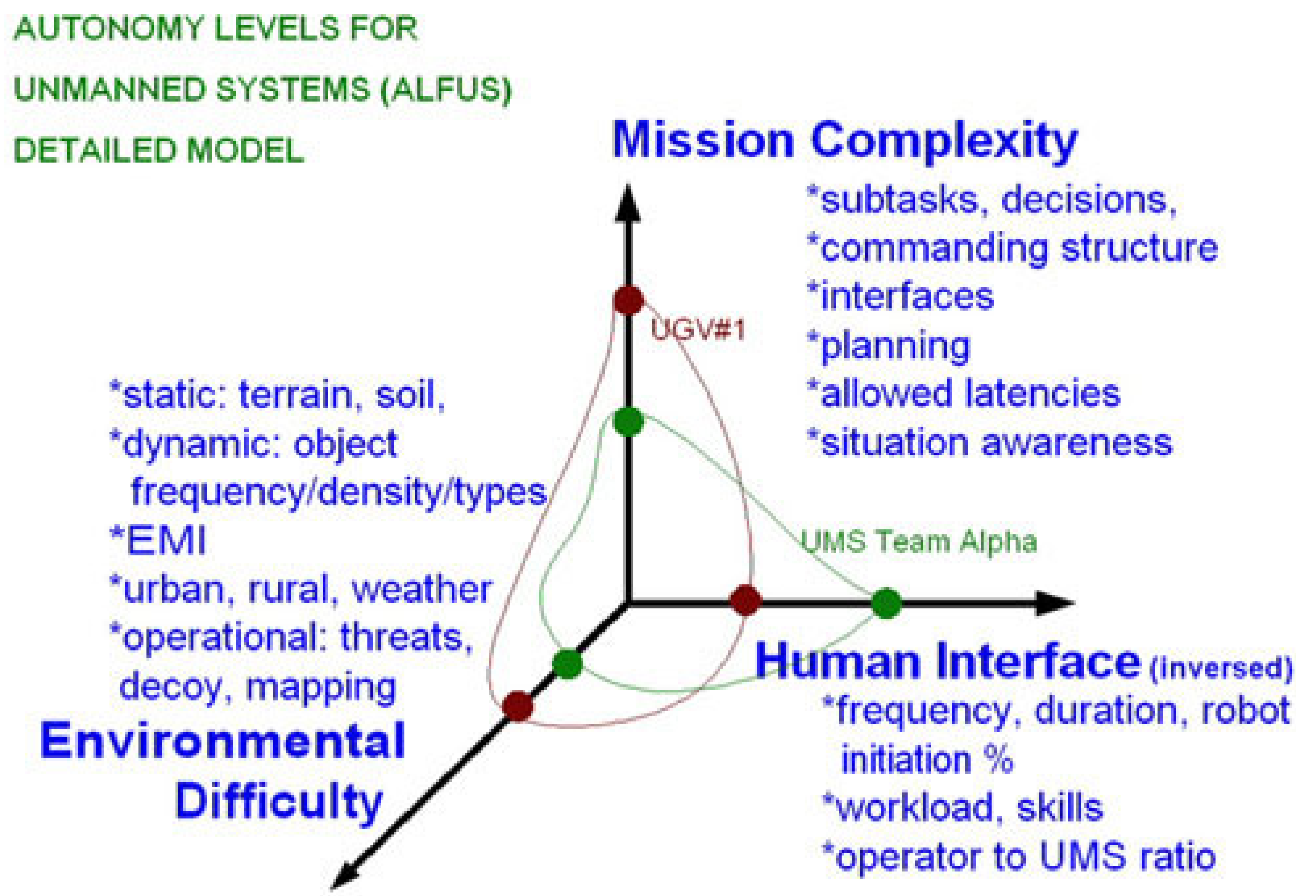
	MC	ED	HRI
10			
9			
8			
2			
1			

MC: mission complexyty,
ED: environmental difficulty
HRI: human-robot interaction



WHAT IS AUTONOMY?

- **ALFUS: Focusing on three key variables: Mission Complexity, Environmental Difficulty, and Human Interface**

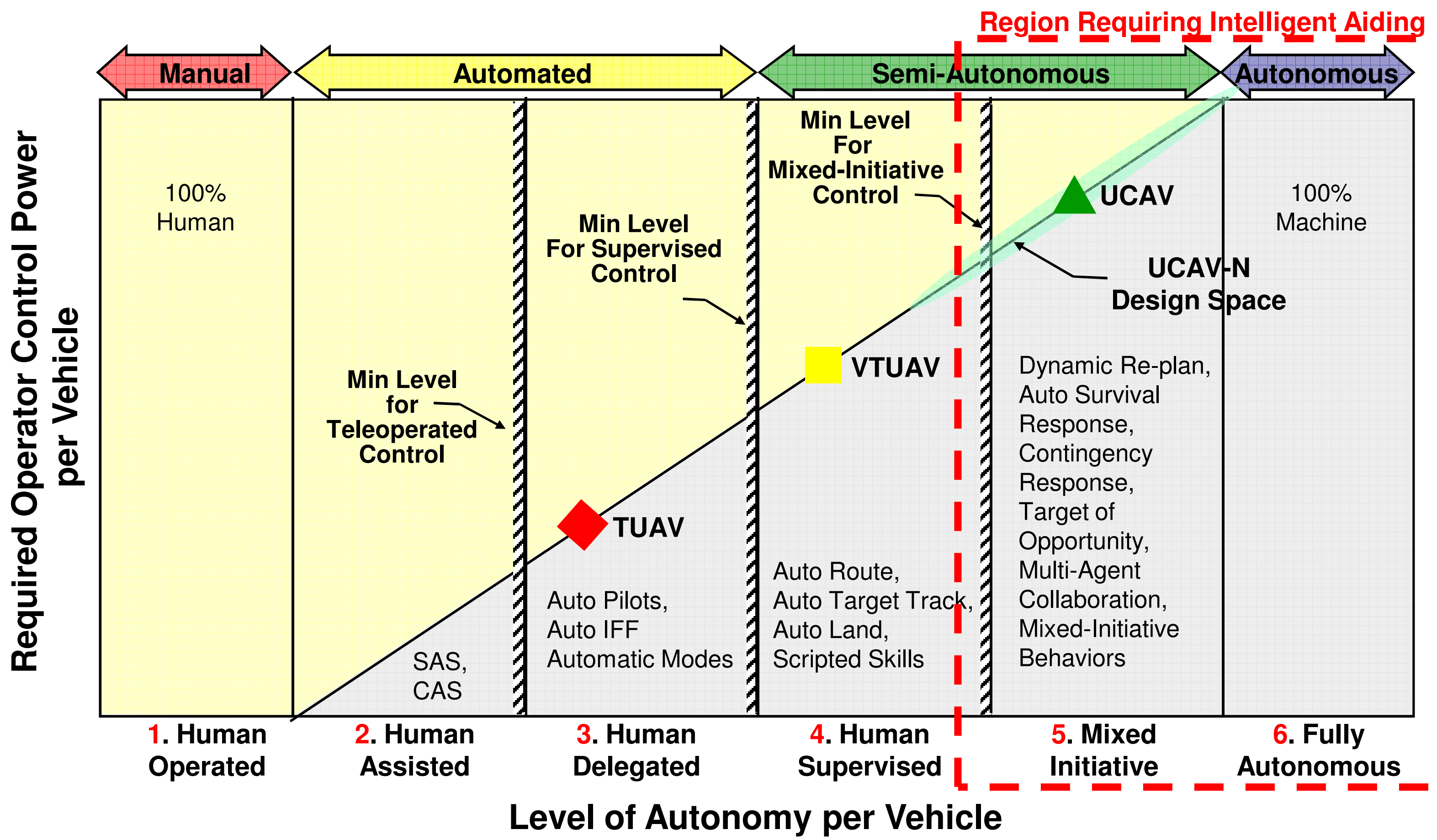


EXAMPLE AUTONOMY TAXONOMY (ONR UCAV PROGRAM 2000)

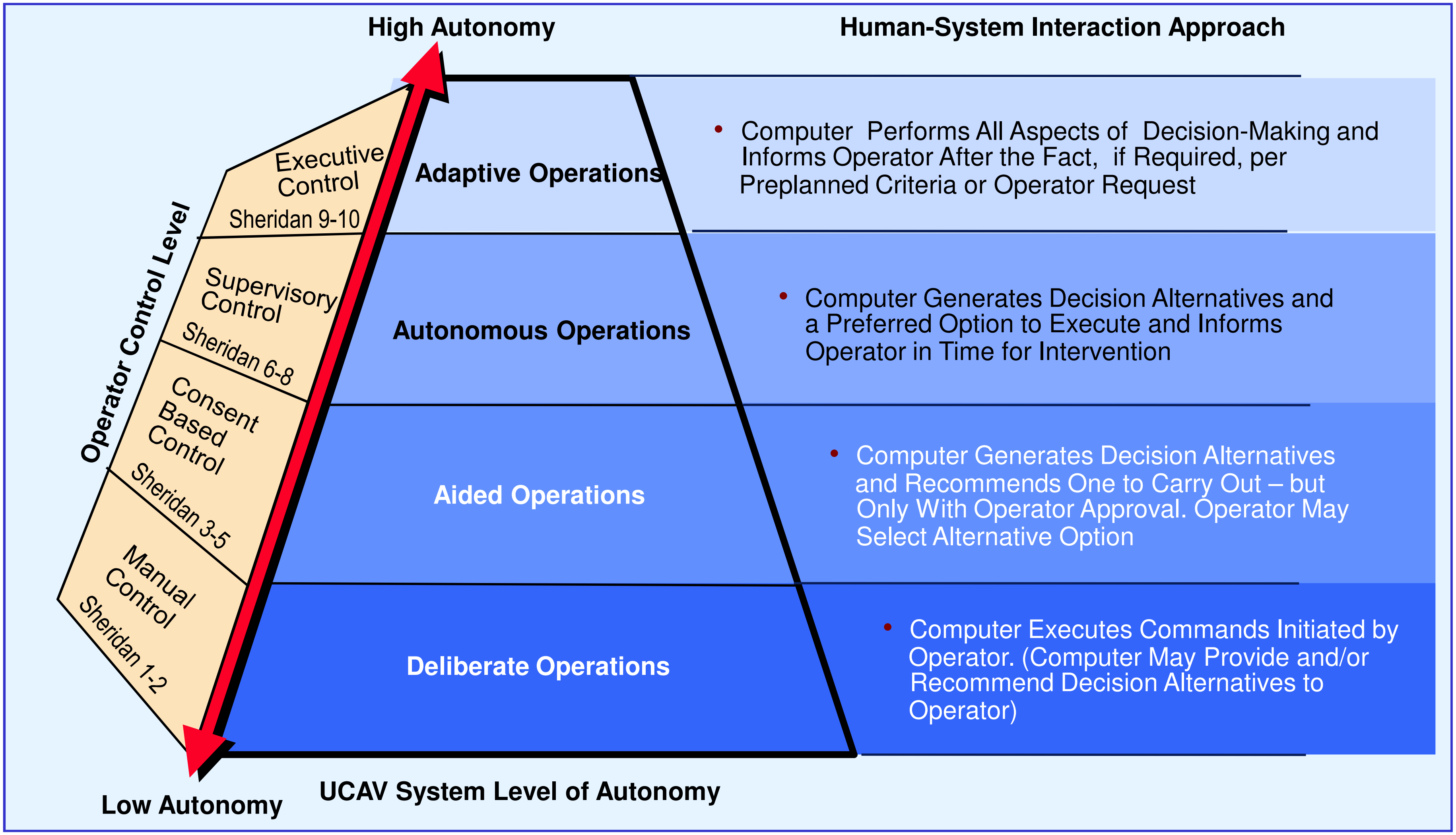
Level	Name	Description	Example
0	Human Operated	All activity within the system is the direct result of human-initiated control inputs. The system has no autonomous control of its environment, although it may have information-only responses to sensed data.	
1	Human Assisted	The system can perform activity in parallel with human input, acting to augment the ability of the human to perform the desired activity, but has no ability to act without accompanying human input	Automobile automatic transmission and anti-skid brakes.
2	Human Delegated	The system can perform limited control activity on a delegated basis. This level encompasses low-level automation that must be activated or deactivated by a human input and act in mutual exclusion with human operation.	Automatic flight controls, engine controls
3	Human Supervised	The system can perform a wide variety of activities given top-level permissions or direction by a human. The system provides sufficient insight into its internal operations and behaviors that it can be understood by its human supervisor and appropriately	
4	Mixed Initiative	Both the human and the system can initiate behaviors based on sensed data. The system can coordinate its behavior with the human's behaviors both explicitly and implicitly. The human can understand the behaviors of the system in the same way that he und	
5	Fully Autonomous	The system requires no human intervention to perform any of its designed activities across all planned ranges of environmental conditions.	

EXAMPLE AUTONOMY TAXONOMY (BOEING)

Six levels (four Regions) stated in terms of degree of operator interaction (adopted from the Naval Studies Board report on ONR UCAV Program, Summer 2000)



EXAMPLE AUTONOMY TAXONOMY (NORTHROP-GRUMMAN)

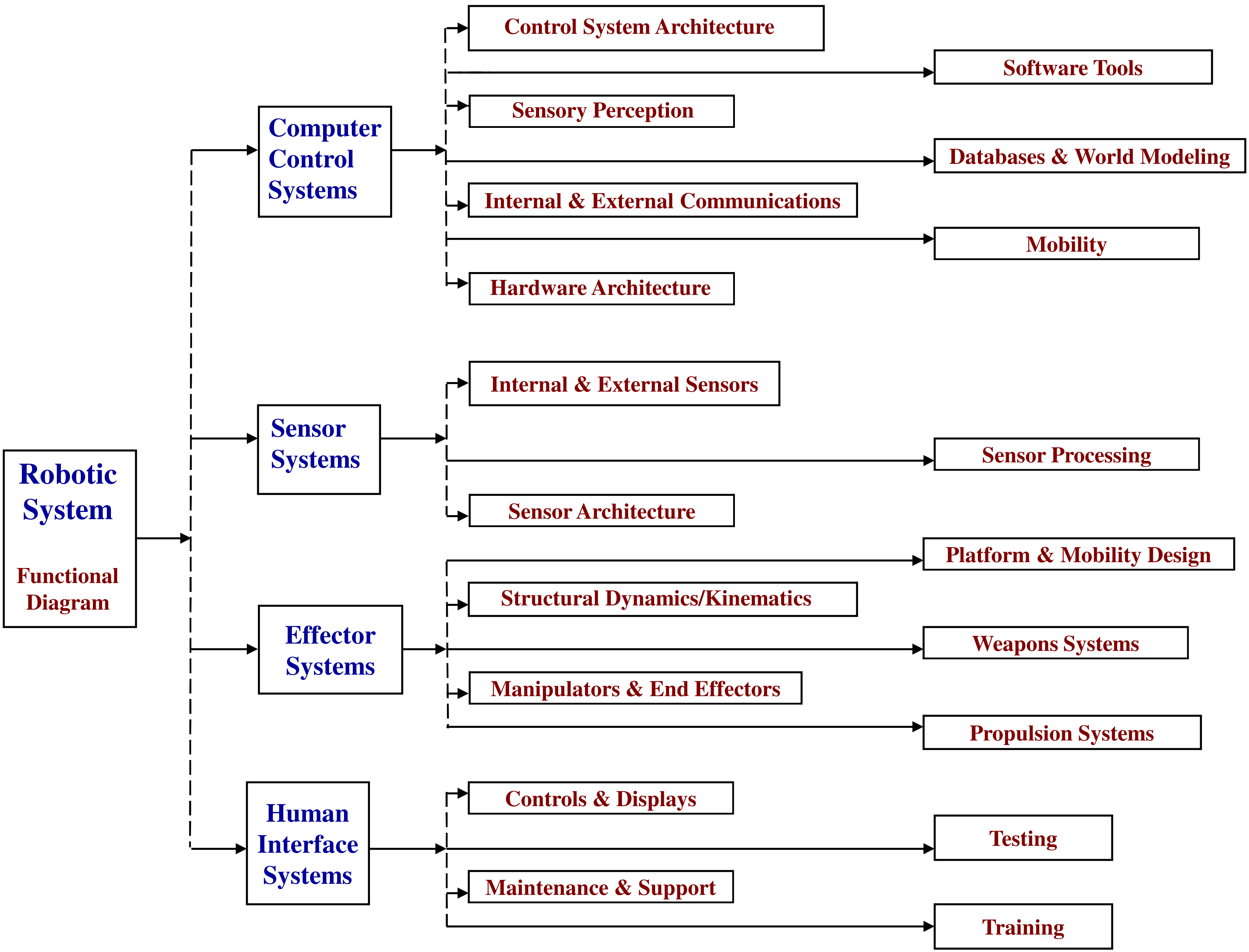


EXAMPLE AUTONOMY TAXONOMY

Level	***Level Descriptor***	***Observe*** Perception/Situational Awareness	***Orient*** Analysis/Coordination	***Decide*** Decision Making	***Act*** Capability
10	***Fully Autonomous***	Cognizant of all within Battlespace	Coordinates as necessary	Capable of total indepenance	Requires little guidance to do job
9	***Battlespace Swarm Cognizance***	Battlespace inference - Intent of self and others (allies and foes). Complex/Intense environment - on-board tracking	Strategic group goals assigned Enemy strategy inferred	Distributed tactical group planning Individual determination of tactical goal Individual task planning/execution Choose tactical targets	Group accomplishment of strategic goal with no supervisory assistance
8	***Battlespace Cognizance***	Proximity inference - Intent of self and others (allies and foes) Reduced dependance upon off-board data	Strategic group goals assigned Enemy tactics inferred ATR	Coordinated tactical group planning Individual task planning/execution Choose targets of opportunity	Group accomplishment of strategic goal with minimal supervisory assistance (example: go SCUD hunting)
7	***Battlespace Knowledge***	Short track awareness - History and predictive battlesp data in limited range, timeframe, and numbers Limited inference supplemented by off-board data	Tactical group goals assigned Enemy trajectory estimated	Individual task planning/execution to meet goals	Group accomplishment of tactical goal with minimal supervisory assistance
6	***Real Time Multi-Vehicle Cooperation***	Ranged awareness - on-board sensing for long range, supplemented by off-board data	Tactical group goals assigned Enemy location sensed/estimated	Coordinated trajectory planning and execution to meet goals - group optimization	Group accomplishment of tactical goal with minimal supervisory assistance Possible close air space separation (1-100 yds)
5	***Real Time Multi-Vehicle Coordination***	Sensed awareness - Local sensors to detect others, Fused with off-board data	Tactical group plan assigned RT Health Diagnosis; Ability to compensate for most failures and flight conditions; Ability to predict onset of failures (e.g. Prognostic Health Mgmt) Group diagnosis and resource management	On-board trajectory replanning - optimizes for current and predictive conditions Collision avoidance	Group accomplishment of tactical plan as externally assigned Air collision avoidance Possible close air space separation (1-100 yds) for AAR, formation in non-threat conditions
4	***Fault/Event Adaptive Vehicle***	Deliberate awareness - allies communicate data	Tactical plan assigned Assigned Rules of Engagement RT Health Diagnosis; Ability to compensate for most failures and flight conditions - inner loop changes reflected in outer loop performance	On-board trajectory replanning - event driven Self resource management Deconfliction	Self accomplishment of tactical plan as externally assigned Medium vehicle airspace separation (100's of yds)
3	***Robust Response to Real Time Faults/Events***	Health/status history & models	Tactical plan assigned RT Health Diag (What is the extent of the problems?) Ability to compensate for most control failures and flight conditions (i.e. adaptive inner-loop control)	Evaluate status vs required mission capabilities Abort/RTB if insufficient	Self accomplishment of tactical plan as externally assigned
2	***Changeable Mission***	Health/status sensors	RT Health diagnosis (Do I have problems?) Off-board replan (as required)	Execute preprogrammed or uploaded plans in response to mission and health conditions	Self accomplishment of tactical plan as externally assigned
1	***Execute Preplanned Mission***	Preloaded mission data Flight Control and Navigation Sensing	Pre/Post Flight BIT Report status	Preprogrammed mission and abort plans	Wide airspace separation requirements (miles)
0	***Remotely Piloted Vehicle***	Flight Control (attitude, rates) sensing Nose camera	Telemetered data Remote pilot commands	N/A	Control by remote pilot

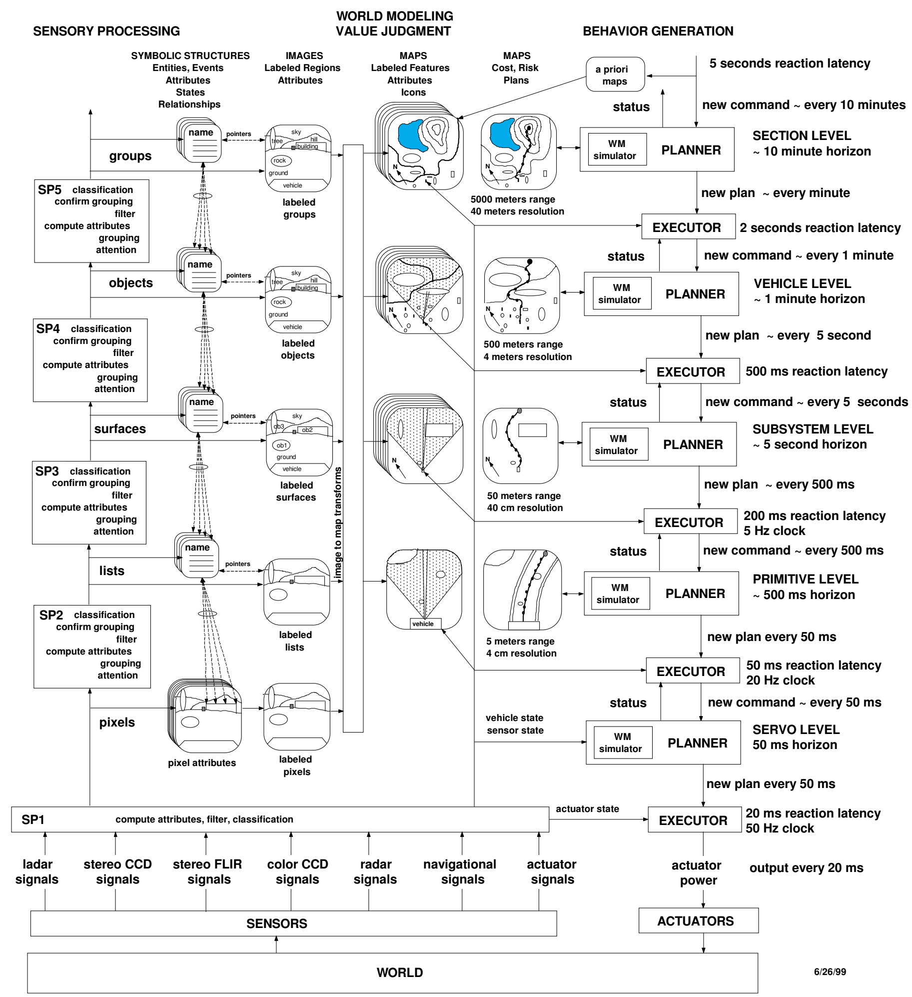
EXAMPLE AUTONOMY TAXONOMY

1) System offers no assistance – operator must do everything
2) System offers a complete set of action alternatives to operator
3) System narrows the action alternatives to a few
4) System suggests a selection, and
5) System executes a selection if operator approves, or
6) System allows operator a restricted time to veto before automatic execution, or
7) System executes automatically, then necessarily informs operator, or
8) System informs operator after execution only if operator asks, or
9) System informs operator after execution - if system decides to
10) System decides everything and acts autonomously, essentially ignoring the human

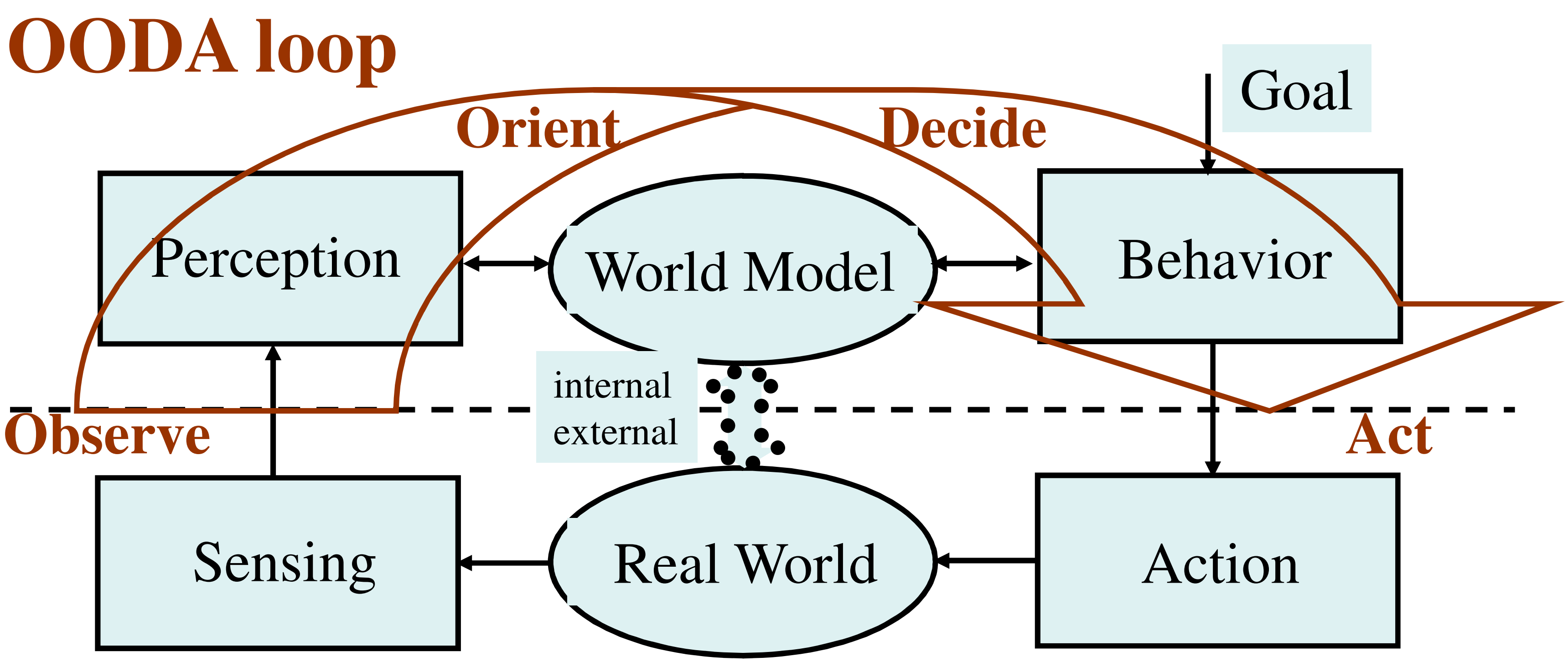

Robotic System
Functional Diagram
Computer Control Systems
Control System Architecture
Software Tools
Sensory Perception
Databases & World Modeling
Internal & External Communications
Mobility
Hardware Architecture
Sensor Systems
Internal & External Sensors
Sensor Processing
Sensor Architecture
Effector Systems
Platform & Mobility Design
Structural Dynamics/Kinematics
Weapons Systems
Manipulators & End Effectors
Propulsion Systems
Human Interface Systems
Controls & Displays
Testing
Maintenance & Support
Training

AUTONOMOUS INTELLIGENT CONTROL

- Many prospective control systems
- NIST 4D/RCS most advanced – and free
  - 30 years development and $100 million invested
  - Demos I, II, III, and many other successful demonstrations
  - Used by GDRS for FCS Autonomous Navigation System (ANS)
  - Used by TARDEC for Vetronics Technology Integration
  - Used by Eagle Systems for Future Force Warrior



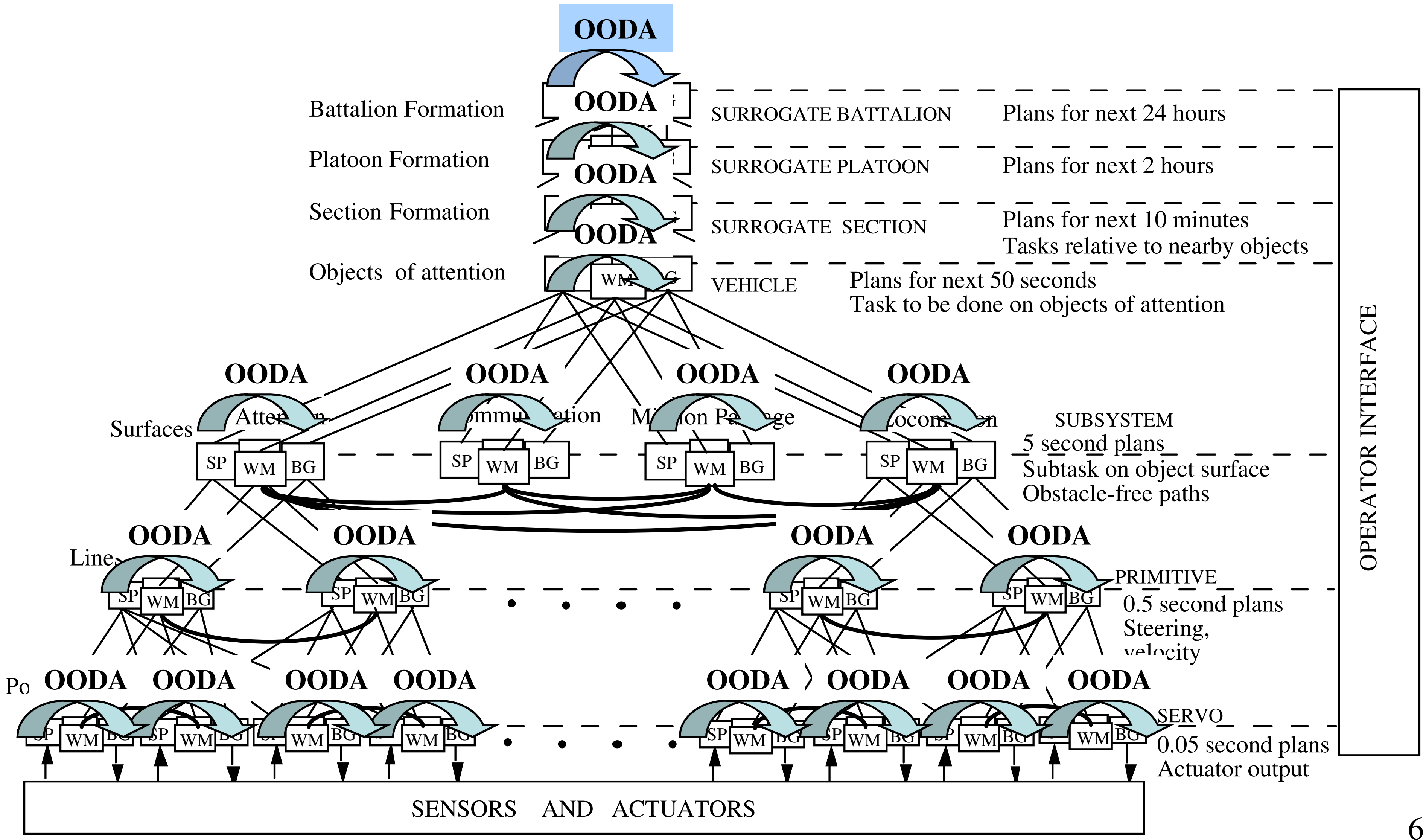
BASIC INTELLIGENT SYSTEM



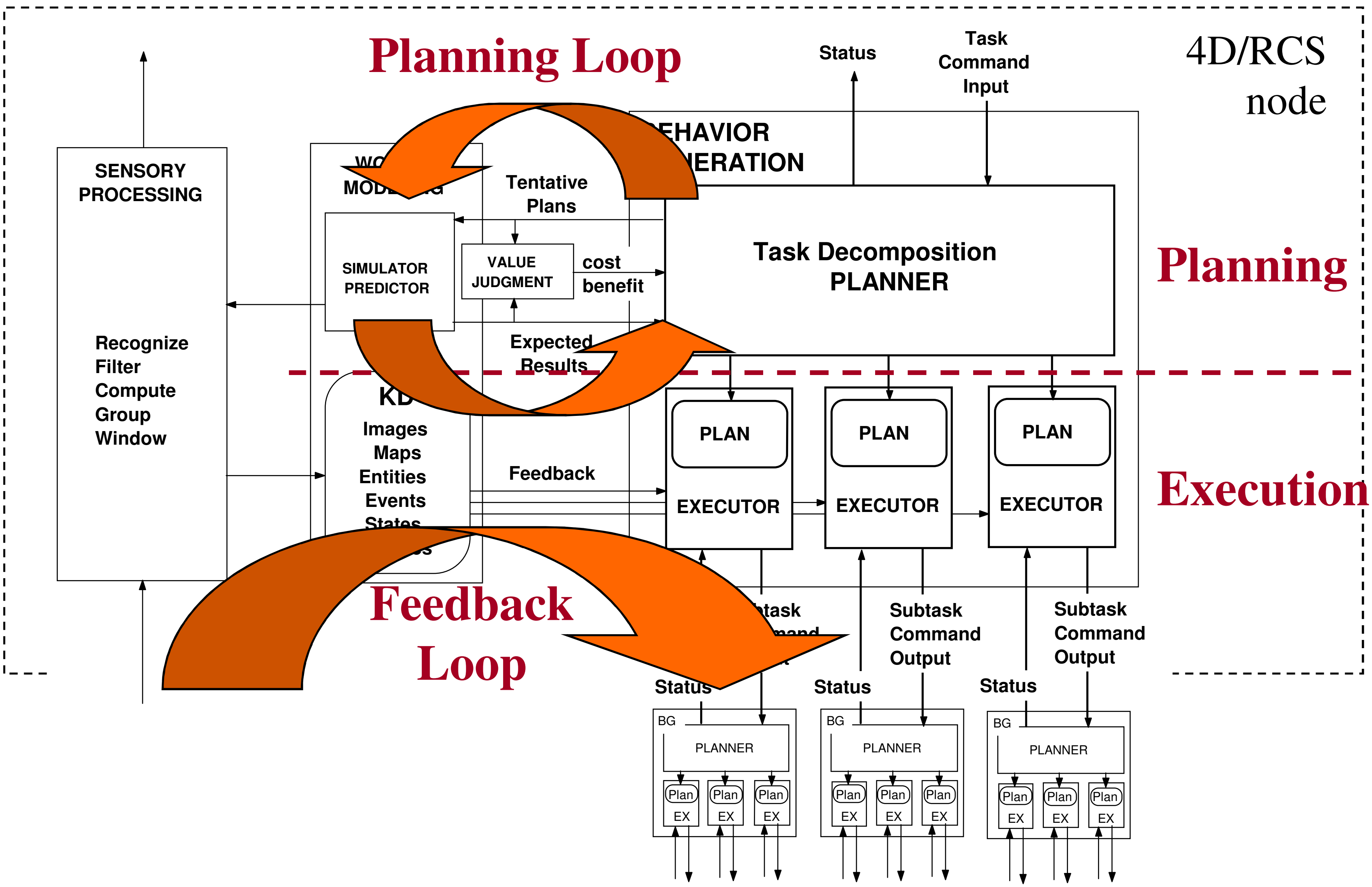
Perception establishes correspondence between internal world model and external real world

Behavior uses world model to generate action to achieve goals

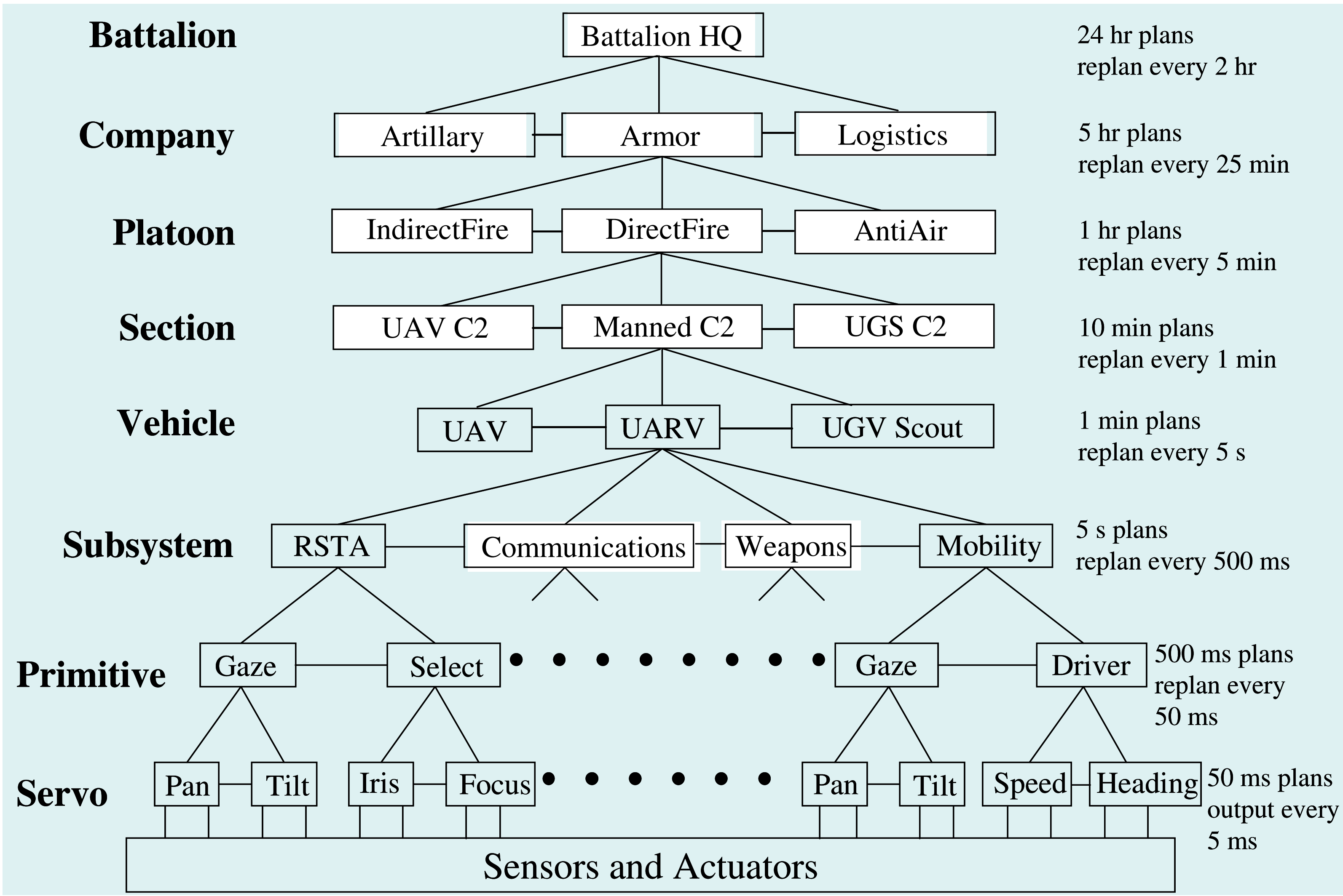
4D/RCS ARCHITECTURE



A 4D/RCS COMPUTATIONAL NODE

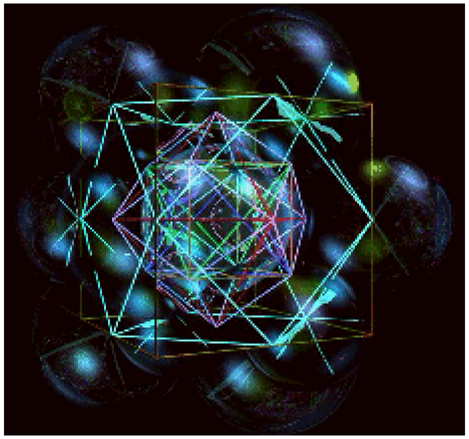


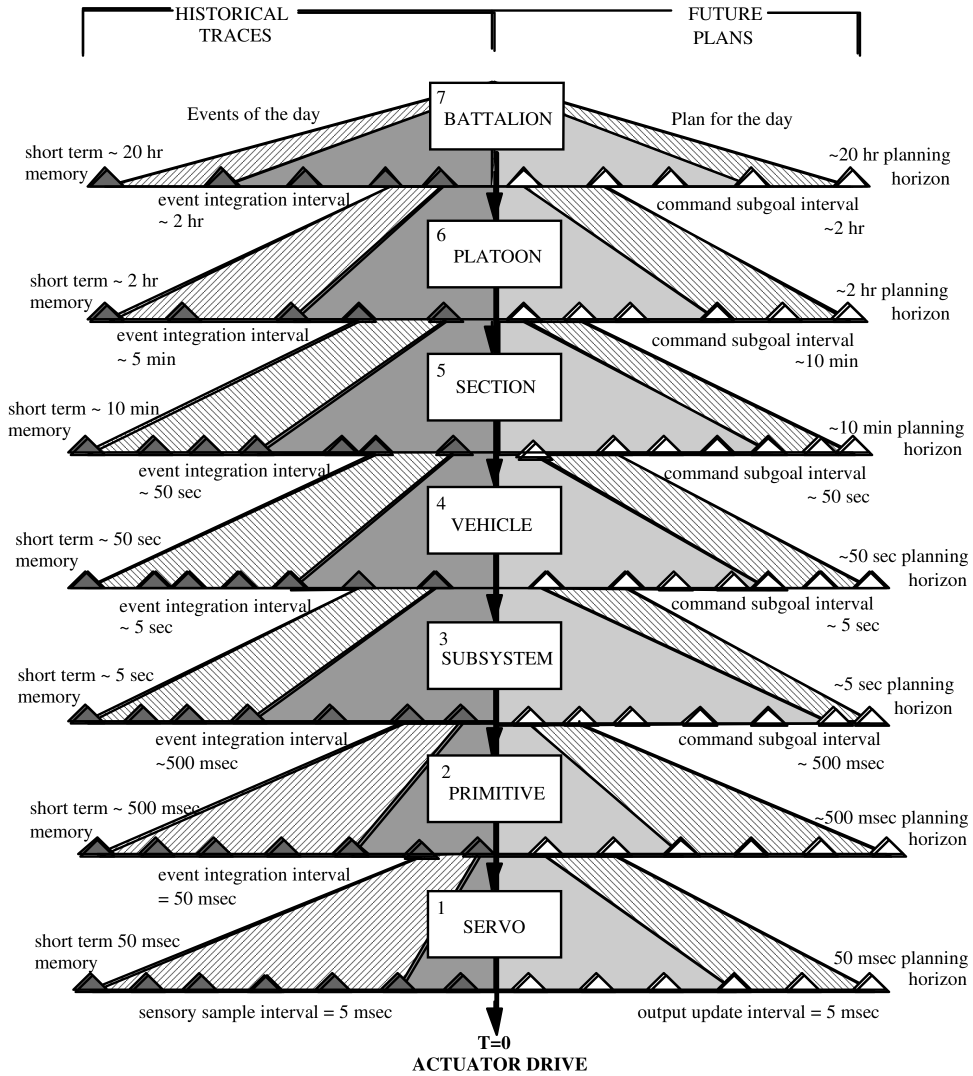
4D/RCS ARCHITECTURE



4D/RCS ARCHITECTURE

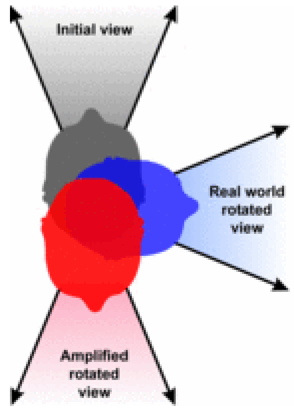
- Technology can be transferred to any company for:
  - Autonomous intelligent vehicles as products
  - Intelligent software as products

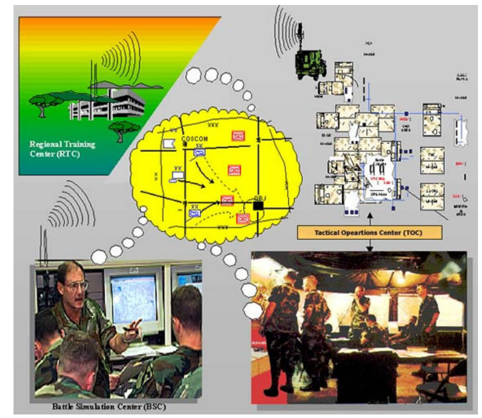




ARCHITECTURE: DESIRED FLEXIBILITY

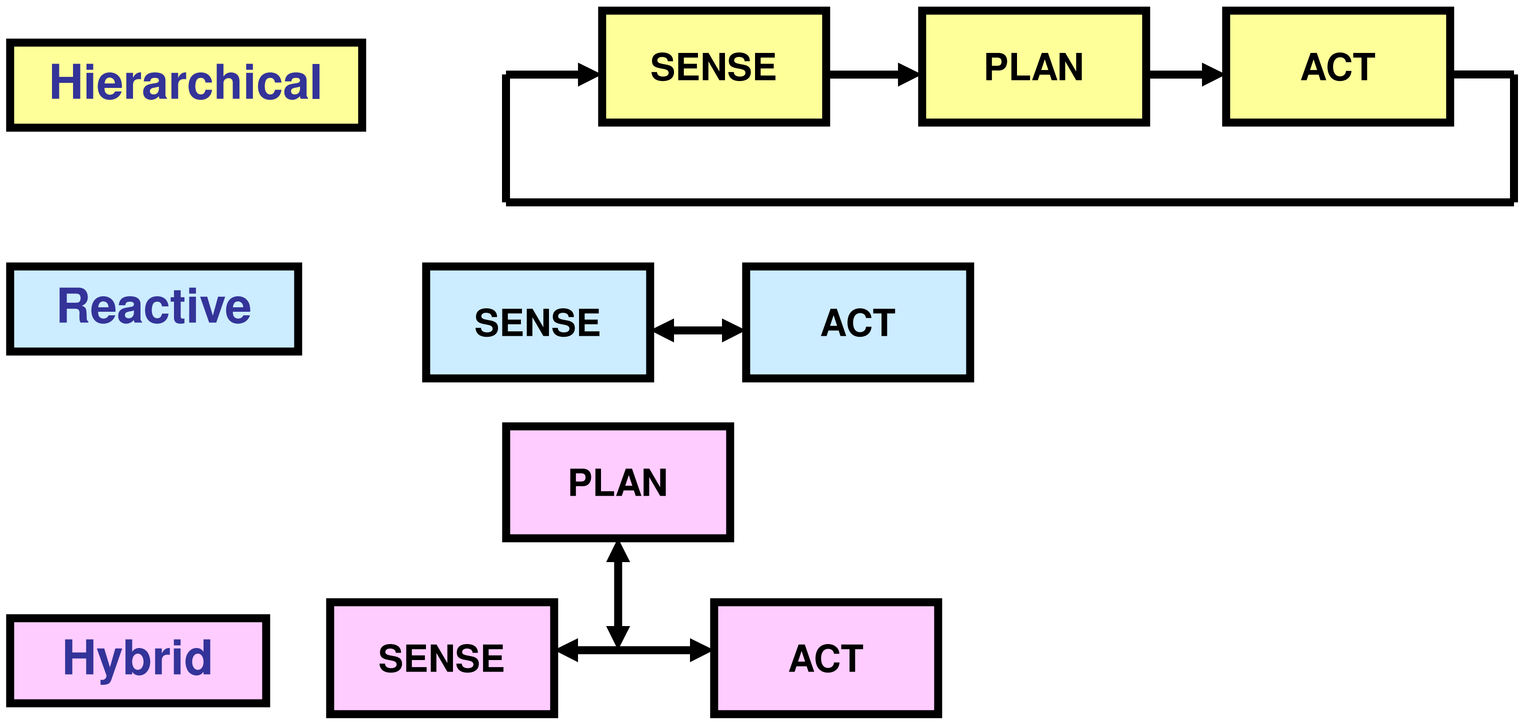
- **Intelligent vehicle architecture: open, interoperable, and common**
- **Open architecture**
  - **Allows different modules to be inserted easily into the system (as in home stereo systems)**
- **Interoperable architecture**
  - **Allows each vehicle or control center to work with different vehicles platforms, payloads, and communications networks**
- **Common architecture**
  - **Allows each vehicle or control center to use the same hardware and software as other vehicles or control centers**





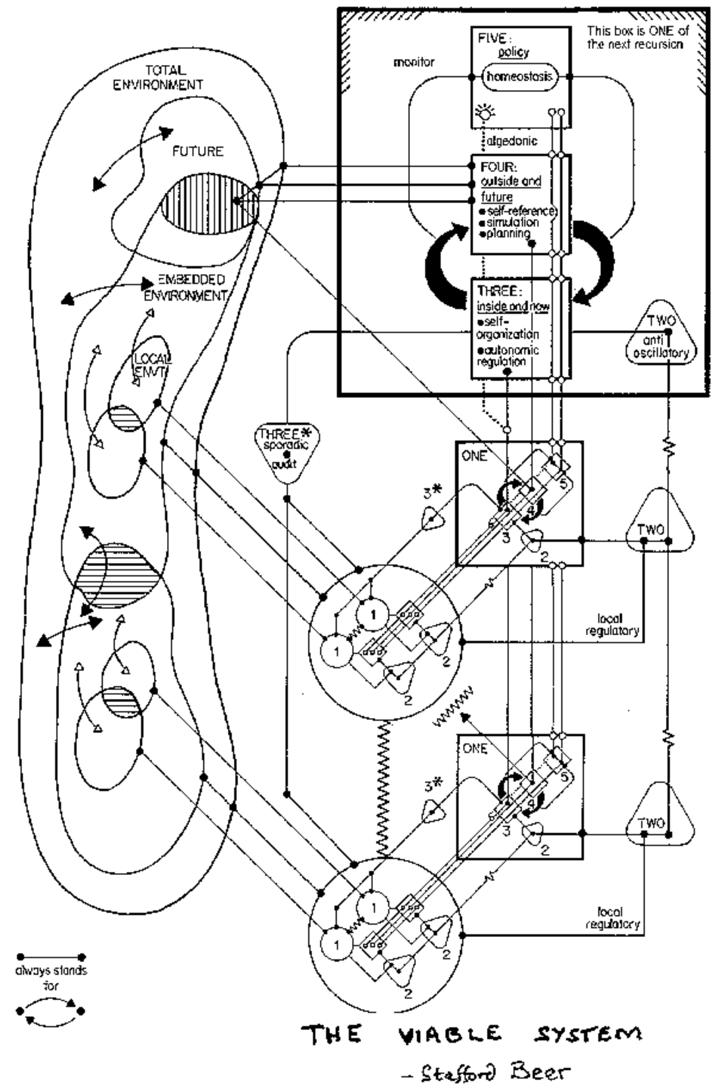
CONTROL ARCHITECTURES

- Three major types: **hierarchical (deliberative); reactive; hybrid (deliberative/reactive)**



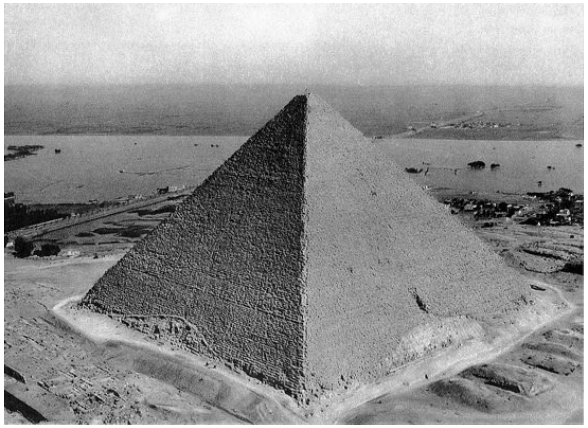
CONTROL ARCHITECTURES

- In addition to deliberative and reactive behaviors, an intelligent control system could also be ***reflective***
  - Able to monitor and alter its behavior (i.e., its critical variables) to better adapt
  - A meta-control system controls the intelligent control system



CONTROL ARCHITECTURES

- Advantages of hierarchical (pyramidal) architectures
  - With a planner and world model, the system can (potentially) emulate human intelligence
  - Ability to engage in strategy and tactics
  - Ability to learn
- Disadvantages
  - Planner and world model can slow performance excessively
  - Requires burdensome a priori programming for world model
  - None have been fully operational (although the NIST RCS has been partially implemented in a number of robotic vehicles)

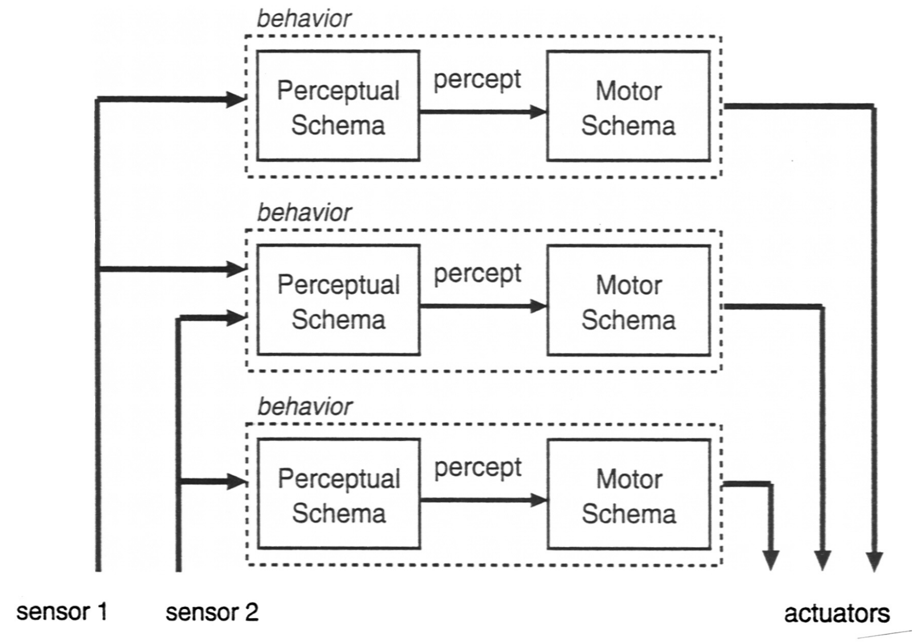


CONTROL ARCHITECTURES

- Reactive control system architectures (e.g., the MIT subsumption architecture) have been successfully implemented in small mobile robots
  - The potential fields type of reactive architectures have certain design advantages over other reactive architectures
- Advantages of reactive architectures
  - Emergent complex behavior from simple programming
  - Lack of planner and world model allows for fast responses
  - Minimal programming required
  - Inexpensive to build
- Disadvantages
  - No learning
  - Unable to replicate human intelligence even in narrow domains (e.g., military tactics)
  - Conflicts can arise among concurrent behaviors

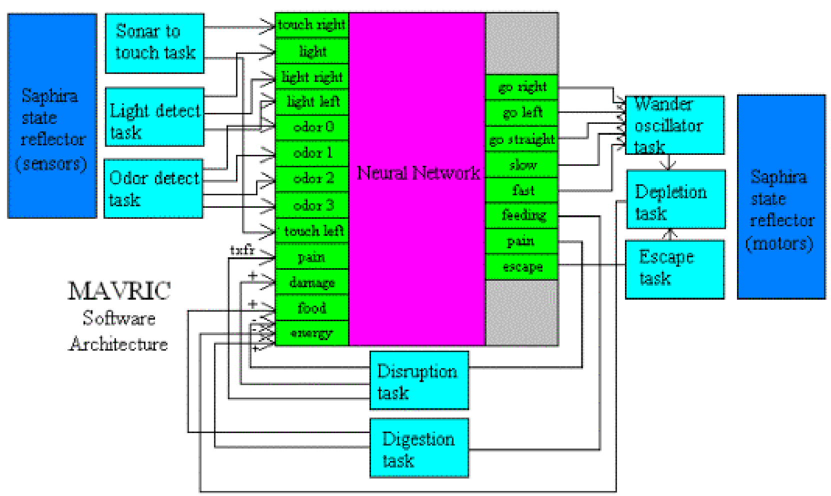
REACTIVE ARCHITECTURE SENSING

- Behavior-specific sensing
- Each behavior has its own dedicated sensing
- Sensing is local but can be shared
- Sensors can be fused locally by behavior
- But one behavior does not know what another behavior is doing or perceiving



CONTROL ARCHITECTURES

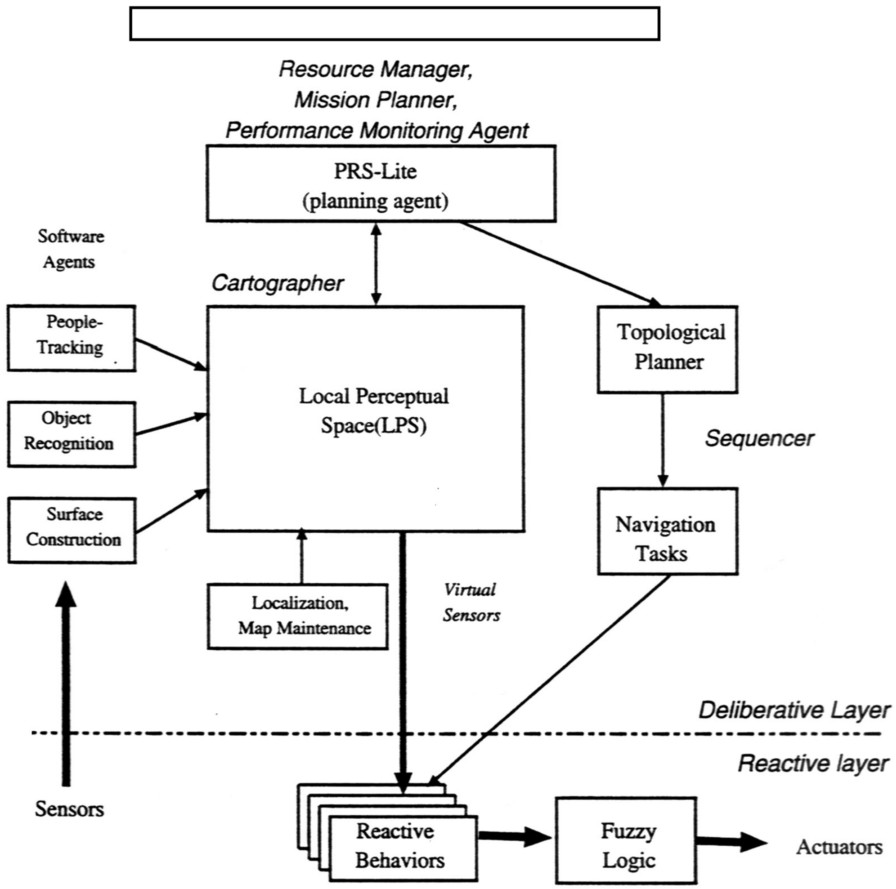
- Hybrid architectures combine the best of hierarchical and reactive architectures
  - Have planners and world models
  - But use a reactive mode whenever it is appropriate (e.g., to avoid hitting a tree at full speed)
- A number of hybrid systems have been designed, such as:
  - The NIST 4D/RCS
  - The 3T architecture used by NASA
  - The Saphira architecture used at SRI on a variety of mobile robots
  - The Task Control Architecture (TCA) used by NASA in mobile robots



Saphira

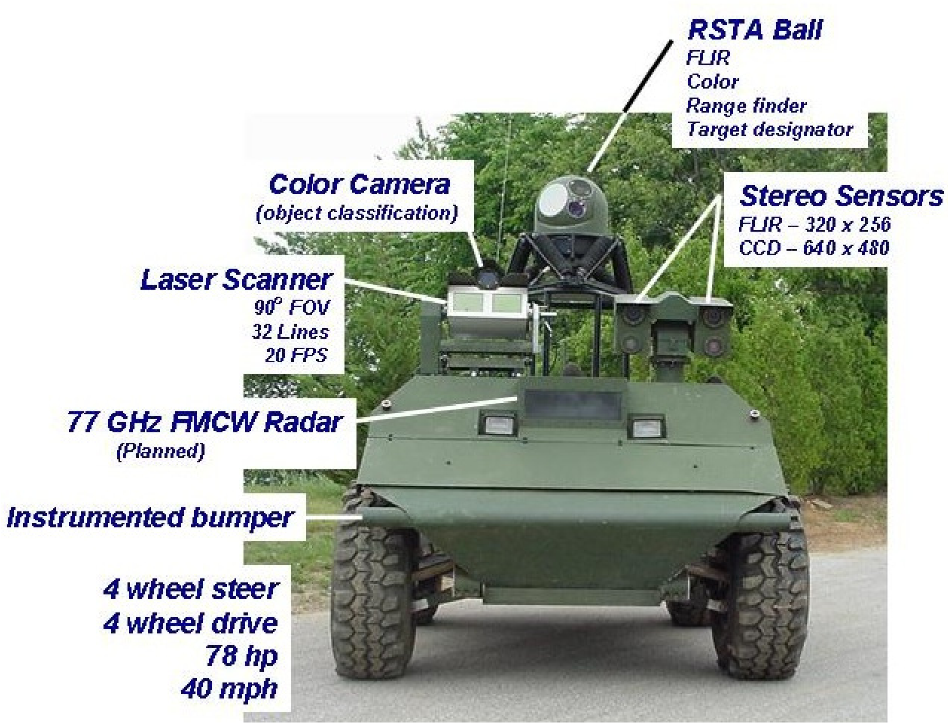
CONTROL ARCHITECTURES

- Saphira hybrid architecture used on a number of mobile robots
- Emphasizes need for: coordination, coherence, communication
- Distinct deliberative and reactive layers



SENSORY PERCEPTION

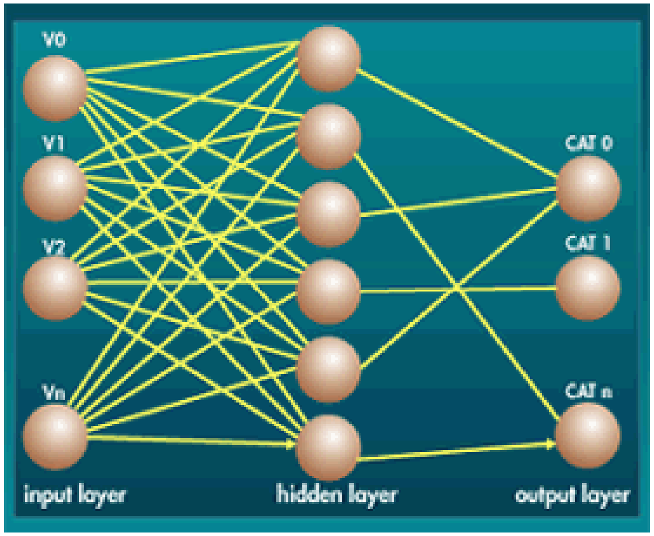
- Hierarchical or hybrid control system incorporates higher-level sensor processing while separate *sensor system* module performs lower-level sensor functions
  - Analogous to an organism=s sensor system: sensor and the neuronal pathways to the brain perform initial filtering and processing on incoming information while brain performs the final processing needed for perception – what is being sensed and its significance in the context of the organism=s (robot=s) world model and purpose (situational awareness)



XUV Sensors

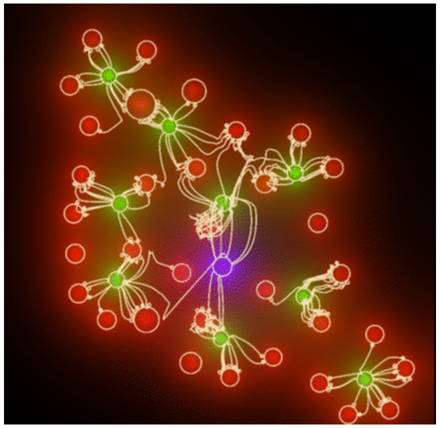
SENSORY PERCEPTION

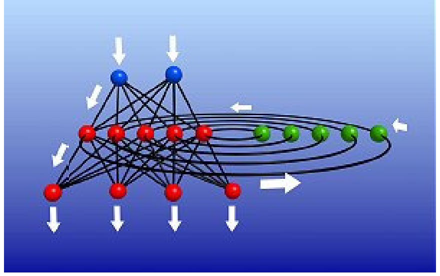
- **First order image processing:** employs algorithms for edge detection, surface texture, shape, dynamic shadowing, spatial relationships, etc. - might discern a moving object having certain dimensions and other properties
- **Second order image processing:** perhaps using look-up tables or neural networks, might conclude that the object is a human
- **Third order image processing:** perhaps using expert systems, might conclude that the human is an intruder and provide the robot with an understanding of the significance of an intruder and the appropriate response - i.e., perception



SENSORY PERCEPTION

- **Sensory perception is the ability to fully understand the object that is sensed in the context of the situation and environment (i.e., situational awareness)**
  - **Level 1:** sense (as with vision) a shape correctly (e.g., an object that is a rectilinear parallelepiped)
  - **Level 2:** recognize the object represented by the shape (e.g., it is a tank – or better, it is an enemy tank)
    - This is sufficient for automated target recognition
  - **Level 3:** understand the significance of the recognized object (e.g., enemy tanks are dangerous and must be avoided or killed; I must seek cover and concealment and I must report the sighting of the enemy tank)
- **Perception in robots depends on the sensors, sensor processors, and intelligent control system architecture (e.g., the world model)**
- **No robot has yet achieved Level 2 perception in a broad domain**
- ***Achieving level 3 perception represents perhaps 60% of the way toward achieving human-level intelligent robots***



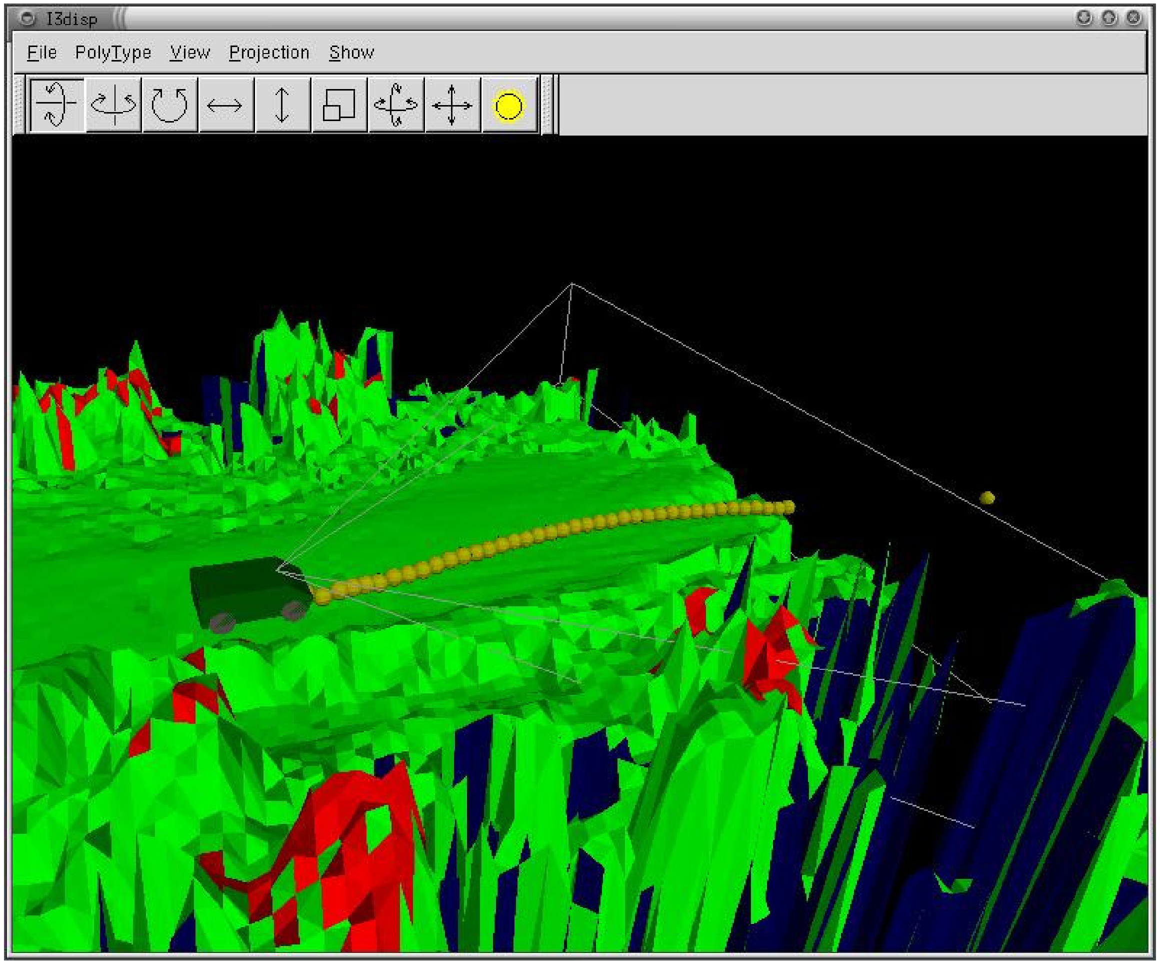


SENSORY PERCEPTION

- **Example: LADAR on XUV proceeding on road**

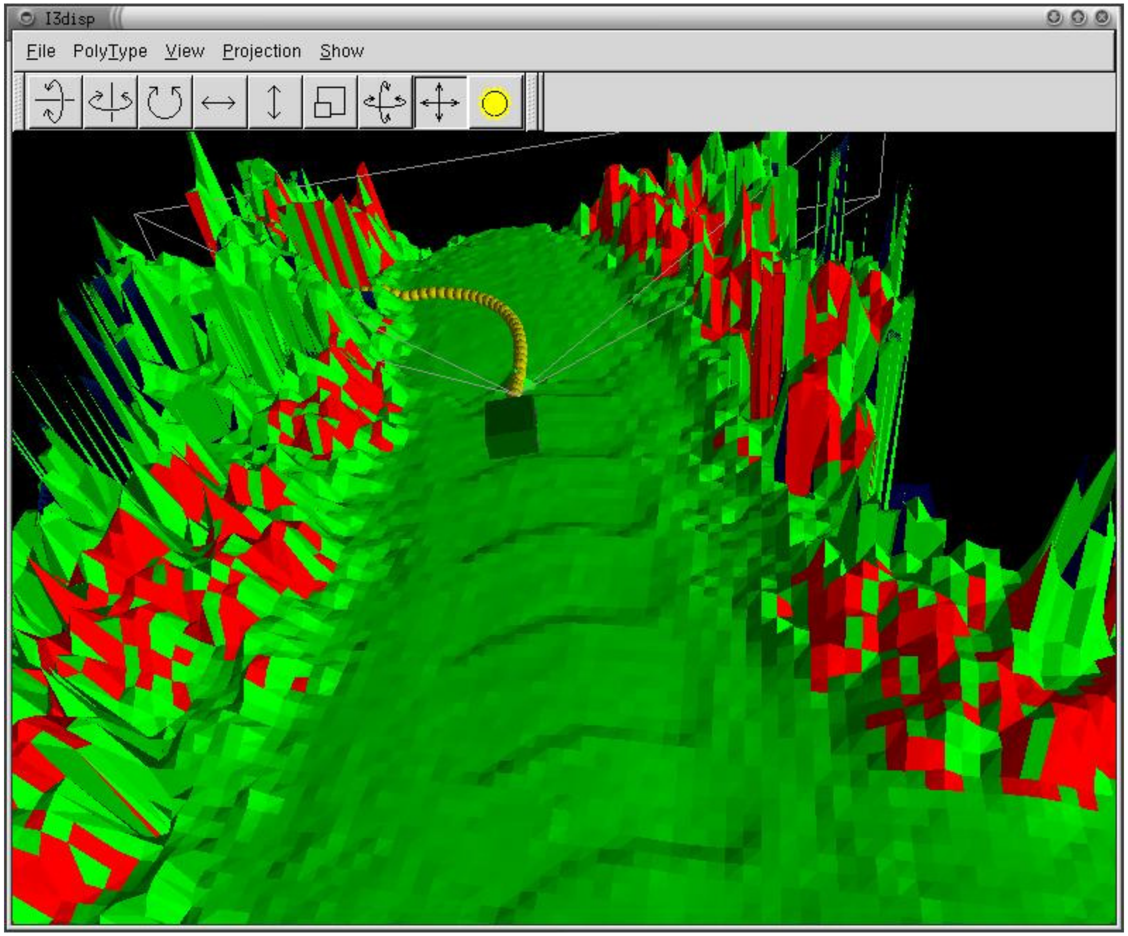
SENSORY PERCEPTION

- **Example: LADAR on XUV proceeding on road**



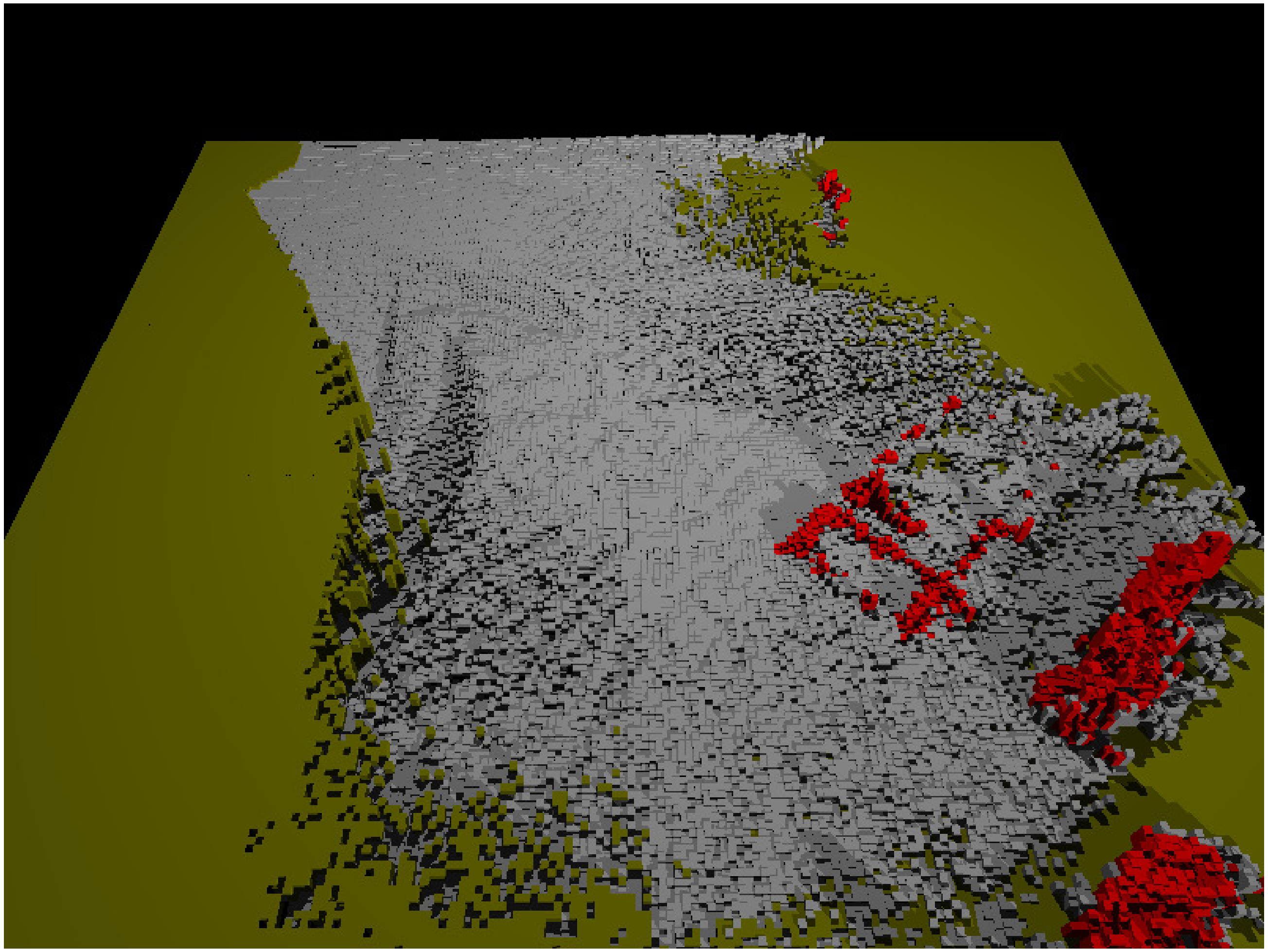
SENSORY PERCEPTION

- **Example: LADAR on XUV proceeding on road**



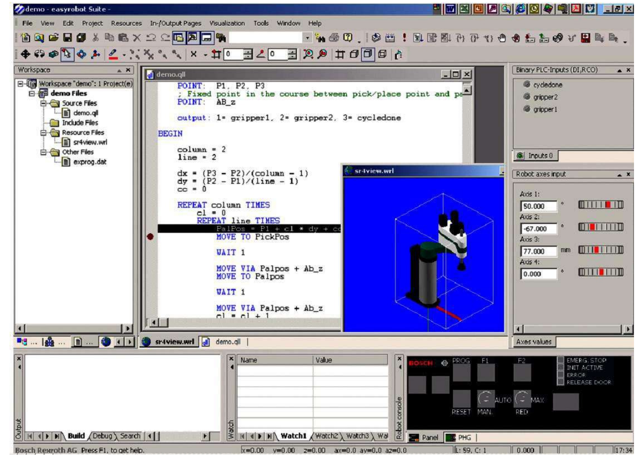
SENSORY PERCEPTION

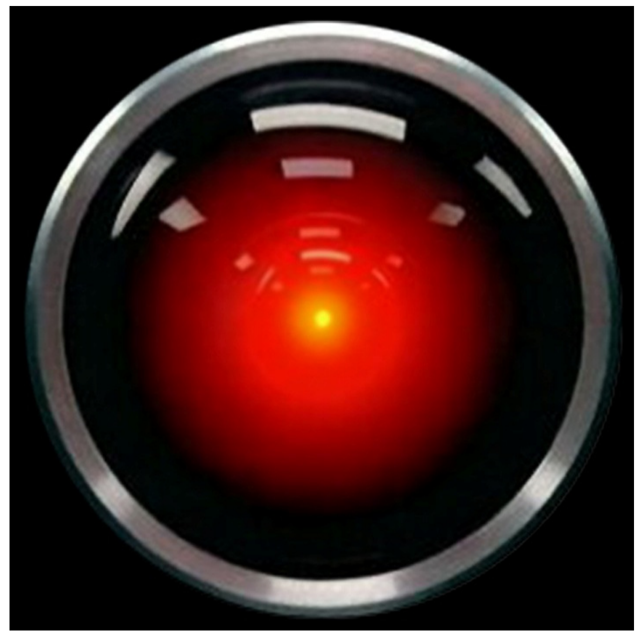
- **Example: LADAR-generated terrain map**



SOFTWARE TOOLS

- The programming of robotic vehicles has largely been ad hoc
- Requirements for robot programming languages include
  - Clarity of program structure
  - Naturalness of the application
  - Ease of extension
  - Debugging and support facilities
  - Ability to incorporate data from sensors
  - Decision-making capabilities
  - Interaction with external devices and sensors
  - Concurrent operation of devices
  - Interaction with world modeling systems
  - A complete set of motion commands
  - User interface suitable for experienced and inexperienced users



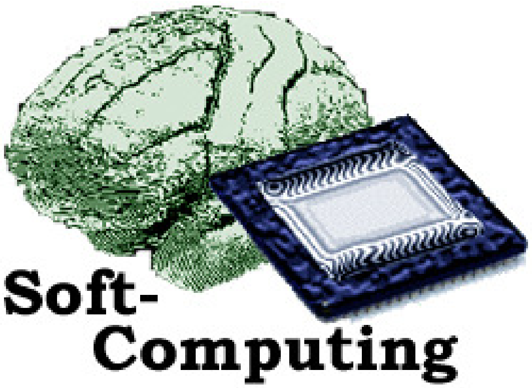


SOFTWARE TOOLS

- There is no universal standard yet for a robot programming language (although attempts have been made)
- Task level programming languages allow the user to command the robot in terms of tasks, rather than specifying the details of each movement and action
- A reusable software framework would permit robots to synthesize the desirable features and capabilities of deliberative (symbol mediated) and reactive (sensor mediated) control
- To allow robots to adapt and function in uncertain environments, software should be created by conventional programming (hand coding) and learning-derivation (automated coding)
  - This would mitigate the intractability of exclusively hand encoding all software-derived robot behavior

SOFTWARE TOOLS

- *Soft computing*, emphasizing programming, is a collection of software technologies designed to be tolerant of imprecision, including such technologies as fuzzy logic, neural networks, and probabilistic reasoning (including evolutionary algorithms, chaos theory, and belief networks)
- Various types and levels of behaviors (or schemas) are programmed, with learning employed to refine the execution and coordination of those behaviors
- Soft computing takes a *behavior-centric* approach to the incorporation of human knowledge and direction in the robot



SOFTWARE TOOLS

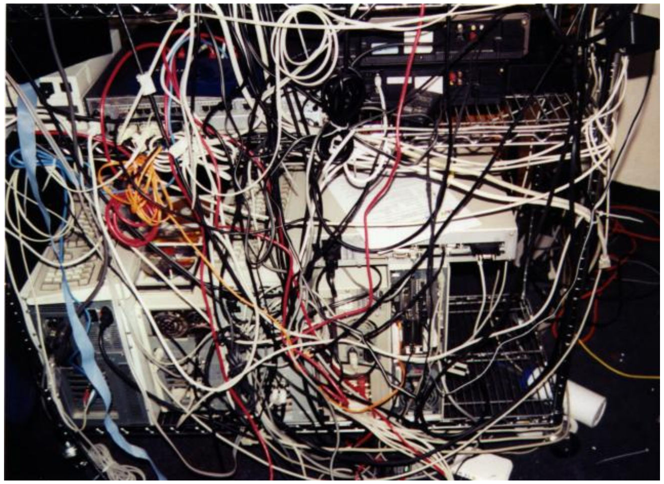
- **Robot *shaping* (training), emphasizing a balance between programming and learning, employs a more automated approach to creating the software**
  - **Humans provide the domain and task knowledge, generally in the form of training protocol, while the computer provides most of the low-level learning needed to compile the taskings into procedural instructions**
  - **This facilitates combining learned sub-behaviors into higher level behaviors without explicit human direction**
  - **Robot shaping takes a *training-centric* approach to incorporating human knowledge and direction in the robot**

SOFTWARE TOOLS

- *Imitation* creates software through robot learning
  - Emphasizes the robot's ability to observe, understand, and reproduce a desired behavior - may take the form of supervised, unsupervised, or self learning
  - Imitation employs an *interactive-centric* approach to incorporating human knowledge and direction in the robot
- Advanced robot software designs are still in early stages of development, but there have been sufficient accomplishments to incorporate robot-oriented software into near-term intelligent robots

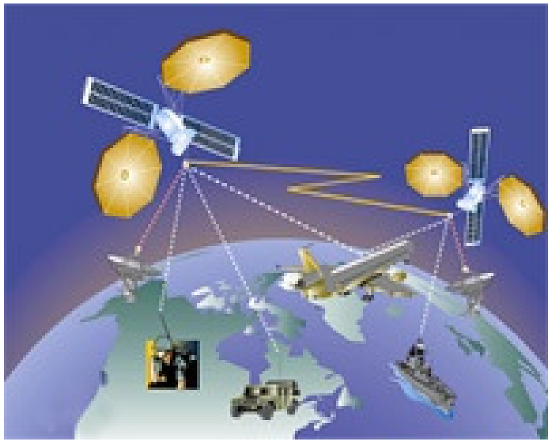
COMMUNICATIONS

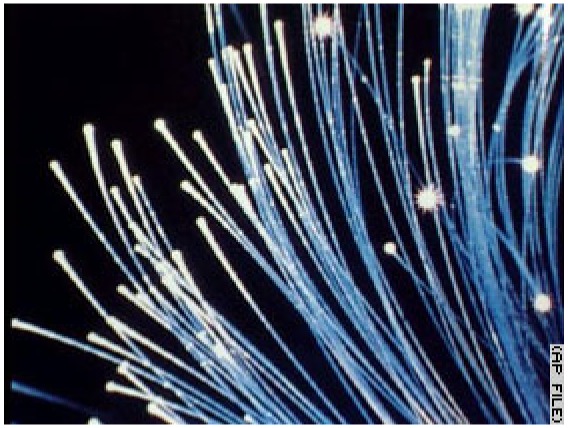
- Internal communications
  - Communications within platforms (e.g., among internal and external sensors, processors, and effectors) is generally not a major problem
  - Complexity and length and quantity of wires and other connections can lead to failure – but bandwidth not a problem
  - Vulnerable to EMP effects
  - When platforms are articulated, two platforms become one and former external communications becomes internal communications
  - New chips and types of links (e.g., optical) can replace wires and improve performance



COMMUNICATIONS

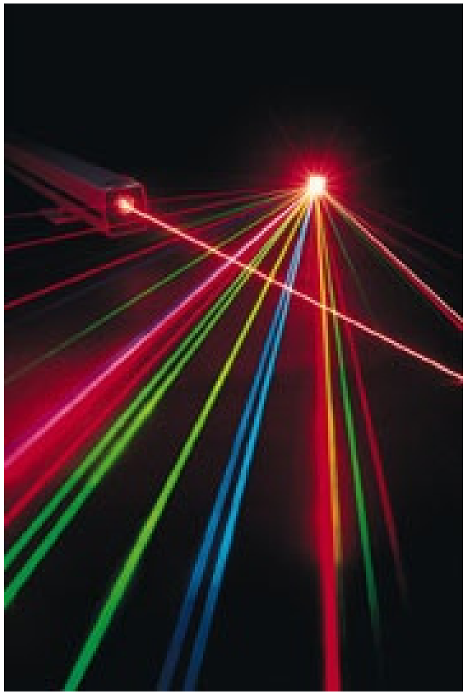
- **External communications**
  - **Radio frequency (RF)**
    - **Benefits: no physical tether; compact; most common and much experience**
    - **Problems: generally low bandwidth; vulnerable to noise, jamming and intercept (unless coded); without satellite, UAV, or meteor burst relays - usually line of sight (LOS); antenna problems**
  - **Fiber optic**
    - **Benefits: high bandwidth; low noise; no jamming; secure; beyond LOS (BLOS)**
    - **Problems: physical tether; usually not recoverable; relatively expensive; can be broken or cut; mechanical deployment; little experience**





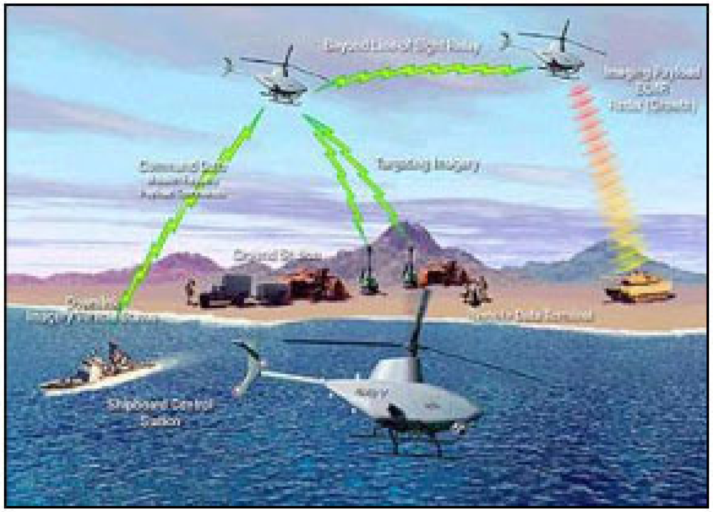
COMMUNICATIONS

- Laser
  - Benefits: high bandwidth; secure; low noise; hard to jam; can be compact on platform (e.g., modulated retro-reflector)
  - Problems: LOS; subject to unintentional or intentional obscurants; developmental and little experience
- Acoustic
  - Benefits: BLOS; simple and inexpensive
  - Problems: low bandwidth; ambient or intentional noise; intercept; short range
- Pheromones
  - Benefits: covert; unexpected by enemy
  - Problems: low bandwidth; BLOS (trail); short range; ambient noise and adverse weather; experimental



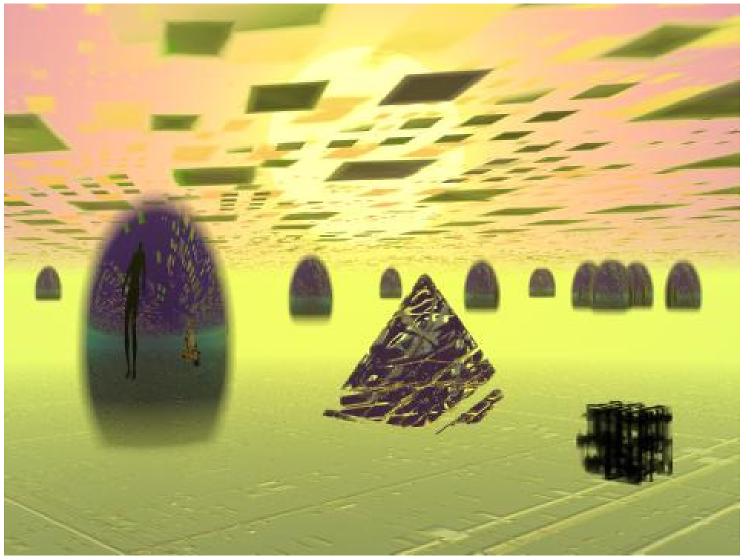
COMMUNICATIONS

- Most military robotics communications will be over RF links
- Desired characteristics of RF links
  - Global availability of frequency (peace and war)
  - Resistance to unintentional interference
  - Low probability of enemy intercept (direction finding)
  - Security (signal encoding)
  - Resistance to deception (false commands or data)
  - Resistance to being acquired by anti-RF weapons seekers
  - Anti-jam (up or down links)
  - Beyond LOS (e.g., special frequency, or satellite or UAV relays)



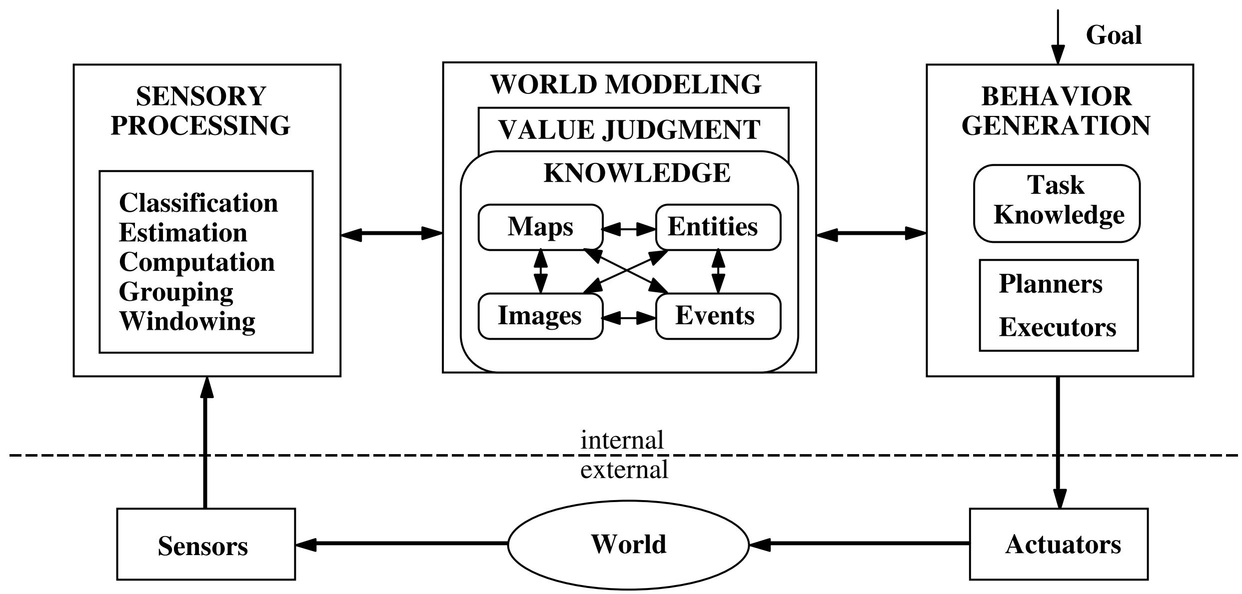
COMMUNICATIONS

- To minimize RF problems
  - Process data on each platform to minimize data transmission requirements (bandwidth, anti-jamming, etc.)
  - Each platform transmits only important, processed information (e.g., annotated snapshot of prospective target instead of streaming video)
  - Optimize use of available data rates (e.g., data compression)
  - Operate with full autonomy or supervised autonomy



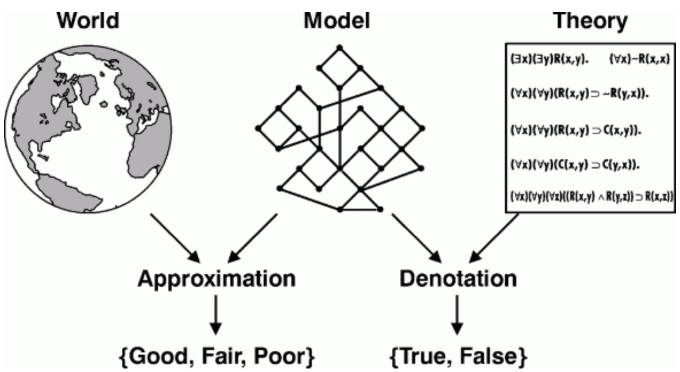
DATABASES AND WORLD MODELING

- A world model contains global memory, knowledge bases, maps, object lists, state variables, etc.
  - It may ask "what if?" questions of a task planner and "what is?" questions of a task executer
  - It may update itself based on sensory input and predict expected sensory input - predicted sensory events may be compared with actual sensory events and differences can lead to changes in the world model
  - It may be a recipient of plans, tasks, and priorities as they are generated by various programs



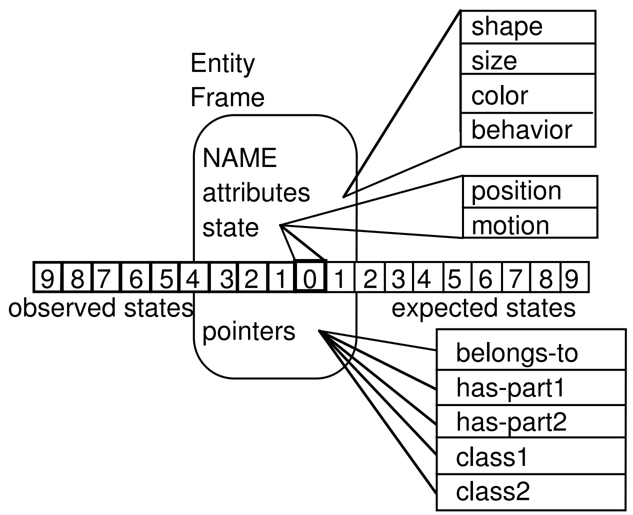
DATABASES AND WORLD MODELING

- A model is a formal representation of a system, and a world model is a representation of the world that is not a direct perception of the world
  - Humans and other organisms map their own brains onto the world, creating a world model; a model is an abstraction of reality, a set of rules and relationships which has the necessary and sufficient means for intelligent action
  - It is a simplified representation of reality that can be substituted for it under certain conditions; it is easier to understand and manipulate than the real system



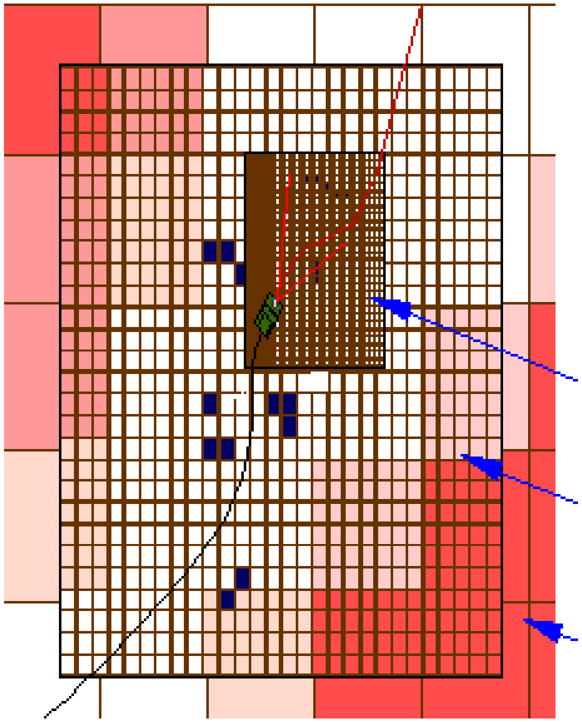
DATABASES AND WORLD MODELING

- Hierarchical and hybrid intelligent control system architectures employ world models
  - It is very difficult to know, a priori, everything that must be in a world model
  - It is very difficult to program a world model for military operations
- Effective world models, once created, can be amortized, updated, and evolved
  - Also, the robots cam learn from experience (and share their experiences in the field in near-real time) and improve their own world models through learning
- Reactive architectures do not use world models – but missions are then limited



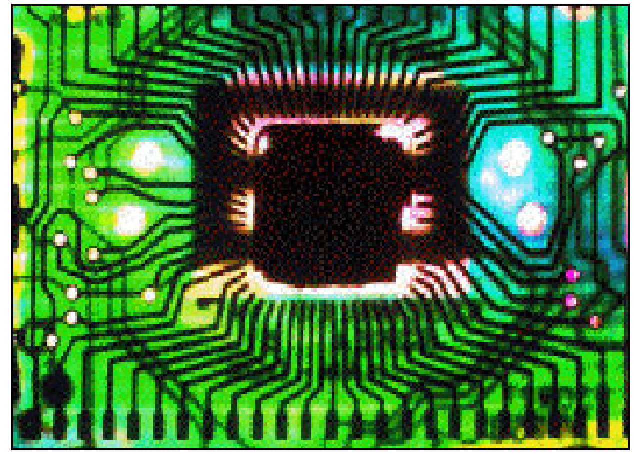
DATABASES AND WORLD MODELING

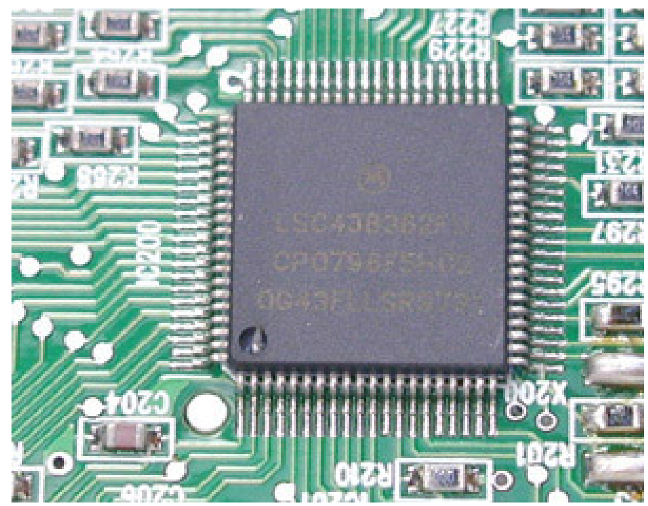
- A database is a critical part of a hierarchical or hybrid intelligent control system
- The contents of the database consists of spatial and temporal entities consisting of states, events, objects, attributes, and processes
  - Examples: mission objectives, tasks, times, object taxonomies, plans, algorithms and heuristic computational tools, constraints and optimization criteria, maps, paths, waypoints, and recovery points, vehicle data, threats and threat locations, search areas, targets and target descriptions, weather data, friendly force locations and descriptions, models of sensors, scenes, and targets, terrain markers and artifacts, tactics and strategies, imagery overlays, video and graphics, internal and external sensor data



HARDWARE ARCHITECTURE

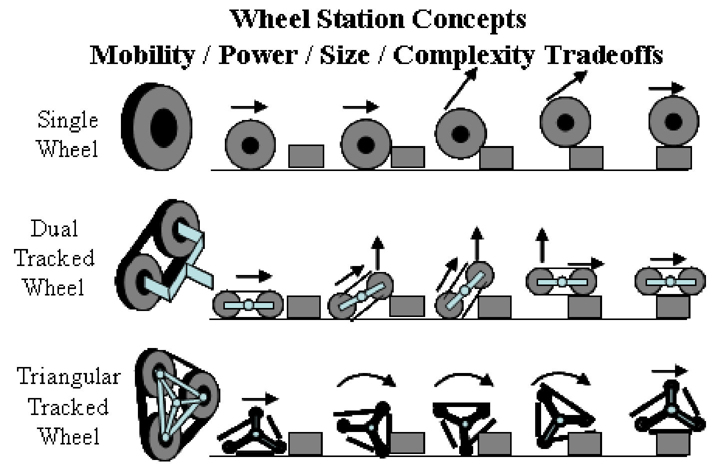
- **Computer hardware still obeys Moore's Law and doubles in processing speed and memory every 18 months or so**
  - **Today's hardware is sufficient for robots at a useful level of intelligence**
  - **Tomorrow's hardware will provide the basis for superior cognition, but the achievement of this cognitive potential will still depend primarily on advances software**
- **The architecture of the hardware is another contributing factor to achieving robot intelligence**
  - **As with neuronal architecture in the organic brain, which uses parallel processing to speed cognition otherwise based on slow individual neurons, the *arrangement* of processors can be important**

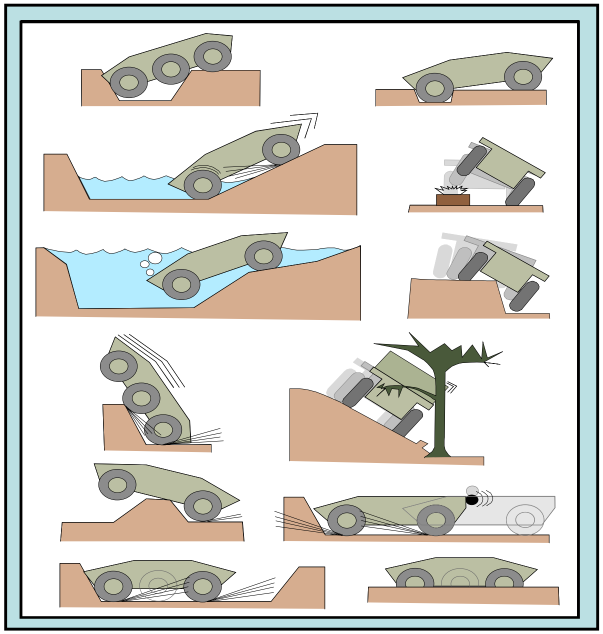




MOBILITY

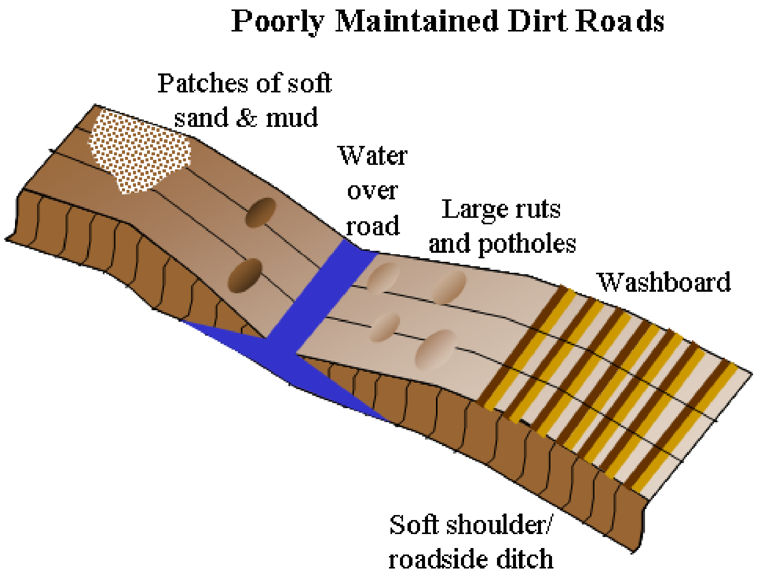
- Robotic mobility is determined by the design of the platform and its mobility components and the ability of the control system to plan, navigate, and pilot the vehicle
- Reactive architectures have demonstrated mobility through the sense-act paradigm
  - But this is too limited for most military missions
  - Reactive behavior can be used effectively by the autonomous pilot to avoid obstacles and threats
- Autonomous mobility has been demonstrated to a degree in a number of DOD programs





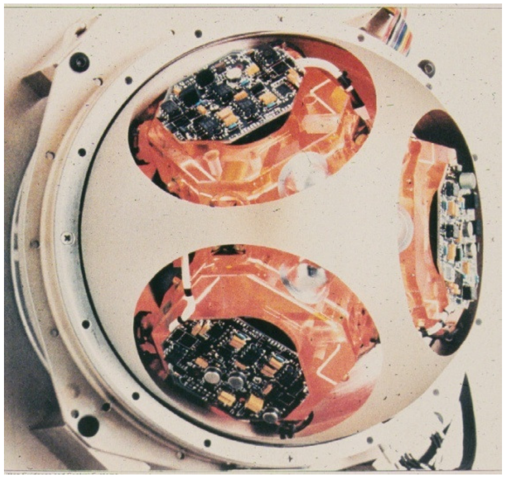
MOBILITY

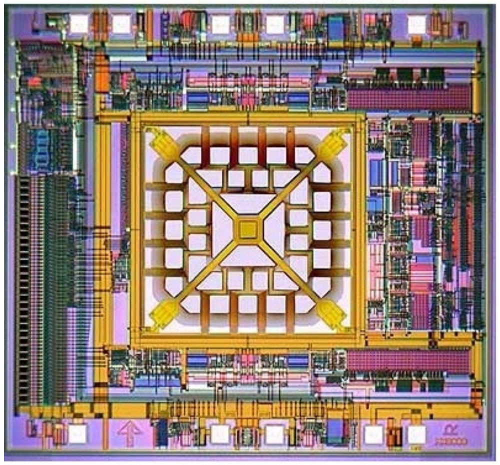
- Autonomous mobility has been demonstrated for
  - Road following; Waypoint operation; Multi-vehicle cooperative mobility and formation driving; Semi-autonomous turnaround; Reverse path following; Obstacle map sharing; Stereo obstacle detection; Negative obstacle detection; Field-of-regard control; Stereo FLIR at night; Navigation LADAR; Multi-spectral terrain classification; Obstacle avoidance; Route history maintenance; Sensor-based hill cresting; Advanced inertial navigation
- The 4-D/RCS has already demonstrated the ability to drive autonomously at 35 kph off-road and 100 kph on-road
- DARPA Grand Challenge successes



SENSOR SYSTEMS

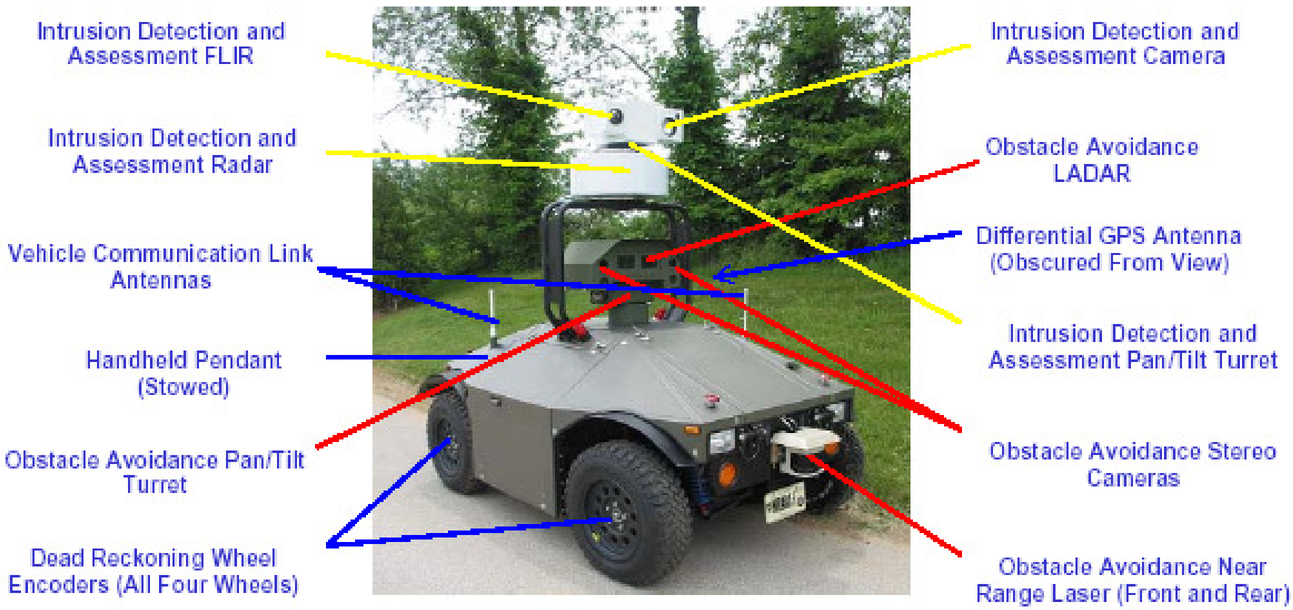
- **The major elements of a robot=s sensor system are its internal and external sensors, the processing needed to extract information from the sensors which can be used by the robot, and the architecture of the sensor system**
- **The number and type of sensors needed by the robot will depend on its size and mission**
  - **Internal sensors might include those for: guidance, navigation, and attitude (such as global positioning system, mechanical or laser gyroscope, and other inertial and dead reckoning systems, accelerometer, pitch and roll sensors, wheel encoders, steering position sensors, compass, odometer, gravitometer, etc.)**
  - **Status sensors might include those for fuel, temperature, engine speed, ground speed, equipment functionality, etc.**





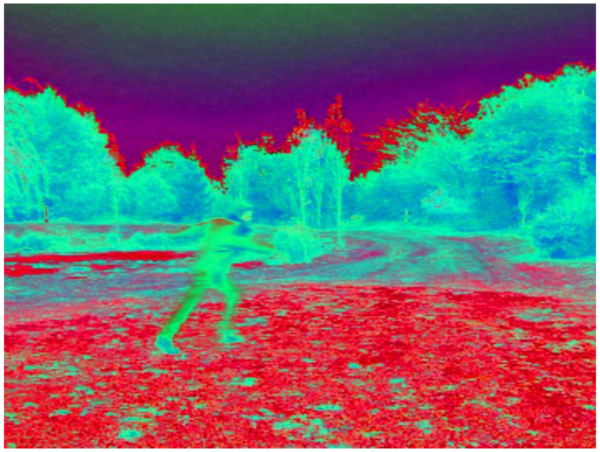
SENSOR SYSTEMS

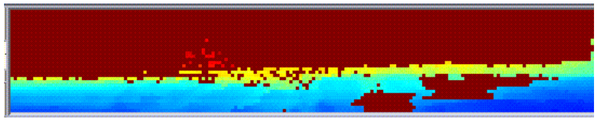
- **External sensors might include: passive and active optical imaging (video, low light level, forward looking infrared, laser scanner, structured light, stereo vision); acoustic detection; proximity sensors (such as ultrasonic acoustic ranging [sonar], laser ranging, microwave radar ranging, Doppler radar, limit switches, bumpers, and whiskers); touch sensors; force sensors; electric field sensors; meteorological sensors (sensing temperature, precipitation, humidity, wind, atmospheric pressure); smell and taste sensors (such as chemical, biological, and radiological sensors)**
- **Many satisfactory sensors are available commercially**

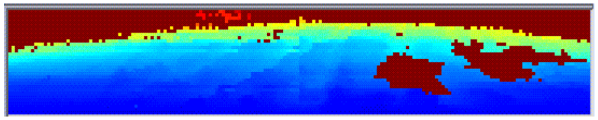


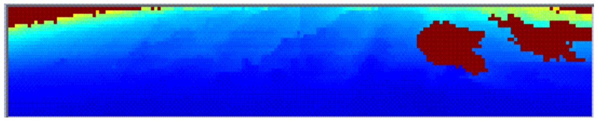
SENSOR PROCESSING

- While there have been many advances in sensor processing, key objectives such as automated target recognition, have not yet been fully achieved
- Machine vision, whether for mobile robots or manufacturing robots, still cannot perform many tasks easily performed by human vision
  - For manufacturing robots, object recognition and 3-D perception are required to automate many assembly tasks; but current technology cannot approach the capabilities of a human
  - Progress in developing machine vision with a number of approaches, such as: coded or structured light; hypothesis generation and verification; anthropomorphic vision with binocularity, foveal vision, and gaze control; 3-D image ranging algorithms; shape and texture recognition algorithms



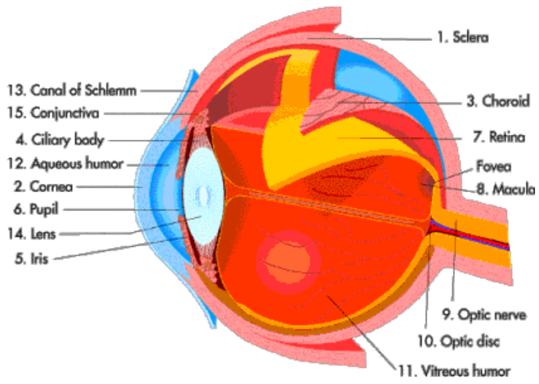






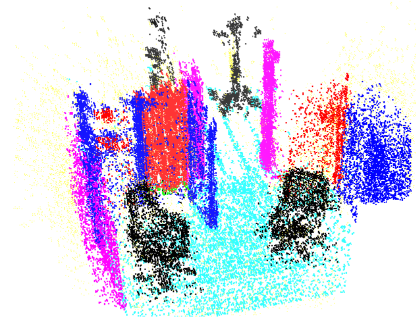
SENSOR PROCESSING

- For mobile robot applications, current sensor processing allows the robot to avoid obstacles and otherwise move about autonomously in known or relatively simple environments
  - Recent progress in cross-country mobility
- State of signal processing is satisfactory for the robot=s active sensors, including microwave, laser, and acoustic (sonar), used primarily for obtaining range data
- Passive acoustic (sound recognition) is suitable for language understanding and other sounds on which the robot can be trained
- Image processing for passive vision in mobile robots is still limited compared with human vision

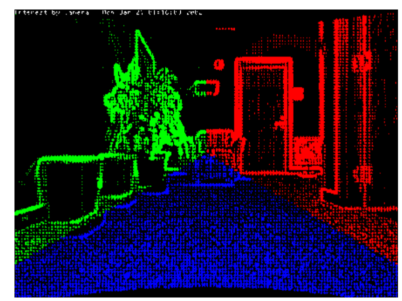


SENSOR ARCHITECTURE

- The ability of the robot to sense its environment depends, in part, on the kinds of sensors on the robot, how they are interfaced with the robot, how they are arrayed spatially, and how they are integrated with each other and the robot's cognitive processes
- Sensor fusion involves combining data from multiple sensors into one data structure, usually within the world model, so that the sensor data can be processed into coherent and accurate knowledge about the world
  - The equivalent of sight, hearing, touch, and smell are combined in the robot to obtain a unified sensorium better than the sum of its sensory parts
  - In the reactive architecture, where there is no world model, sensor fusion is replaced by sensor fission and behavior fusion (i.e., the individual behaviors triggered by various sensors are fused into a coherent set of behaviors, but the sensory data is not directly fused)

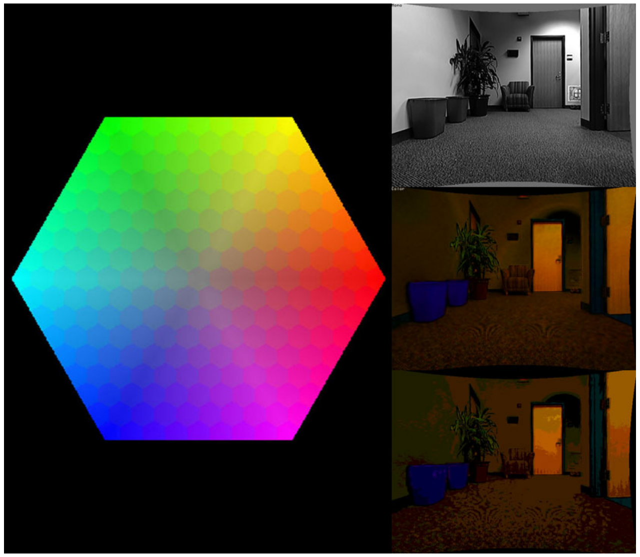


Robot 3D Maps



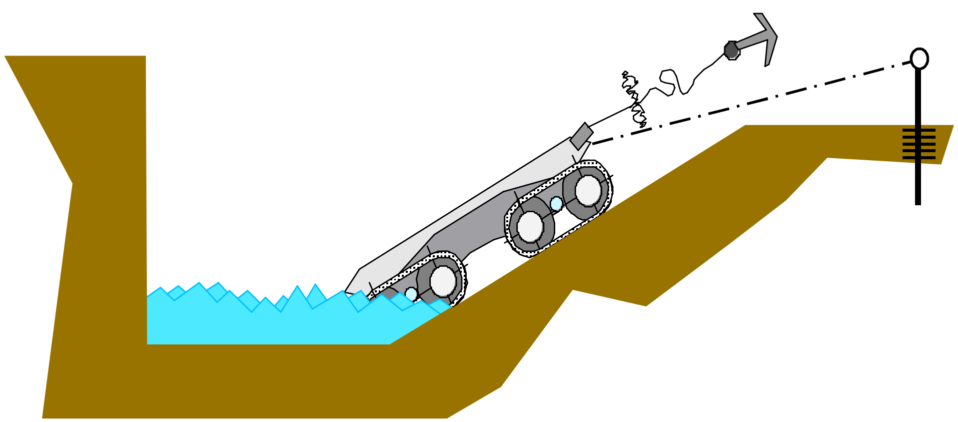
SENSOR ARCHITECTURE

- The proper arraying of sensors on robots is reasonably well understood
  - But the ability to fuse (combine) sensor output is still limited
  - Several different ways of fusing sensor information
- Behavior fusion is less computationally intensive, but the reactive architecture is not appropriate for many DOD missions
- In relatively well-structured or understood environments, current sensor architecture technology is generally sufficient
- More development is needed for sensor architectures in unstructured, hostile, and adversarial environments

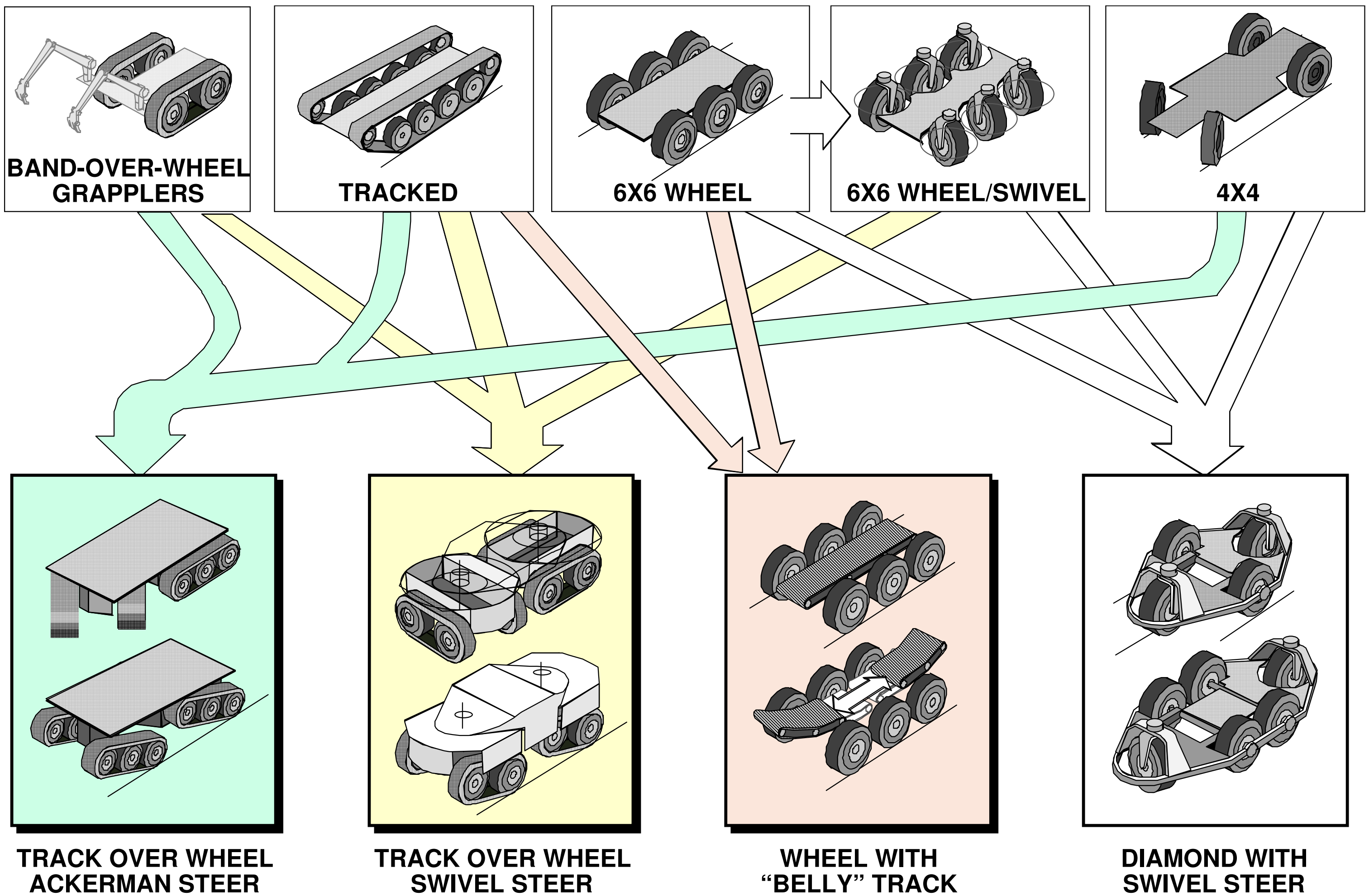


PLATFORM & MOBILITY DESIGN

- TACOM has been developing "intelligent mobility" concepts where the inherent design (intrinsic, physical mobility assets) of the robotic platform allows it to move better in an unstructured environment without the need for excessive active participation of the intelligent control system
  - Example: vehicles with better wheel or track design, or articulated vehicles, are better able to cross terrain gaps (e.g., ditches) or climb hills and slippery slopes
- Hybrid track/wheel designs look promising
  - Flexible, lightweight, suitable for much cross-country terrain

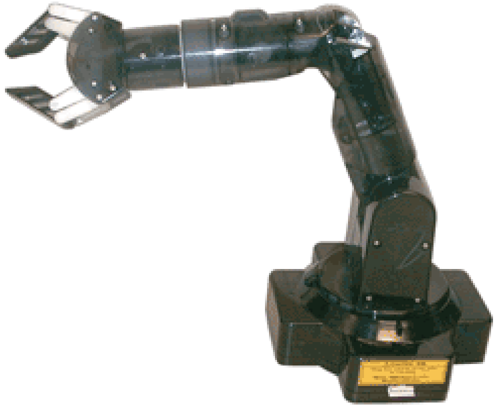


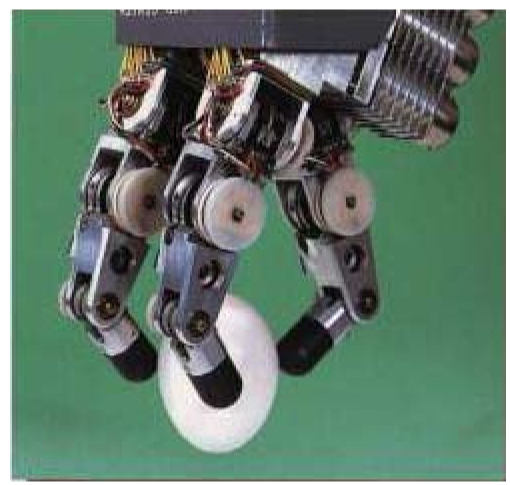
INTELLIGENT MOBILITY: EXAMPLE HYBRID CONCEPTS



EFFECTORS: MANIPULATORS AND END EFFECTORS

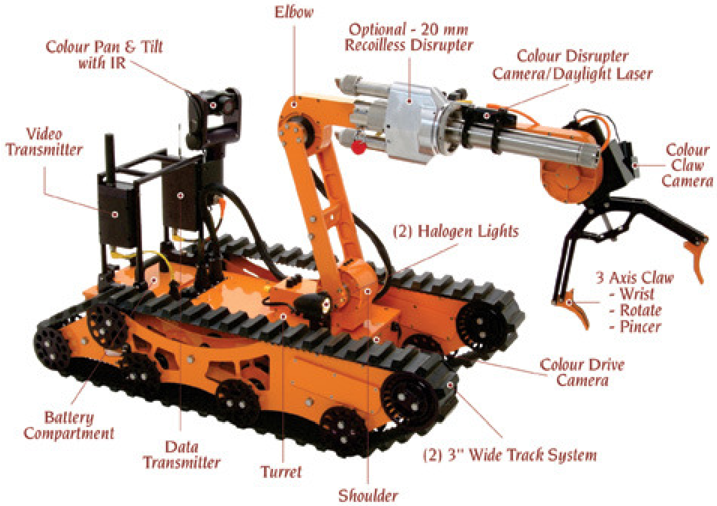
- It would be useful for some robotic ground vehicles to have manipulator arms and end effectors to move objects (e.g., munitions and supplies, wounded soldiers, obstacles)
  - Manipulator: a robot arm and gripper at the end of the arm
  - End effector: a device or tool connected to the end of a robot arm - the design depends on what the arm is supposed to do
    - End effector might consist of a gripper, welding torch, screw driver, probe, anthropomorphic hand with fingers, water jet nozzle, etc.





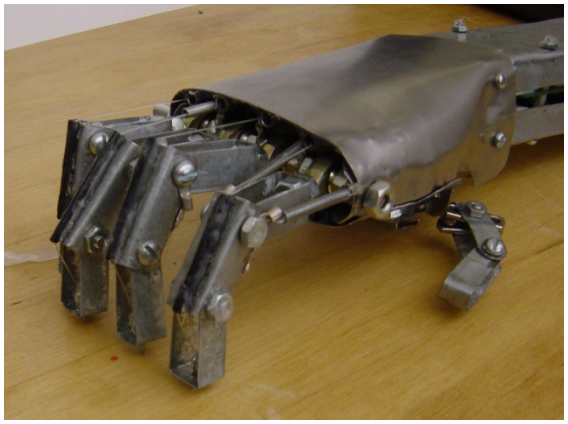
EFFECTORS: MANIPULATORS AND END EFFECTORS

- Most current mobile robots do not have manipulators and end effectors
  - Major exception: EOD (explosive ordnance disposal) robots (have manipulators and end effectors but are currently only telerobots - although there is a new program to develop supervised autonomous EOD robots)
- Many robotic vehicles do have tools which can be considered as end effectors: dozer blades, backhoes, etc.
- Many applications in which manipulators would be useful on mobile platforms (i.e., people find arms and hands to be useful)
  - Example: enemy capture, wounded recovery, urban warfare, IED and object inspection, logistics, etc.



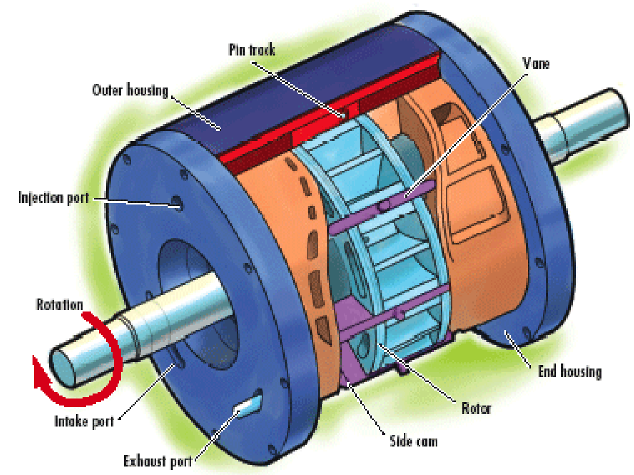
EFFECTORS: MANIPULATORS AND END EFFECTORS

- Many attempts to duplicate the human hand – nothing suitable yet
- While designing a good mechanical hand is itself a difficult problem, the real problem appears to be integrating the control, sensory, and perceptual components of manipulation
- Growing area of research concerned with the theory of grasping and the development of universal gripping strategies
- Dexterous manipulation, in one taxonomy, is divided into:
  - Grasp stability analysis, grasping force analysis, contact conditions, finger tip sensors, and manipulation of objects
  - Areas of research for grasping includes grasp taxonomy, grasp quality measure, grasp type of contact, grasp compliance, and grasp stability



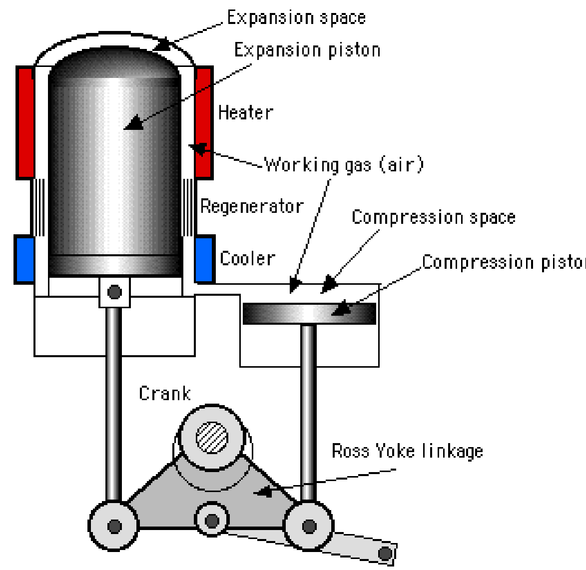
EFFECTORS: PROPULSION SYSTEMS

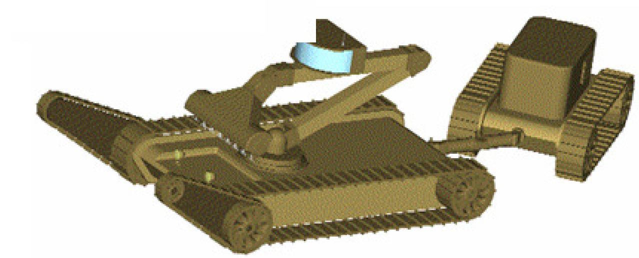
- Propulsion systems, consisting of a power source and mobility system, are used in all robotic vehicles
  - Power sources are typically internal combustion engines of various types or electric motors of various types
    - Four and two cycle reciprocating internal combustion engines, rotary engines, turbines, electric, etc.
    - Energy sources of various types: gasoline, gasoline/oil mixture, diesel oil, kerosene, batteries, fuel cells, solar cells, etc.
- Mobility systems are the proximate cause of the robot's motion employing wheels, tracks, legs, propellers, jets, etc.



EFFECTORS: PROPULSION SYSTEMS

- **Under development are new types of propulsion systems (fuel cells, steam, batteries, micro engines, etc.)**
- **Concept: *Energetically Autonomous Tactical Robot* (EATR) with hybrid external combustion (Stirling) engine able to perform long-range missions indefinitely, without the need for conventional refueling**
  - **Equivalent of *foraging* and *eating* – an ability to find, ingest, and digest available biomass sources of energy from the environment, such as grass, manure, carrion and other vegetation – or paper, furniture, etc.**
  - **Can also use conventional fuel: gas, diesel, etc.**
- **But existing propulsion systems are satisfactory for nearly all potential robotic applications**





EFFECTOR SYSTEMS: WEAPONS SYSTEMS

- Many current and near-term conventional lethal weapons are suitable (after modification) for robotic ground vehicles
  - Anti-personnel, anti-vehicle, anti-armor weapons
  - Machine guns, rockets, mortars, direct and indirect artillery, and anti-tank missiles
  - Examples: MK 19 grenade machine gun; M42 Bushmaster chain gun; BGM-71 TOW antitank missiles; TRAP T-2 telerobotic weapons platform
  - Automated re-supply and loading are needed (but the human supervisor will authorize weapons firing)
  - Metal Storm system
  - Advanced weapons (e.g., directed energy weapons) can be incorporated as they become available

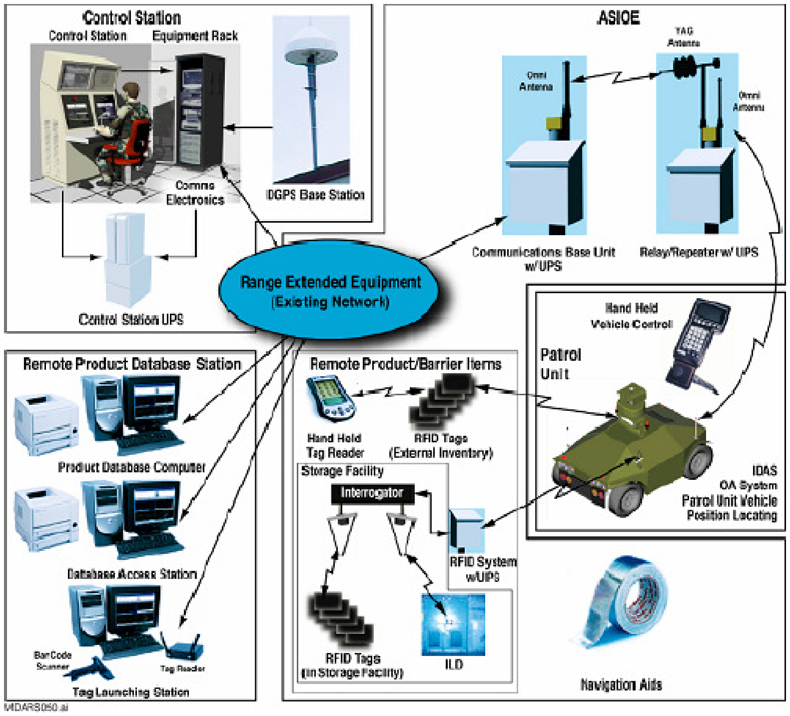
Metal Storm On Talon Robot

EFFECTOR SYSTEMS: WEAPONS SYSTEMS

- Non-lethal weapons are still largely under development
  - Examples: immobilizers an entanglement systems (rigid, slippery, and sticky foam and nets); chemical agents; infrasound and noise generators; lasers; microwave and non-nuclear electromagnetic pulse; rubber, wooden, and bean bag bullets and sponge grenades; anesthetic darts and pellets; electric shock devices
  - Actually, "less-than-lethal"
    - Some people die

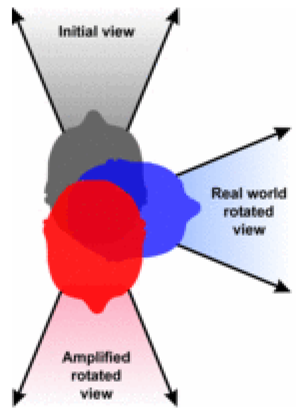
INTERFACES: CONTROLS AND DISPLAYS

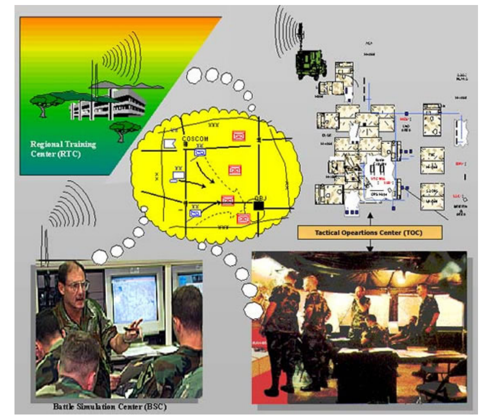
- The interface between the robot and the human controller or supervisor consists of controls and displays
- Also consists of the attentions to the robot which must be paid by people over its lifetime: testing, maintenance, and support
  - People associated with the robot must be trained in its operation, maintenance, and repair
  - The communications system (command, control, and data links, antennas, transmitters, receivers, power supplies, computers, signal processing, etc.) is also an interface system - even autonomous robots will generally be supervised or transmit sensor information to a control center



INTERFACES: CONTROLS AND DISPLAYS

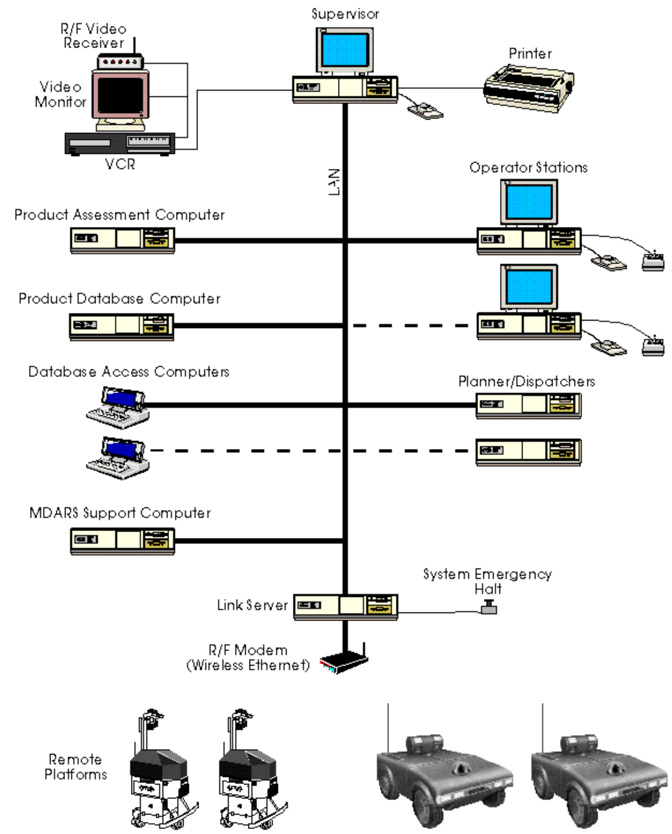
- Robotic systems should have a control station architecture that is open, interoperable, and common
  - Open architecture allows different modules to be inserted easily into the system (as in home stereo systems)
  - Interoperable architecture allows each control center to work with different robotic platforms, payloads, and communications networks
  - Common architecture means that each control center uses the same hardware and software as other control centers





INTERFACES: CONTROLS AND DISPLAYS

- Each control center will typically have computers and software for:
  - Controlling or supervising the remote robot and its payload; planning missions; processing data and sensor information; communicating with the robot; testing the performance of the robot; and training operators
  - Also displays of the status of the vehicle and payloads and associated controls
  - Digital map displays for mission planning and monitoring and tracking the robot=s path and progress
  - Data recording and playback devices (e.g., disks and tape) and input/output devices (e.g., keyboards, monitors, plotters, printers, etc.)



INTERFACES: CONTROLS AND DISPLAYS

- Progress
  - Graphic displays and reconfigurable, touch screen controls are improving rapidly, along with voice control
  - Mission and path planners are also becoming proficient
  - Virtual reality and synthetic environments, as a means of robot control, are being developed but are not ripe for near-term applications
- A number of current robot (UAV and UGV) control and display systems are suitable for near-term applications

INTERFACES: TESTING

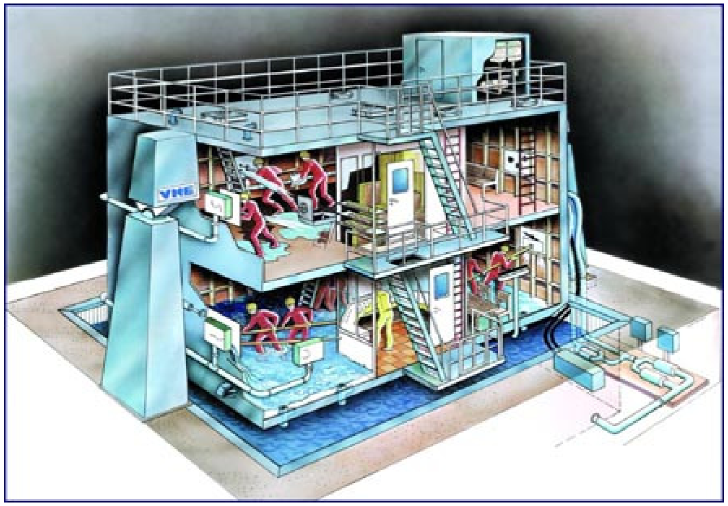
- A continuing testing program will be needed for robotics to ensure safety, reliability, and efficacy
- A test plan will be needed to describe the types of tests, the level of the tests, and the test processes
  - Example: the types of tests might include pre-employment tests (ground/bench tests and operational tests) and user tests (pre-operation, during operation, post-operation)
  - The level of tests might range from chips through boards, subsystems, modules, and systems
  - Test processes might include, among others, status checks or diagnostics
- The means for fully testing robotic systems are still to be developed

MAINTENANCE AND SUPPORT

- Maintenance and support for robotics will include issues and plans relating to:
  - Reliability (e.g., mean time between maintenance and mean time between failure)
  - Availability (e.g., systems readiness requirements and mission performance requirements)
  - Maintainability
    - Including considerations of: design (robustness and redundancy); production (suitable parts and quality control); environment (system insensitivity and ease of repair); resources (personnel, equipment, and funding); and tasks (type, location, sequence, and duration)
- The requirements for maintenance and support (and testing) should be part of the metrics used in selecting robotic systems

TRAINING

- Simulators will be used to train robot operators or supervisors - and they can be used to train the robots themselves
  - Suitable simulator technology is available for training operators of mobile robots
- However, physical training facilities are needed to validate the simulators
  - Provide experiences, often unexpected, which are not included in the simulations
- Training will be made more difficult if the military robotics program encompasses a wide variety of robotic vehicle types



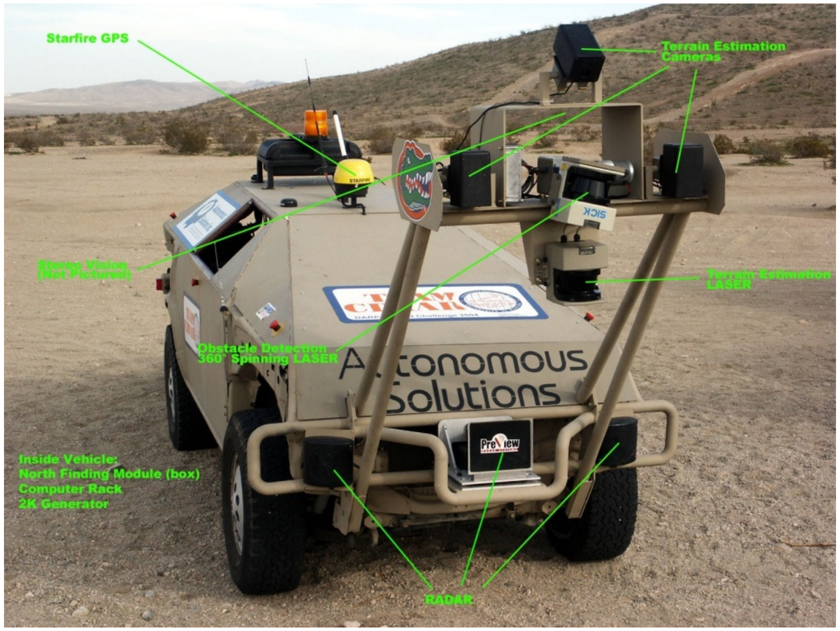
TECHNOLOGY:CURRENT MATURITY

- **Useful robotic ground vehicles suitable for a number of missions can be built with current technology (i.e., nothing new need be invented)**
  - **Missions: RSTA (including MOUT); BDA; direct and indirect fire weapons (lethal and non-lethal); physical security; material handling; EOD/UXO/IED; countermine; NBC detection; mule**
  - **We know this is true because we can build – at the minimum – *telerobotic* platforms that work now**

Gladiator

TECHNOLOGY:CURRENT MATURITY

- Current technology also provides *autonomy* for some robotic functions, including:
  - Driving on roads and some cross-country driving
  - Moving in buildings, pipes, and tunnels, and climbing stairs
  - Convoy following
  - Some detection, recognition, and location of objects and targets (including NBC threats)
  - Obstacle breaching, digging ditches, moving earth, handling materiel, etc.
  - Searching, detecting, and neutralizing mines
  - Providing interior and exterior physical security
  - Deploying smoke and obscurants



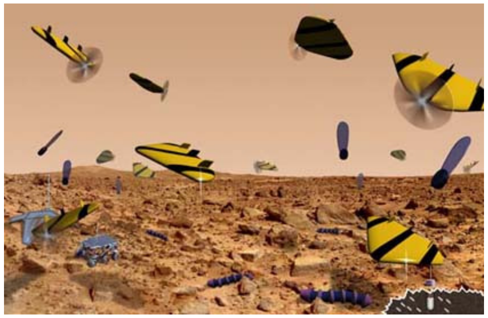
TECHNOLOGY:CURRENT MATURITY

- Robot control systems
  - Autonomous intelligent robot control systems are in various stages of development
  - World models are still primitive with insufficient database content
  - Current database designs (e.g., object-oriented databases) are sufficient for military missions; but content is deficient
  - Planners are reasonably competent for low-level planning (e.g., movement on roads)
  - Portions of autonomous control systems can be installed now
  - Telerobotic control systems are available for use now, but insufficiently ergonomic
  - Hybrid autonomous control systems look the most promising
  - Control (whether autonomous or supervised) of robotic groups or swarms is rudimentary
  - Military robots can be built now with some degree of semi-autonomy (perhaps 30% autonomous operation and 70% teleoperation for nominal missions)

DARPA Grand Challenge

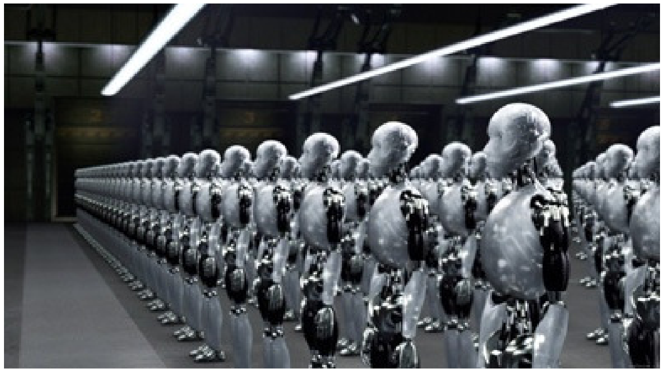
TECHNOLOGY:CURRENT MATURITY

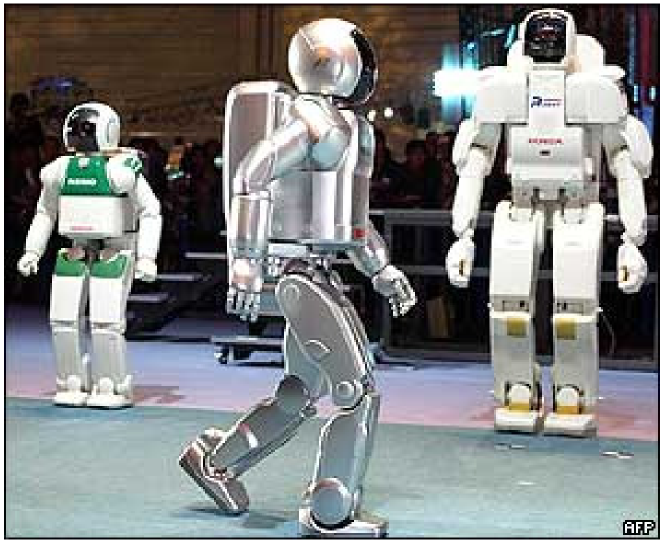
- Control of the robotic collective
- Cooperation among groups of robots
  - Avoids resources conflicts
    - Need to share space, objects, communications media
    - Sharing space involves multiple robot path planning, collision and deadlock avoidance, i.e., traffic control
- Eusocial behavior vs. leader-follower behavior
  - Eusocial cooperation results from the behavior of individuals and not necessarily an a priori effort at cooperation (an insect paradigm)
  - Many kinds of self-organizing systems
  - The aggregation of limited individuals leads to the collective's more capable intelligence
  - Individuals (robots or humans) that are selfish and utility-driven, but must cooperate to survive, will display emergent cooperative behavior
  - It is difficult for human designers to account for the multiplicity of control variables and contingencies to achieve cooperative behavior in robots easier to design robots so that they learn to cooperate and adapt to the environment



TECHNOLOGY:CURRENT MATURITY

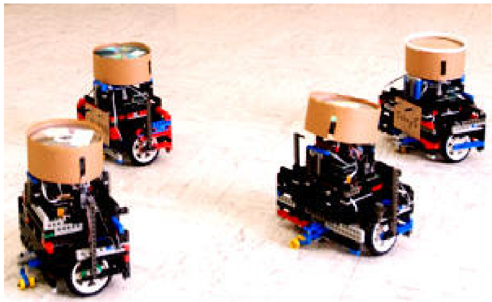
- Communications in the collective
  - Interaction using the environment is communications medium
    - Most limited type of interaction
    - Equivalent of shared memory among group
    - No explicit communications or interaction among individuals
  - Interaction by sensing
    - Individuals sense and perceive one another without engaging in explicit communications
    - Using suitable sensor (e.g., vision, acoustic, chemical, touch) individuals distinguish members of the group from other entities in the environment
    - Resulting collective behavior includes flocking and pattern formation relative to neighboring individuals





TECHNOLOGY:CURRENT MATURITY

- Communications in the collective
  - Explicit communications among individuals
    - Needed to achieve higher-order tactical group behavior
    - Can be directed to known recipients or broadcast to unknown recipients
    - Need communications networks and protocols
  - Communications need reduced if individuals can model others in group
    - Model intentions, beliefs, actions, capabilities, states
    - Individuals can make inferences about actions of others without explicit communications
    - Highly desirable to reduce the need for communications on the battlefield
      - Bandwidth and processing limitations; noise; jamming; interception

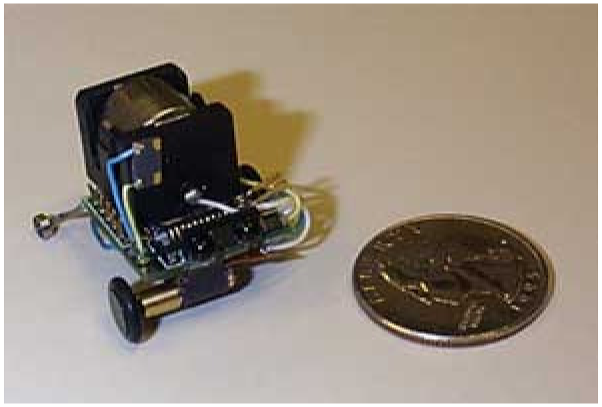


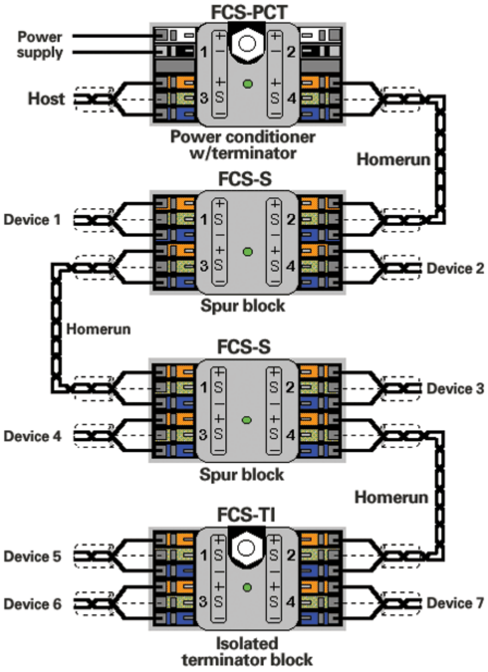
TECHNOLOGY:CURRENT MATURITY

- Sensors
  - Suitable robot sensors (internal and external) are available now
  - Some COTS sensors may be suitable for military missions
  - Off the shelf military sensors are suitable for robots
- Sensor processing is
  - Sufficient for *all* internal sensing (e.g., fuel status, engine temperature, tire pressure, inertial guidance)
  - Sufficient for *some* external sensing (e.g., laser ranging, object and shape detection, acoustic signature detection)
  - Insufficient for other external sensing (e.g., general object recognition, vision understanding, smell)
- Sensor fusion is rudimentary, but sufficient for some tasks
- Achieving machine vision is 60% of the way to achieving autonomous mobility

TECHNOLOGY:CURRENT MATURITY

- Communications
  - Current means of communications among robotic ground vehicles, or between robotic ground vehicles and a control center are marginal
  - Secure, jam-resistant, noise resistant RF links are too expensive for inexpensive platforms
    - And too bulky for small platforms
  - Fiber optics works, but has its own severe constraints for mobile platforms
  - Other non-RF communications techniques for robotic ground vehicles (e.g., laser, acoustic, pheromones) are largely developmental or have limited use
  - Use of robotic air vehicles to serve as communications relays is developmental
  - Tradeoff needed: onboard sensor processing vs. broad bandwidth
    - Robotic vehicles transmit key annotated snapshots to control center, not continuous imagery





MISSIONS

- Reconnaissance, Surveillance, Target Acquisition (RSTA)
  - Serving as scouts for attacking or defending forces, or “pointmen” for patrols; target acquisition and designation for direct or indirect fire weapons; battle damage assessment; bio-chemical and radiological sensing
- Military Operations in Urban Terrain (MOUT)
  - RSTA; sensor placement; lethal and non-lethal weapons; operations inside structures
- Rescue missions
  - Reconnaissance; supplies; personnel recovery
- Counter-mine/IED
  - Mine detection, marking, and neutralization; route proofing

MISSIONS

- **Area denial**
  - **RSTA; weapons platforms; communications relays**
- **Tactical offense or defense**
  - **RSTA; weapons platforms; communications relay**
- **Logistics**
  - **Deliver supplies (e.g., convoy); perform maintenance (e.g., UGV changing tire on another UGV)**
- **Physical Security and Peacekeeping**
  - **Security patrols; surveillance; lethal and non-lethal weapons; checkpoints; internal and external patrol**

DOD PROGRAMS: DARPA GRAND CHALLENGE

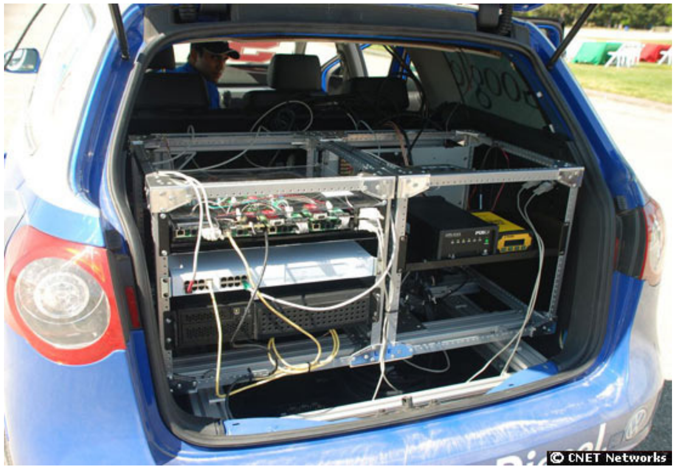
- DARPA Grand Challenge
  - Created in response to a Congressional and DoD mandate
  - A field test intended to accelerate research and development in autonomous ground vehicles that will help save American lives on the battlefield
  - Individuals and organizations from industry, the R&D community, government, the armed services, academia, students, backyard inventors, and automotive enthusiasts

DOD PROGRAMS: DARPA GRAND CHALLENGE

- Grand Challenge 2004
  - Ran from Barstow, California to Primm, Nevada
  - Offered a $1 million prize
  - From the qualifying round at the California Speedway, 15 finalists emerged to attempt the Grand Challenge
  - However, the prize went unclaimed as no vehicles were able to complete the difficult desert route
- Grand Challenge 2005
  - Held on October 8, 2005 in the desert Southwest
  - Stanford Racing Team won the $2 million prize with the winning time of 6 hours, 53 minutes
  - Five teams completed the Grand Challenge course which was 132 miles over desert terrain (10-hour limit)

DOD PROGRAMS: DARPA URBAN CHALLENGE

- **Features autonomous ground vehicles maneuvering in a mock city environment, executing simulated military supply missions while merging into moving traffic, navigating traffic circles, negotiating busy intersections, and avoiding obstacles**
  - **Program is conducted as a series of qualification steps leading to a competitive final event, scheduled to take place on November 3, 2007, in Victorville, California**
  - **DARPA is offering $2M for the fastest qualifying vehicle, and $1M and $500,000 for second and third place**

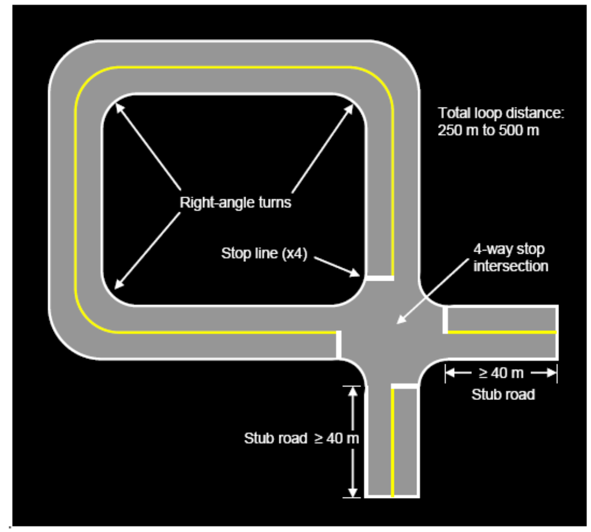


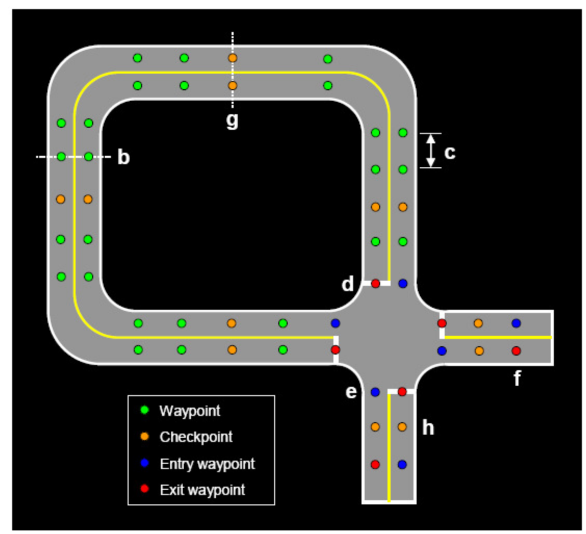
DOD PROGRAMS: DARPA URBAN CHALLENGE

- 36 semifinalists will compete in the Urban Grand Challenge, whittled down from 89 original contestants
- Qualifiers Include:
  - Stanford Racing Team (won the 2005 Grand Challenge with a modified Volkswagen SUV)
  - Team Oshkosh Truck; Team Gray; Carnegie Mellon University; Princeton University; MIT; University of Utah; Austin Robot Technology; and Cornell University

DOD PROGRAMS: DARPA URBAN CHALLENGE

- According to Tony Tether, Director of DARPA, the robots must obey all California traffic laws without human intervention
  - "The vehicles must perform as well as someone with a California driver's license"
  - "The depth and quality of this year's field of competitors is a testimony to how far the technology has advanced“
- So far, Dr. Tether has seen some sophisticated robotic vehicles that may out-drive some people



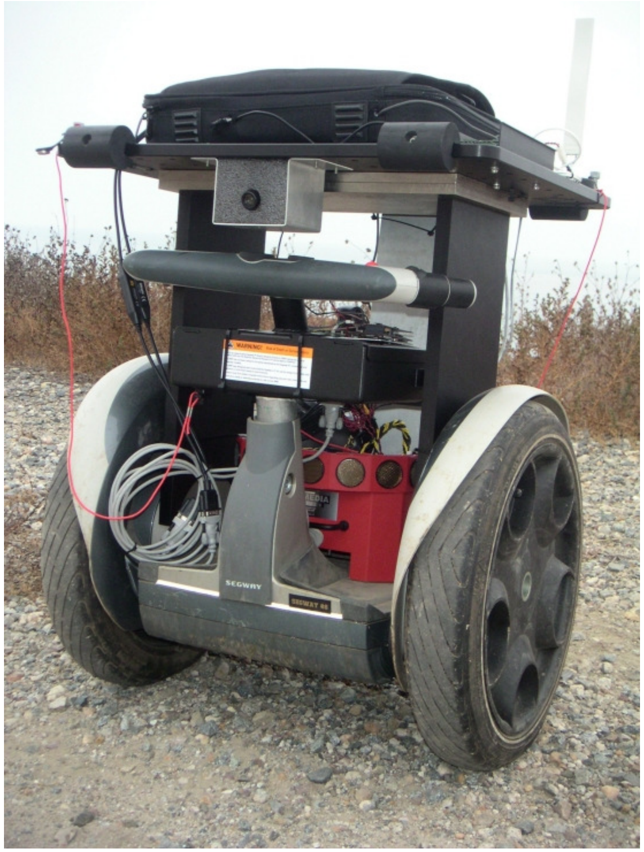


DOD ROBOTIC VEHICLE PROGRAMS

- DOD supporting development of a number of intelligent ground vehicles through the Joint Robotics Program (JRP)
  - Including Future Combat System (FCS) Program and programs supported by the Defense Advanced Research Projects Agency (DARPA), and other agencies
- DOD programs developing and fielding first-generation robotic ground vehicles
  - With current technologies while pursuing advanced technologies critical to autonomous vehicles
  - Evolutionary improvement to first generation vehicles
- Followed by second generation intelligent, autonomous vehicles
- JRP currently developing 22 distinct intelligent vehicle systems across a variety of weight classes, from less than 8 pounds (micro) to more than 30,000 pounds (large)

DOD ROBOTIC VEHICLE PROGRAMS

- The JRP Coordinator supports the development of intelligent vehicle technology and systems in a multiplicity of DOD agencies, including:
  - Joint Architecture for Unmanned Systems (JAUS)
  - US Army Product Mgr. Force Protection Systems
  - US Army Aviation & Missile Research, Development & Engineering Center
  - Robotic Systems Joint Project Office (Army/Marine Corps)
  - Agile Combat Support (USAF AAC/YBC)
  - Air Force Research Lab (Robotics Group)
  - Space & Naval Warfare (SPAWAR) Systems Center (Navy)
  - Program Management Office for EOD Robotics (Navy)
  - US Army Tank-automotive & Armaments Command (TACOM) Research, Development & Engineering Center (TARDEC)



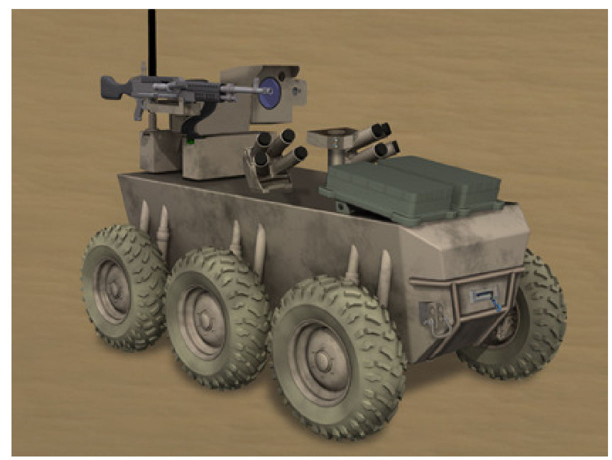
SPAWAR Robot Based On Segway

DOD ROBOTICS TECHNOLOGY BASE

- DARPA
- Army Research Lab (ARL)
- Special Operations Command (SOCOM)
- Military R&D Centers
- Academia
- Product Manager for Robotic & Unmanned Sensors (PM-RUS);
- National Center for Defense Robotics (NCDR)
- National Unmanned Systems Experimental Environment (NUSE2)
- Advanced Concept Technology Demonstrations (ACTD)
- Office of Naval Research (ONR)
- Army RDECOM Simulation Training Technology Center (STTC)

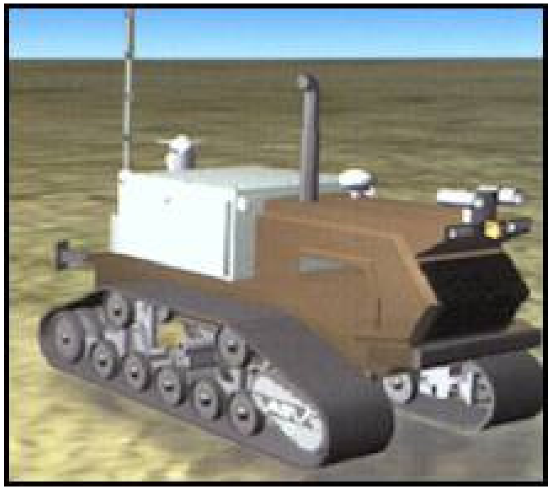
EXAMPLE DOD ROBOTIC VEHICLES

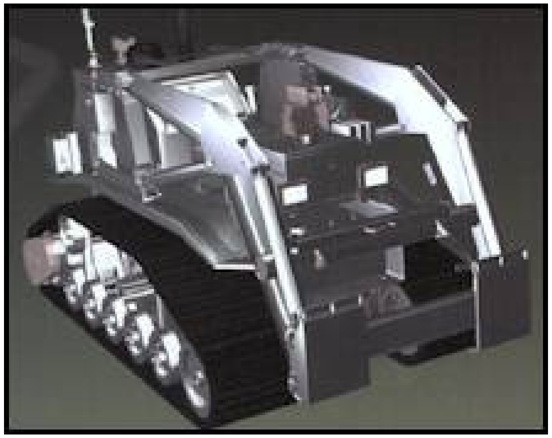
- Robotic Systems Joint Project Office
  - Common Robotic System (CRS)/Panther
  - Robotic Combat Support System
  - Tactical Unmanned Ground Vehicle (TUGV)
  - Future Combat System Unmanned Ground Vehicles

EXAMPLE DOD ROBOTIC VEHICLES

- Air Force Research Laboratory (Robotics Group)
  - Robotics for Agile Combat Support (RACS)
  - Advanced Robotic Systems (ARS)
  - Next Generation EOD Remote Controlled Vehicle (NGEODRCV)
  - Remote Detection, Challenge, and Response System (REDCAR)



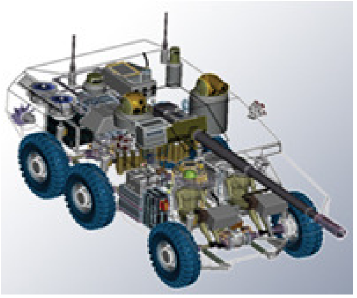


EXAMPLE DOD ROBOTIC VEHICLES

- Program Management Office for EOD (Navy)
  - Remote Ordnance Neutralization System (RONS)
  - Explosive Ordnance Device, Man-Transportable Robotic System (EOD MTRS)

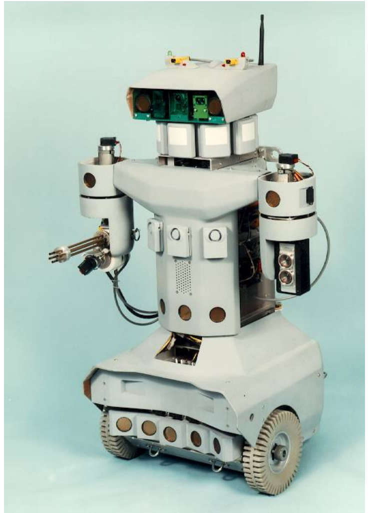
EXAMPLE DOD ROBOTIC VEHICLES

- US Army Tank Automotive Research, Development and Engineering Center (TARDEC)
  - Intelligent Mobility
  - Crew Integration and Automation Testbed (CAT) Advanced Technology Demonstration
  - Armed Reconnaissance Vehicle Robotic Technologies (ART) Army Technology Objective (ATO)
  - Robotic Follower (RF) Advanced Technology Demonstration (ATD)
  - Human Robot Interface (HRI) ATO



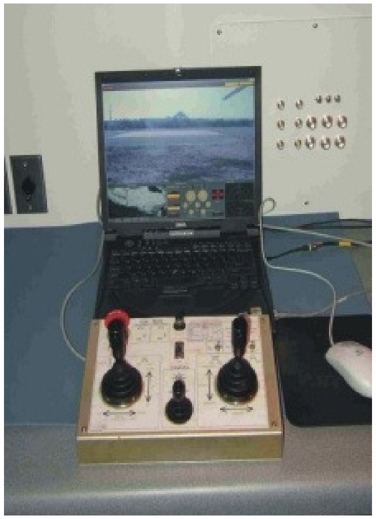
EXAMPLE DOD ROBOTIC VEHICLES

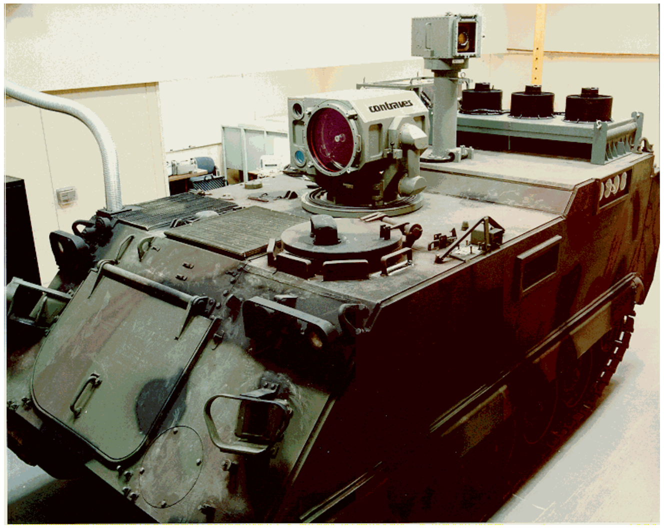
- Space and Naval Warfare Systems Center (SPAWAR)
  - Mobile Robot Knowledge Base (MRKB)
  - Robotic Systems Pool (RSP)
  - Novel Unmanned Ground Vehicle



EXAMPLE DOD ROBOTIC VEHICLES

- **Air Armament Center Agile Combat Support (AAC/YBC) Program Office**
  - **All-purpose Remote Transport System (ARTS)**





EXAMPLE DOD ROBOTIC VEHICLES

- **Product Manager, Force Protection Systems**
  - **Mobile Detection Assessment Response System (MDARS)**

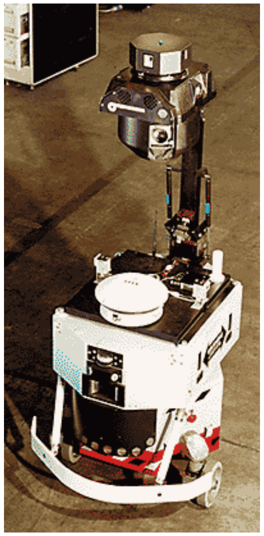


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Figure 2. MDARS-E detects an intruder and is reporting its finding to the military police.

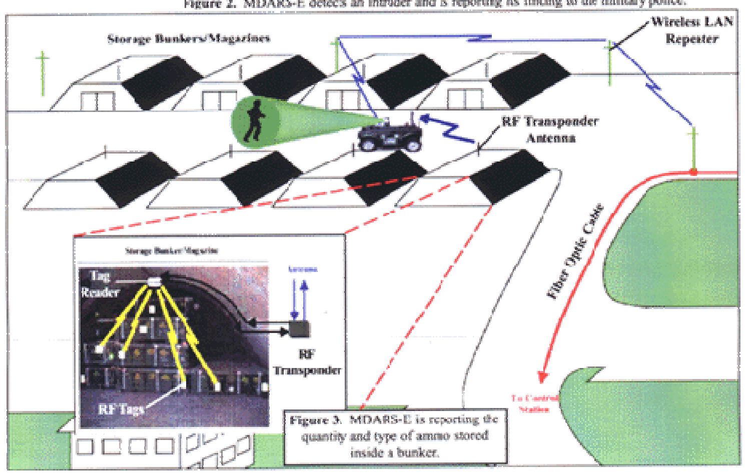
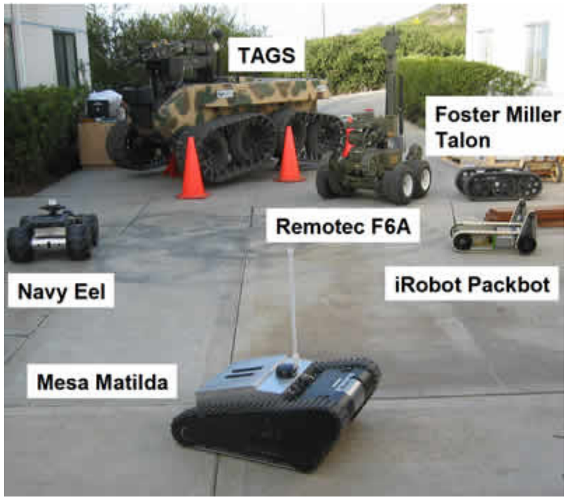


Figure 3. MDARS-E is reporting the quantity and type of ammo stored inside a bunker.

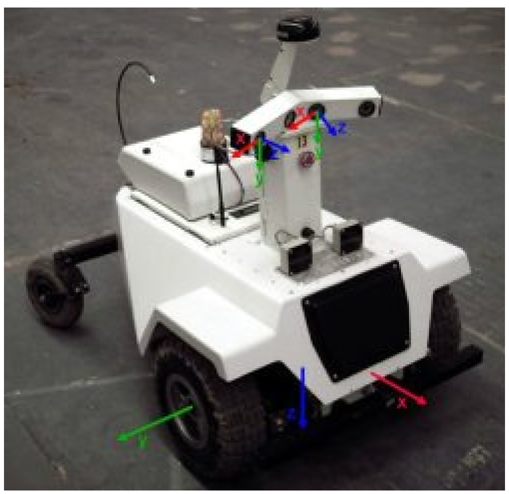
EXAMPLE DOD ROBOTIC VEHICLES

- Army Materiel Command (AMCOM) Research, Development & Engineering Center
  - Joint Architecture for Unmanned Systems (JAUS)
  - Cooperative Unmanned Ground Attack Robot (COUGAR)
  - Collaborative Robotics Operations Initiative



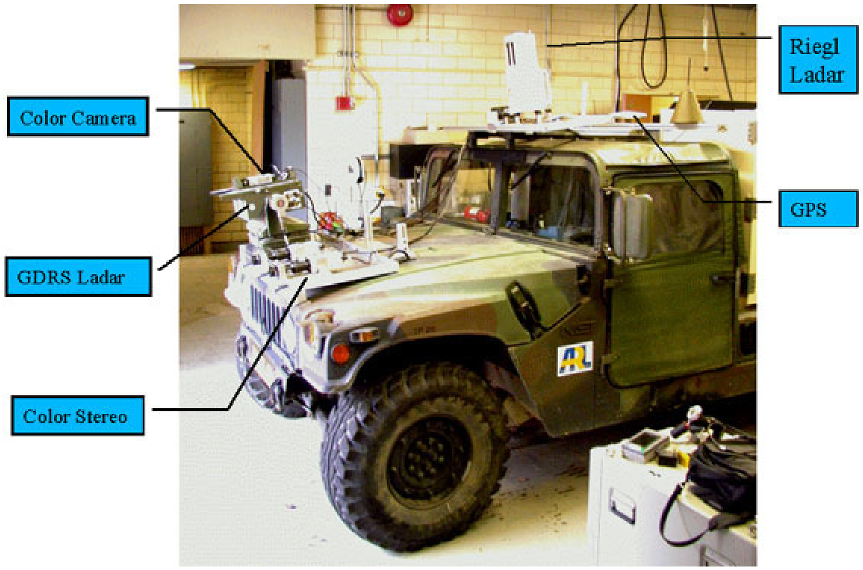
EXAMPLE DOD ROBOTIC VEHICLES

- Defense Advanced Research Projects Agency (DARPA)
  - Perception for Off-Road Robotics (PerceptOR)
  - Unmanned Ground Combat Vehicle (UGCV)
  - Learning Applied to Ground Robots (LAGR)



EXAMPLE DOD ROBOTIC VEHICLES

- Army Research Laboratory (ARL)
  - DEMO III (Experimental Unmanned Ground Vehicle (XUV))
  - Semi-Autonomous Robotics for FCS
  - Robotic Collaborative Technology Alliance (CTA)



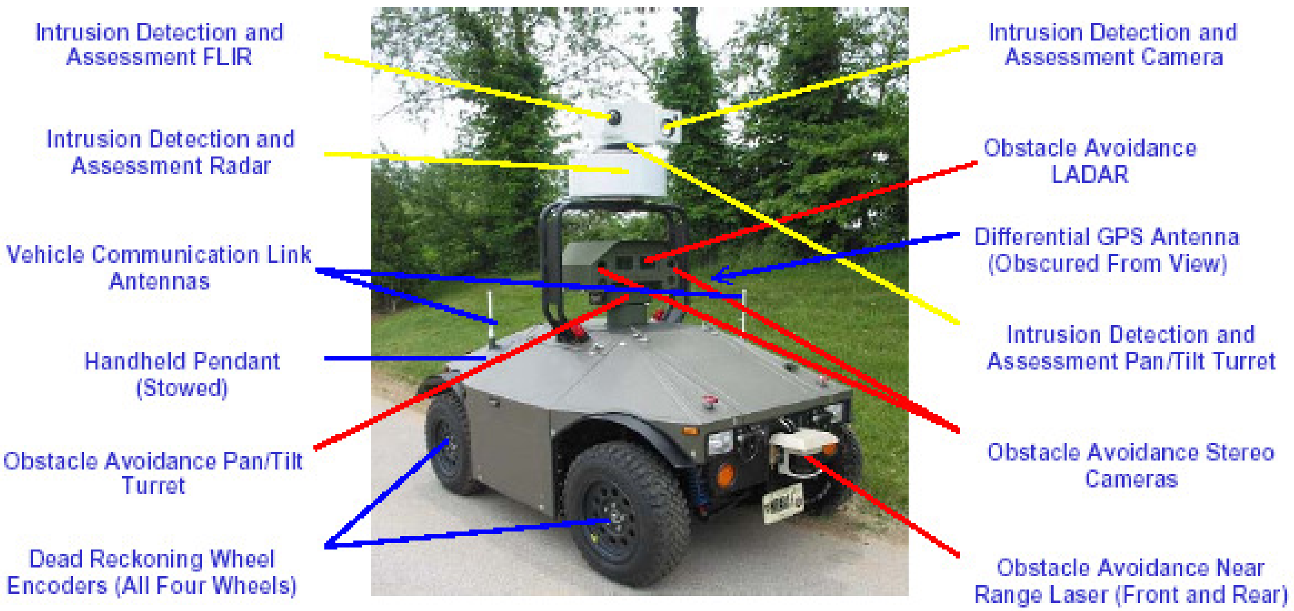
MDARS-E OVERVIEW

- **Mobile Detection Assessment Response System Expeditionary (MDARS-E)**
  - **Sponsor:** Funded under PE 0603228D (Physical Security) and the Joint Robotics Program (JRP)
  - **Managed by:** Physical Security Equipment and Management Office, Ft. Belvoir, Virginia (Product Manager, Force Protection Systems (PM-FPS))
  - **Overall technical direction:** Space and Naval Warfare Systems Center, San Diego
  - **Contractor:** General Dynamics Robotics Systems, Westminster, MD

- **Purpose**
  - Provide Army, Navy, Air Force, & Defense Logistics Agency (DLA) with area security and patrolling
    - Intruder detection & assessment; fire & gas detection; barrier assessment; and inventory control
    - Other: airfield, base, & weapons storage security; CBR detection

MDARS-E OVERVIEW

- Program Status
  - In development since 1993 (Robotic Systems Technology)
  - Pre-production units delivered in 2004 (after program delays)
  - Full-scale production decision: 2007
  - Fielding in 2008
  - Early prototypes used in testing could be used in Iraq

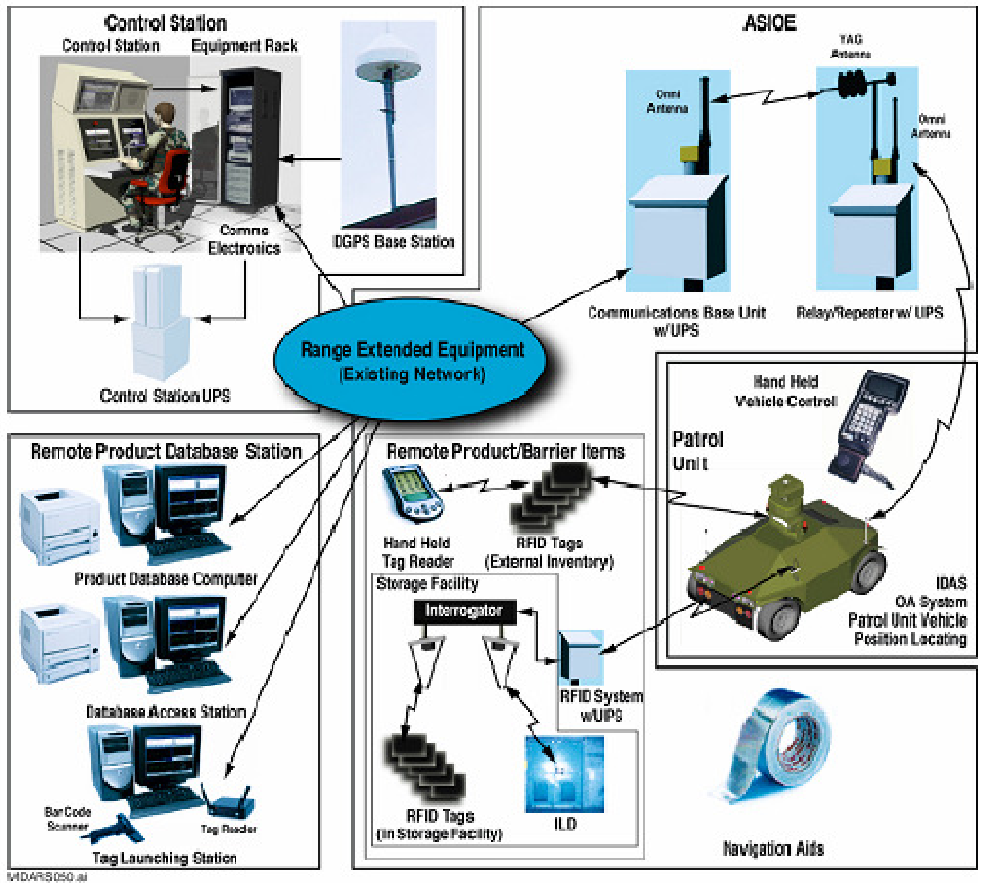


MDARS-E CHARACTERISTICS

CHARACTERISTIC	MDARS-E
Length	98 in. (8.2 ft.)
Width	62.5 in. (5.2 ft.)
Height	46 in. (3.8 ft.)
Weight, Max	2,640 lb.
Weight, Payload	300 lb.
Wheels/Tracks	4 wheels
Speed	19 mph
Range	60 miles (6.2 miles teleop with relays)
Endurance	12 hrs.
Cost	$500,000 (Initial Price); Original Target: $10,000

MDARS-E SUBSYSTEMS

- Autonomous with pre-programmed patrol path
  - Can avoid unexpected obstacles
  - Can be teleoperated as needed
- Control console at command & control station
  - Multiple Resources Host Architecture can control 32 platforms simultaneously
  - One operator can teleoperate 6 platforms

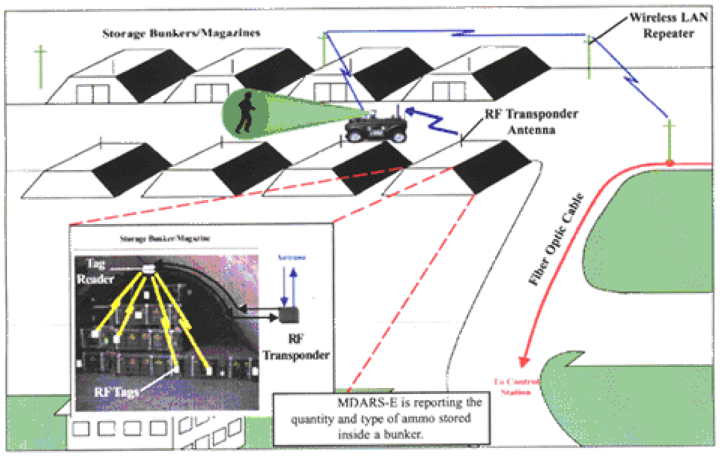


MDARS-E SUBSYSTEMS

- Vehicle
  - 4-wheel, hydrostatically-driven, all-terrain platform
  - 24-hp Kubota D1005 engine using diesel fuel & two 12-volt, sealed, 55-amp/hr batteries
- Navigation
  - Differential GPS (DGPS)
  - Dead Reckoning (DR)
  - Landmark Referencing
- Obstacle Detection/Avoidance
  - Scanning laser
  - Optical stereo ranging
  - Ultrasonic
  - Data fusion from all sensors

MDARS-E SUBSYSTEMS

- **Intrusion Detection System (IDS)**
  - **Narrow field-of-view radar**
  - **Forward-looking infrared (FLIR) with motion detection software**
- **Inventory Control Interface**
  - **Tag/lock reading**
  - **Inventory control**
  - **Verifies whether locks compromised or contents of facility disturbed**
- **Potential**
  - **Smoke, fire, CBR detection**
  - **Lethal & non-lethal response**



MDARS-E MISSIONS

- Current
  - Security patrols, intrusion detection, & product assessment
  - Benign environments
    - CONUS-based installation or logistics depot
- Near Future
  - Overseas Contingency Operations & Homeland Security
  - More austere environments
    - Overseas port facilities, ammunition supply points, forward-operating & logistical bases
    - Homeland critical infrastructure (e.g., airport perimeters, nuclear & hydroelectric power plants, fuel storage sites, pipelines)

DOD ROBOTIC VEHICLES : FIRRE

- Family of Interconnected Rapid Response Equipment (FIRRE)
  - Response to FY05 Congressional plus-up ($11.55 million) for force protection for forward-deployed, soldiers, airmen, marines, & sailors
  - Initial Deployment: FY07
- FIRRE Subsystems
  - Camera-aided Monitoring System
  - Battlefield Anti-Intrusion System
  - Ground Surveillance Radars
  - Semi-autonomous UGV
  - Command & Control
    - Multiple Resource Host Architecture (MRHA) developed for MDARS-E (one OCU for all FIRRE unmanned systems)

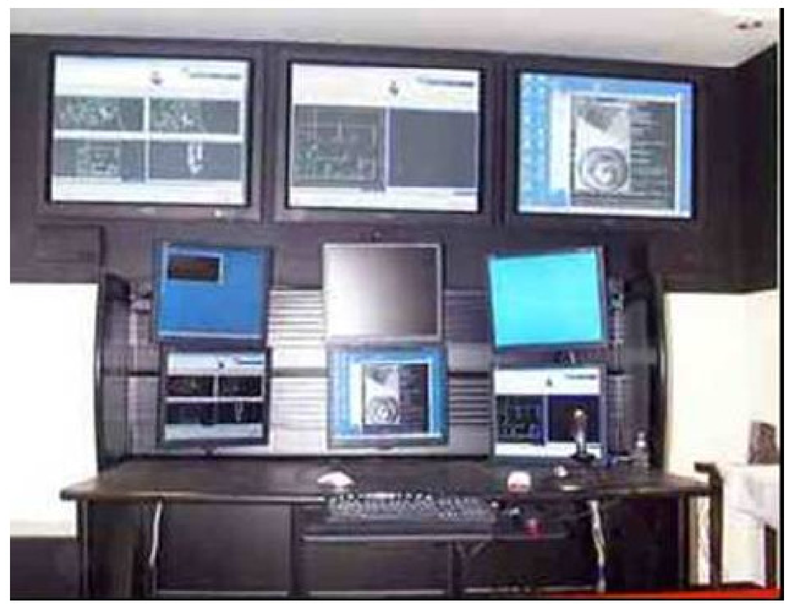
MDARS-E Prototype with Gunpod

DOD ROBOTIC VEHICLES: FIRRE

- Potential missions include:
  - Persistent site surveillance
  - Site security
  - Patient recovery
  - IED detection & neutralization
  - Route security
  - Lethal/non-lethal response
  - CBR detection/decontamination
  - Wide area security (UAV launched from UGV)
  - Soldier support (e.g., carry backpacks & equipment for light forces)
  - Countermine operations
  - Robotically-manned checkpoints

DOD ROBOTIC VEHICLES: FIRRE

- Semi-autonomous robotic vehicle: "centerpiece" of FIRRE
  - High-speed, cross-country capability with fully-integrated surveillance mission payload (FLIR & GSR) detecting to 1-1.5 km
  - MDARS-E is a candidate platform
  - Tactical Amphibious Ground System (TAGS): High-speed (48kph), cross-country capable platform with automated obstacle detection & avoidance with semi-autonomous and teleoperation ability for persistent detection, intrusion detection, & assessment in forward deployment in Iraq & Afghanistan



DOD ROBOTIC VEHICLES: REDCAR

- Remote Detection, Challenge, and Response System (REDCAR)
- An Air Force, Force Protection Battlelab (AFFPB) Initiative to demonstrate the benefits of unmanned systems for the security force mission
  - Force Protection Branch, Robotics Research and Development Group of the Air Force Research Laboratory is the Technical Developer and Program Manager for the unmanned ground robotic system component of the REDCAR initiative

DOD ROBOTIC VEHICLES: REDCAR

- **Operational requirements for REDCAR development are found in the Integrated Base Defense 2020 Concept of Employment (IBD2020 CONEMP)**

REDCAR MODULAR MOBILITY PLATFORM

MISSION PROFILE

Perimeter Security, Reconnaissance, Detection, Challenge, Lethal and Non-lethal Response

MISSION PACKAGE PAYLOADS

PLANNED:
Navigation System w/Inertial and GPS, Obstacle Avoidance System, Tele-operated Driver Assistance System, EO-IR Camera System, Automatic Target Tracking System, Range Finder, Strobe/flashing light system, Speaker/microphone system, Paintball/Pepper spray gun, Semi-Automatic Rifle, Machine gun, Chem/Bio Sensor, Marsupial Deployment System, Modular Payload Attachment System

SIZE	WEIGHT	MAX. PAYLOAD
105" x 46" x 48"	1000 lbs.	750 lbs.

CONTROL		ENDURANCE
Automatic Waypoint Navigation	Teleoperation via Radio Control	8 hours
	1/2 mile range from furthest repeater	

INTEROPERABILITY

CURRENT: JAUS compatible
PLANNED: Interface into Air Force TASS and IBDSS systems

DOD ROBOTIC VEHICLES: REDCAR

- **REDCAR program focuses on application of mobile unmanned ground systems to support and augment security force personnel in the perimeter defense of Air Force installations and forward deployed units**
  - **Network of robotic platforms integrated with existing security force sensors and Tactical, Area Security System (TASS)**
  - **Limited simulation and modeling capabilities to interact with the current AFFPB modeling systems**
  - **All components and platforms in the REDCAR system will be capable of communication using JAUS for system interoperability and control**

DOD ROBOTIC VEHICLES: REDCAR

- **REDCAR will use at least three different robotic platforms:**
  - **(1) A surveillance platform (e.g., MDARS)**
  - **(2) An engagement platform (e.g., REDCAR Scout)**
  - **(3) A small-scale platform for limited access areas (e.g., Packbot)**
- **AFRL coordinating with MDARS-E, Gladiator, and Packbot programs to leverage technologies and synergies between the programs**

DOD ROBOTIC VEHICLES: REDCAR

- Surveillance platform
  - Perform area surveillance duties with limited intruder challenge and response capabilities
  - Able to travel up to 15 mph and traverse all types of roads and mild terrain
  - Ability for teleoperated and waypoint navigation with obstacle avoidance and path correction
- Engagement platform
  - REDCAR Scout: Perform challenge, response, and delay
  - Travel at high speeds (up to 40 mph) over rough terrain and through heavily wooded

DOD ROBOTIC VEHICLES: R-GATOR

- Under development by iRobot teamed with Deere & Company
- Intended to serve as scout, perimeter guard, and pack mule
- At flip of switch, can be driven manually, teleoperated, or fully autonomously
- Uses iRobot control system
- No DOD sponsor – Deere funding
- SPAWAR bought one (not delivered yet)
- Claimed to be first of kind to use off-the-shelf technology (making it easier and less expensive to produce than custom-made UGVs)

DOD ROBOTIC VEHICLES: R-GATOR

- Pilot production: middle of 2006
  - Full production to begin in 2006
- Production cost: about $250,000 each
- Characteristics
  - 6-wheeled
  - Length: 9 ft.
  - Height: 3 ft.
  - Width: 5 ft.
  - Weight: 1,450 lb.
  - Ground Clearance: 10 in.
  - Engine: Diesel; 18 hp
  - Max Speed: 18 mph
  - Hauling: 1,400 lb

DOD ROBOTIC VEHICLES: R-GATOR

- Operational capabilities:
  - Teleoperation
  - Autonomous waypoint navigation with "Teach & Playback"
  - Robotic following
  - Obstacle avoidance
  - Manual operation
  - May be equipped with arm and end effector in future

DOD ROBOTIC VEHICLES: R-GATOR

- Missions:
  - Reconnaissance on- and off-road (relay real-time video, sounds and sensor readings from hostile area)
  - Autonomously shuttle between rear supply points and forward operating positions, using either down-loaded GPS waypoints or waypoints collected dynamically during operations
  - Patrols perimeters & inspect sensitive areas, like pipelines
  - Following soldiers carrying heavy backpacks, ammunition, & supplies
  - Nuclear/Biological/Chemical, ChemRad and Explosive Ordnance Disposal missions

DOD ROBOTIC VEHICLES: TAGS

- TAGS: Tactical Amphibious Ground System
- MDARS-like platform
- Being developed by: Remotec, Applied Perception Inc., TAGS Systems, Autonomous Solutions Inc., AEA Technology Engineering Services
- Missions: RSTA & Perimeter Security in Iraq; lethal and non-lethal weapons
- Used to support carrier for evacuating and extracting casualties by Applied Perception Inc. in demonstration project
- Characteristics: 3,000 lb.; 10 ft. long; 4 ft. high, 29 mph speed

DOD ROBOTIC VEHICLES: TAGS

- Prototype design
  - Larger robotic evacuation vehicle (REV) transports one or two smaller robotic extraction vehicles (REX) in marsupial fashion to a position somewhere in-between safety and front-line action
  - REV stays back and helps remotely guide and track REX which rolls solo into battle and helps recover and safely transport back to REV one wounded soldier
  - REX's primary role is to aid medic with its patient localization and basic stretcher transport capabilities
  - While REX embarks on another guided extraction and/or reconnaissance mission, REV transports the wounded soldier(s) via its onboard life support litters to a field hospital, and returns to the collection-and-dispatch point to create a closed-loop cycle for safe, efficient robotic patient recovery

DOD ROBOTIC VEHICLES: TAGS

- Characteristics
- REV
  - 3,500 pounds
  - 10 × 6.5 × 6 feet
- REX
  - 600 pounds
  - 4 × 2 × 2 feet
- Applications for civilian law enforcement, including biological and chemical countermeasures

DOD ROBOTIC VEHICLES: SWORDS

- SWORDS: Special Weapons Observation Reconnaissance Detection System
  - For urban warfare in Iraq
- Remotely-controlled, tracked, Talon robot (Foster-Miller) with TRAP (Telepresence Rapid Arming Platform)
- Weapon examples
  - 40 mm grenade launcher
  - M202 LAW rocket launcher
- Characteristics: 5 mph; 2.8 ft. long, 1.9 ft. wide, 0.9 ft. high
- 185 conventional Talons already in Iraq & Afghanistan

DOD ROBOTIC VEHICLES: SWORDS

DOD ROBOTIC VEHICLES: SPARTAN AND WOLVERINE

- Developed by Mech Foundry
- Missions
  - RSTA
  - Anti-Terrorism
  - Boarder Patrol
  - NBC Detection
  - Robotic Retrieval
  - Perimeter Defense
  - Check Points
  - Force Protection
  - MOOTW
  - Tactical Operations
  - Crowd/Riot Control
  - Search & Rescue Evacuation
  - Special Operations
  - Disaster Response
  - Payload Deployment

DOD ROBOTIC VEHICLES: SPARTAN AND WOLVERINE

- **Specifications**
  - **Power Source: Electric Traction**
  - **Drive Transmission: Continuously Variable**
  - **Dimensions: 96"/240"cm L, 48"/122cm W, 44"/112"cm H**
  - **Weight: 3500Lbs/1587 kg.**
  - **Forward Speed: 30mph / 50kph**
  - **Operator Control Unit: Wireless**

DOD ROBOTIC VEHICLES: GLADIATOR

- **The Gladiator Tactical Unmanned Ground Vehicle (TUGV) will provide the Marine Air-Ground Task Force (MAGTF) with a tele-operated/semi-autonomous unmanned ground vehicle for remote combat tasks, increasing survivability by identifying and neutralizing threats and reducing risk to Marines**
- **Gladiator will provide Marines with remote, unmanned scout, reconnaissance and surveillance while the operator remains concealed at a distance**

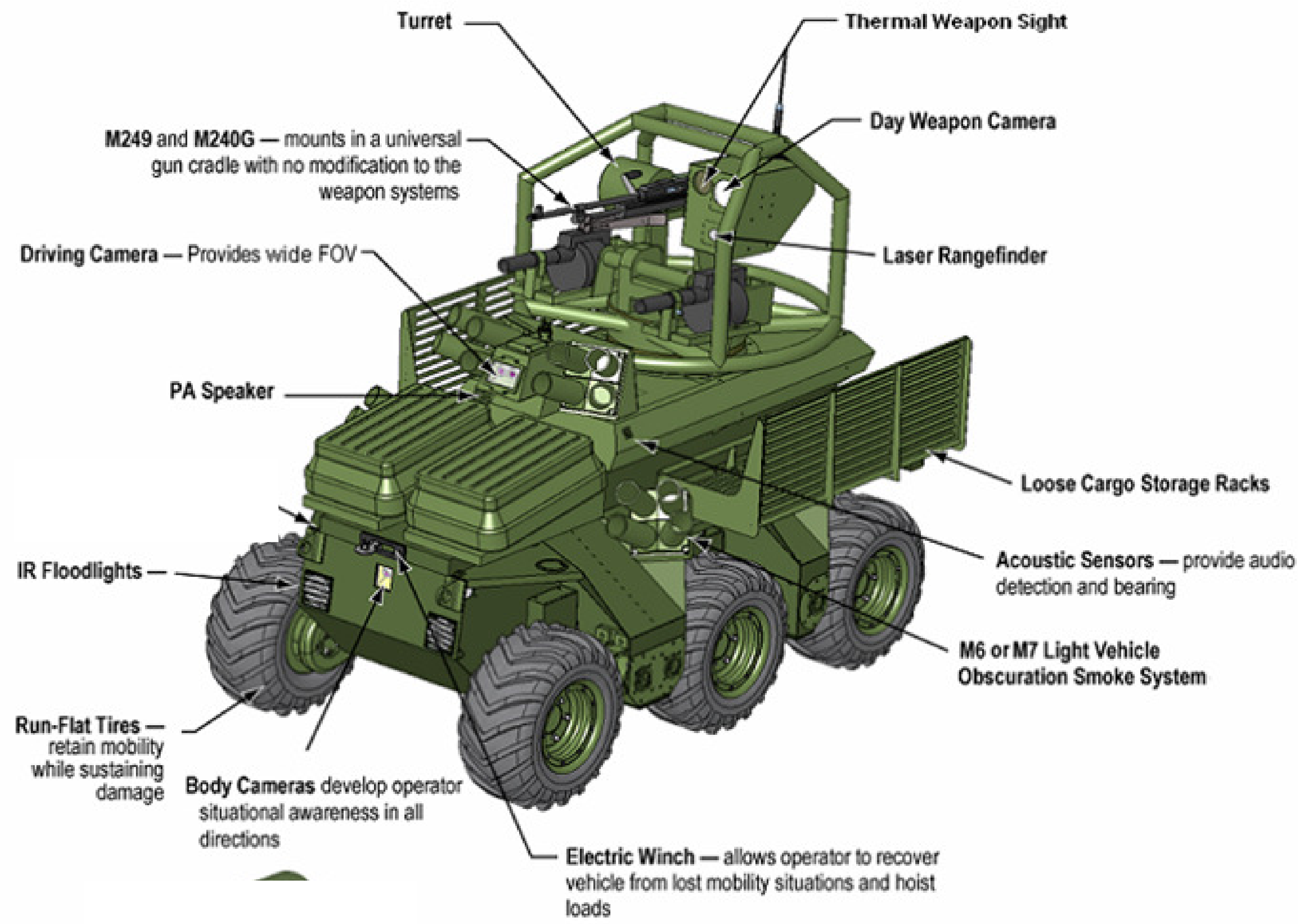
DOD ROBOTIC VEHICLES: GLADIATOR

- Preliminary design complete
- All major system and component trades complete
- Key vendors selected
- Systems engineering process used and requirements database created to assist traceability of all requirements
- Planning for future expansion (e.g., full autonomy)

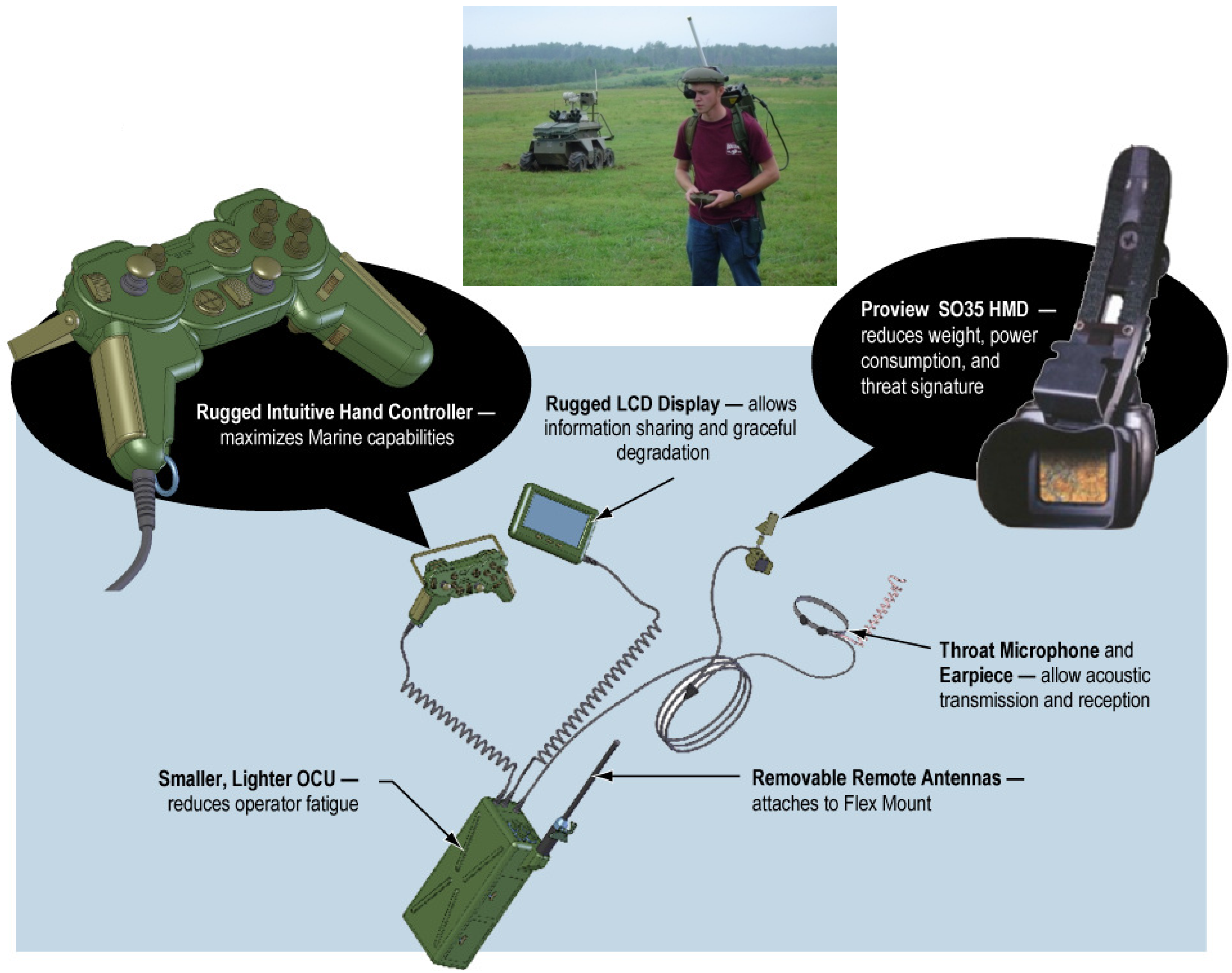
DOD ROBOTIC VEHICLES: GLADIATOR

- Support Dismounted Marines in the following missions:
  - Direct Fire
  - Scouting
  - Day/Night Reconnaissance
  - Remote Surveillance & Target Acquisition (RSTA)
  - Detection of Nuclear, Biological, & Chemical Agents
  - Obstacle Breaching

DOD ROBOTIC VEHICLES: GLADIATOR

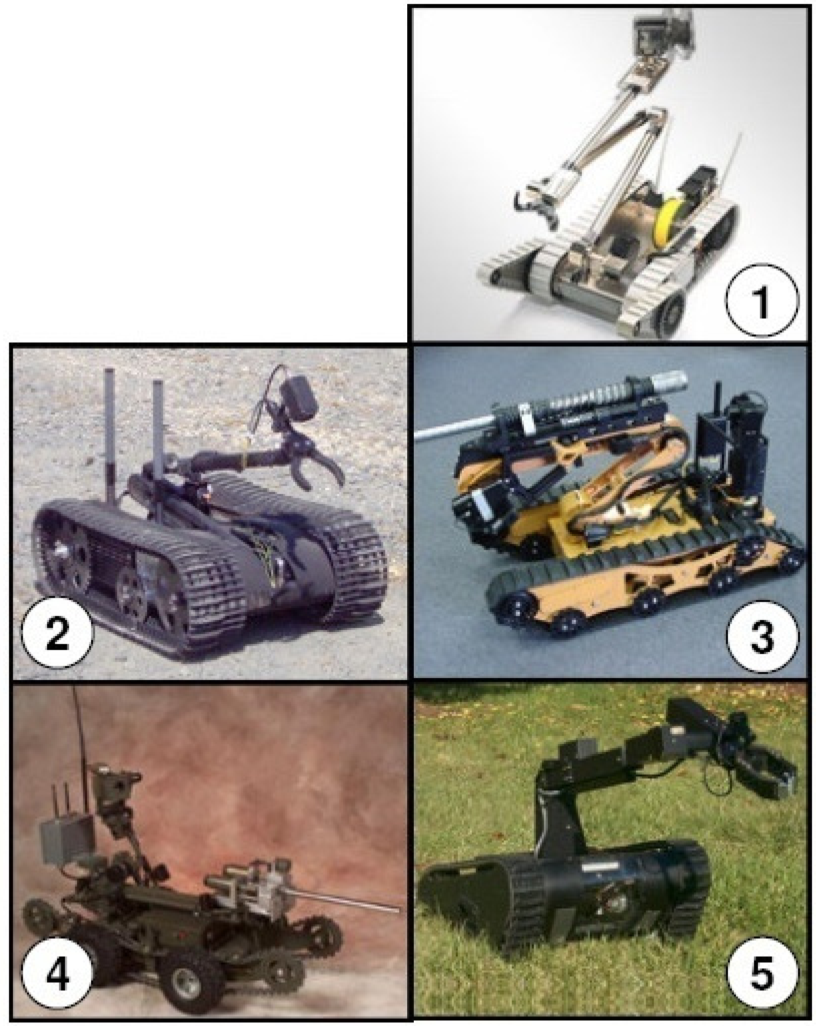


DOD ROBOTIC VEHICLES: GLADIATOR



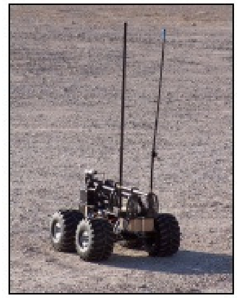
ROBOTS IN AFGHANISTAN AND IRAQ

- Operations in Southwest Asia: 2006
  - Afghanistan
    - Cave searches
    - Anti personnel mines
  - Iraq
    - Counter IEDs as Precision Munitions
    - Vehicle Born IED
    - Next Generation Threat
  - Initial: 150 robots
    - (1) PacBot
    - (2) Talon
    - (3) Vanguard
    - (4) Mini Andros
    - (5) Matilda



ROBOTS IN AFGHANISTAN AND IRAQ

- Operations in Southwest Asia: 2006 mission growth
  - Estimated 4000 systems in theater (12,000 in 2007)
  - Parts required: $4M-$6M per month
  - Over 22 different robot types
  - Missions: EOD, Force Protection, Countermine, Urban Operations
  - Support facility will double in size in Iraq
  - Creation of embedded repair teams



Marcbot

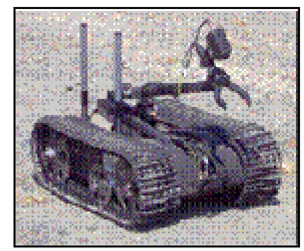
Mini Flail

Throwbot

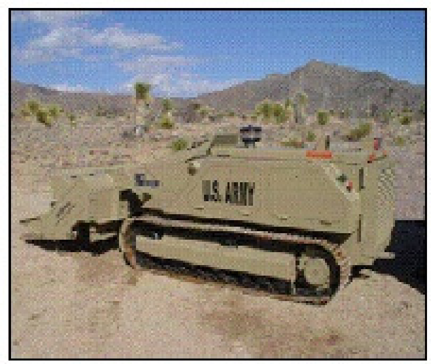
Scout

Toughbot

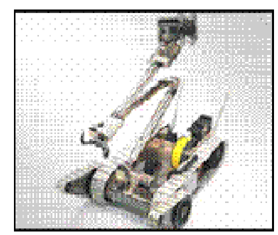
Panther



Talon

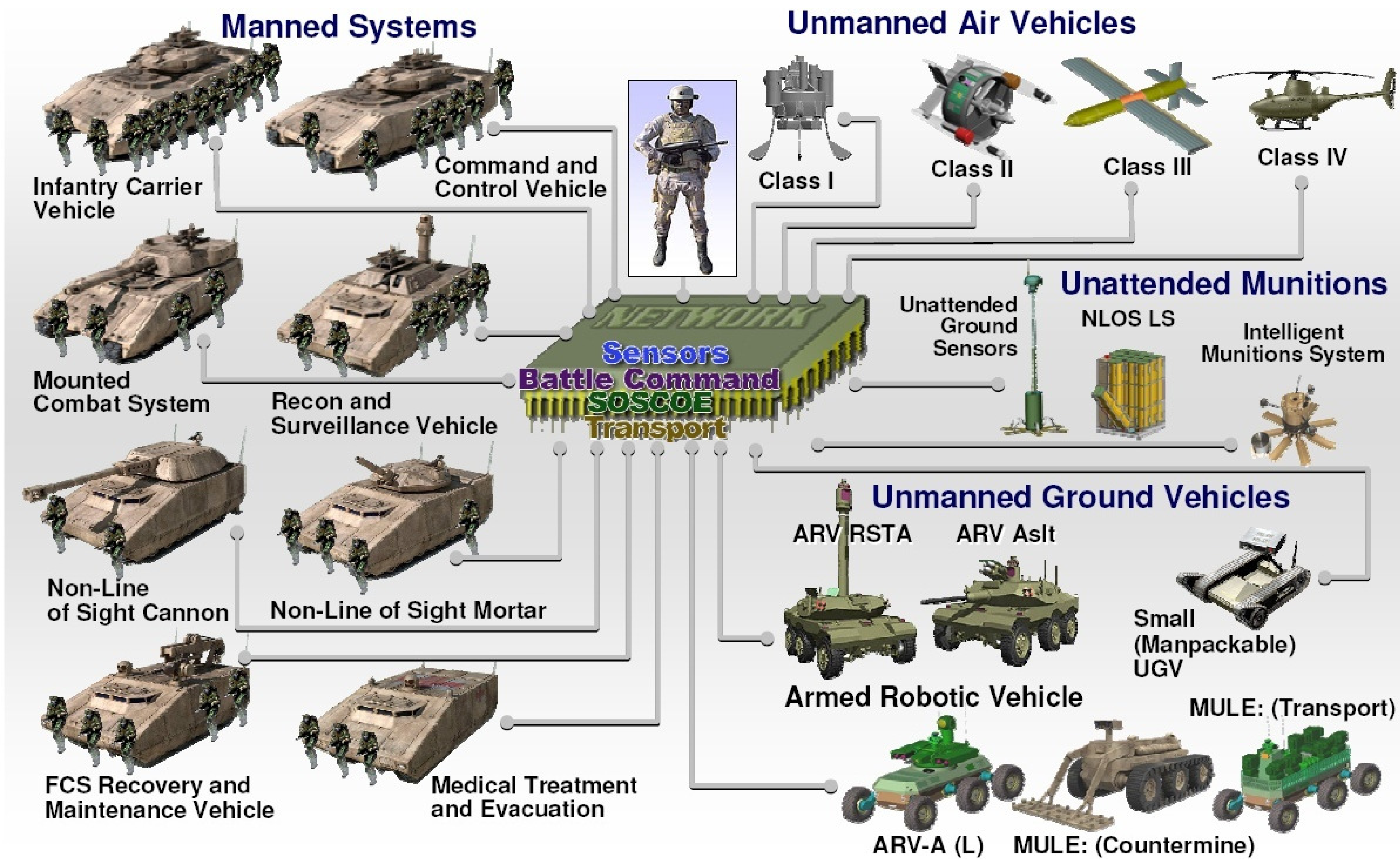


DOK-ing MV4



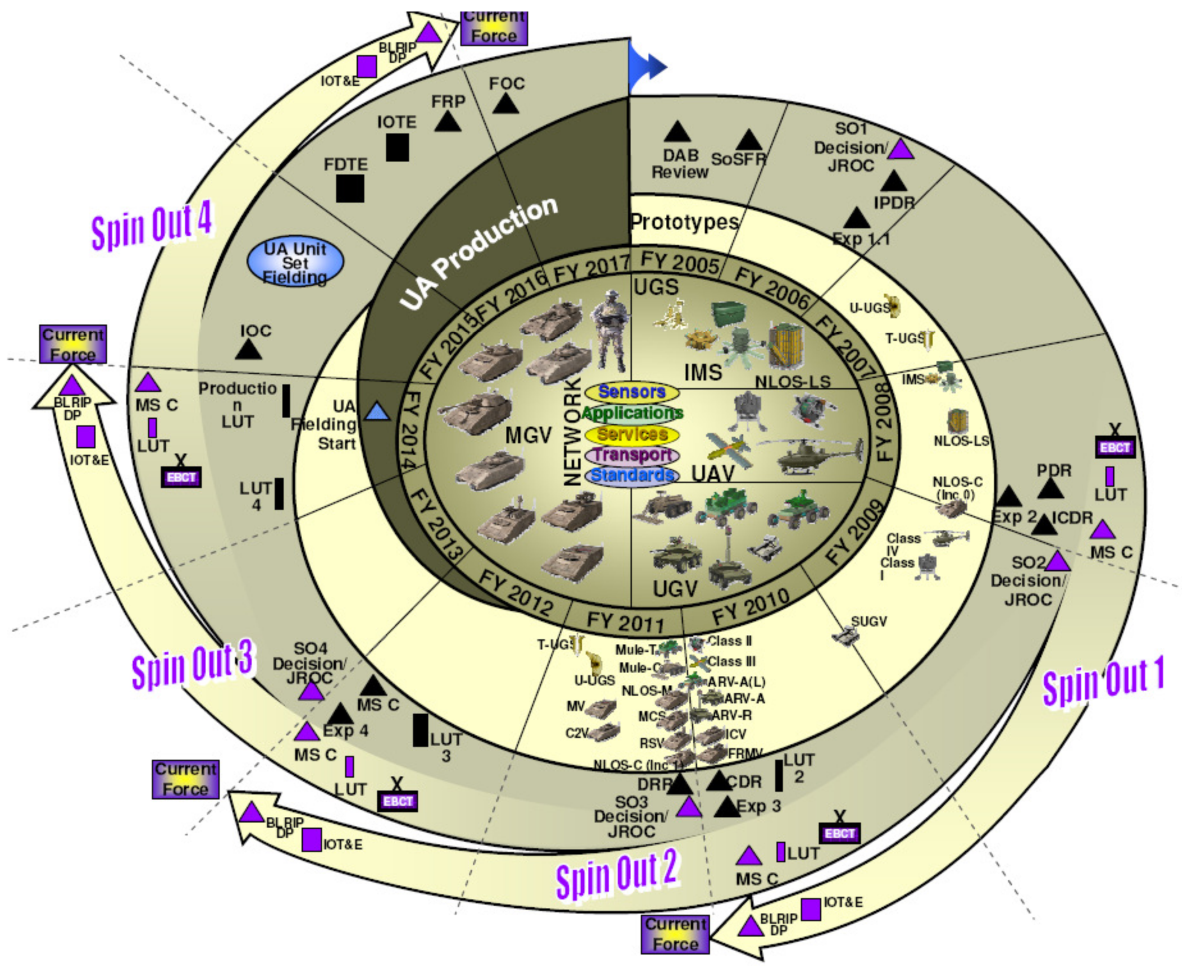
PacBot

FUTURE COMBAT SYSTEM (FCS)



FUTURE COMBAT SYSTEM (FCS)

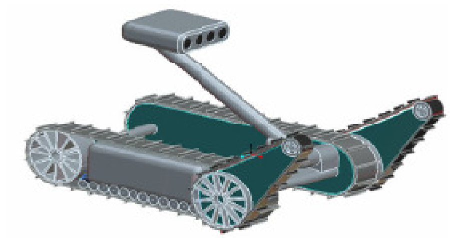
- Congress: one-third of all combat vehicles to be robots by 2015
- Development cost by 2014: $130-$250 billion



FUTURE COMBAT SYSTEM (FCS)

Armed Robotic Vehicle
- ARV-Assault
- ARV-RSTA

BAE Systems

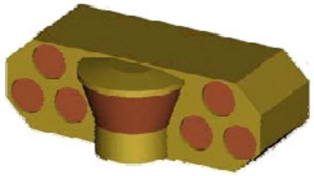


Small Unmanned Ground Vehicle (SUGV)

iRobot

Multifunction Utility/Logistics Equipment (MULE)
Mule-Transport, Countermine Mule, ARV-A-L

Lockheed-Martin

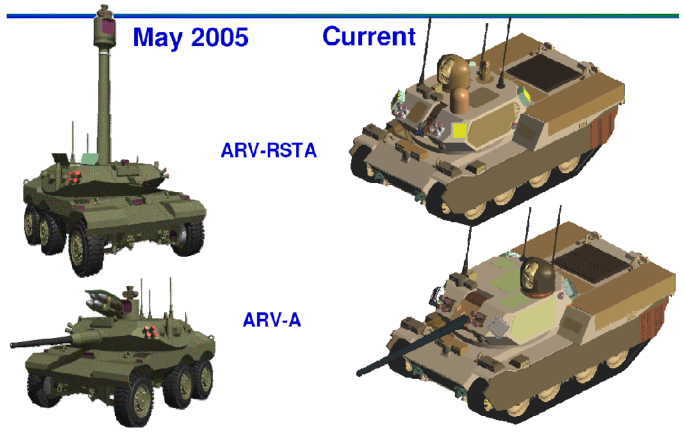


Autonomous Navigation System (ANS)

General Dynamics Robot Systems

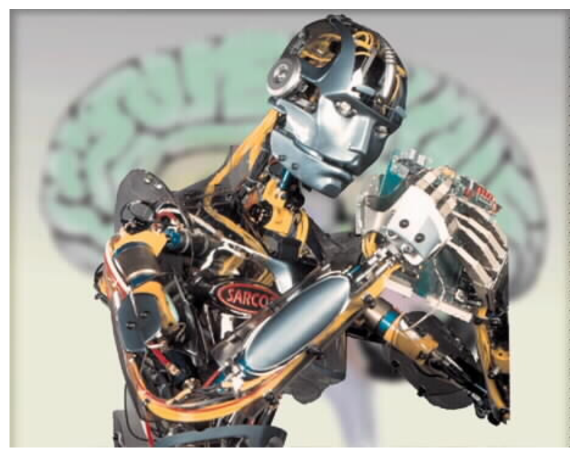
FUTURE COMBAT SYSTEM (FCS)

- Technology Issues
  - Automated avoidance of moving humans and traffic
  - Reduced Bandwidth and/or Latency tolerant teleoperation
  - Guarded Teleoperation (“keep me from doing something I’ll regret”)
  - Through Foliage Autonomous Navigation
    - Sensing
    - Fusion with a priori overhead data–
    - Planning with “operator intent”
  - High Speed (>40 kph) following in traffic/narrow roads (with and without GPS)
  - Battery (power and energy) density increases
  - Armor technology (protection/weight ratio)
  - User Interfaces (low power, low weight)



ARV Variant Concepts

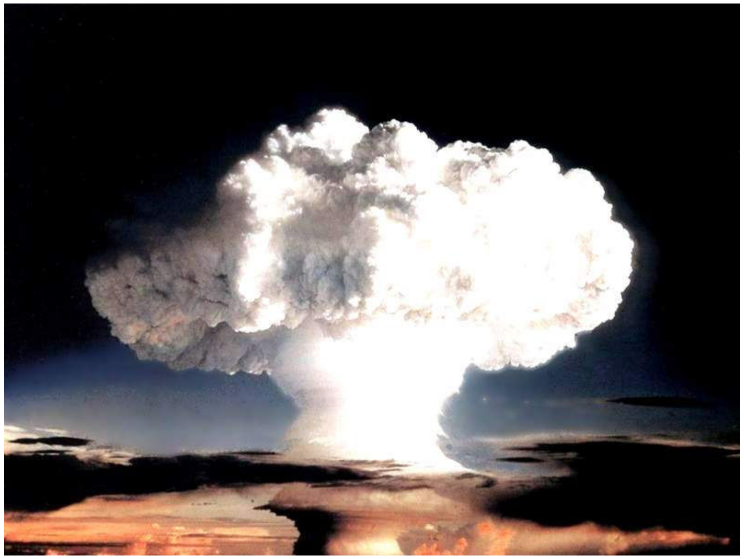
ROBOTIC SYSTEMS FOR HOMELAND SECURITY AND COUNTER-TERRORISM

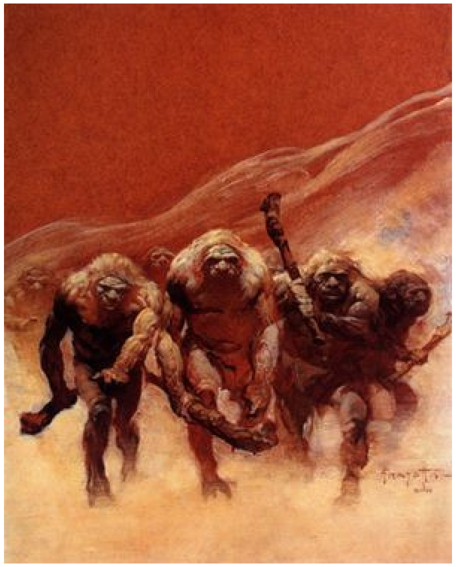


THE MIASMA

"[In war] the latest refinements of science are linked with the cruelties of the stone age."

-- Sir Winston Churchill (1942)

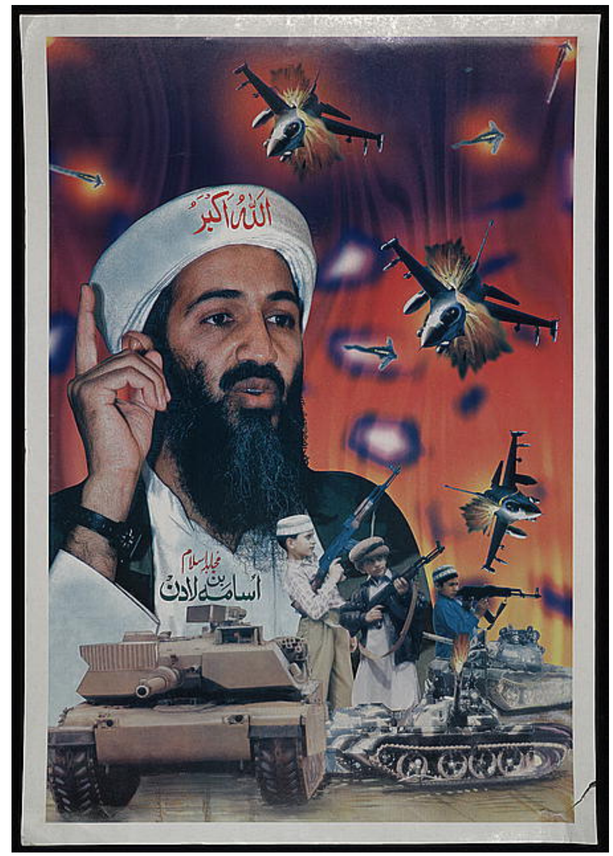




THE MIASMA

Terrorism is the threat or act of violence, against non-combatants, intended to influence an audience.

-- Jessica Stern, *The Ultimate Terrorists*



THE MIASMA

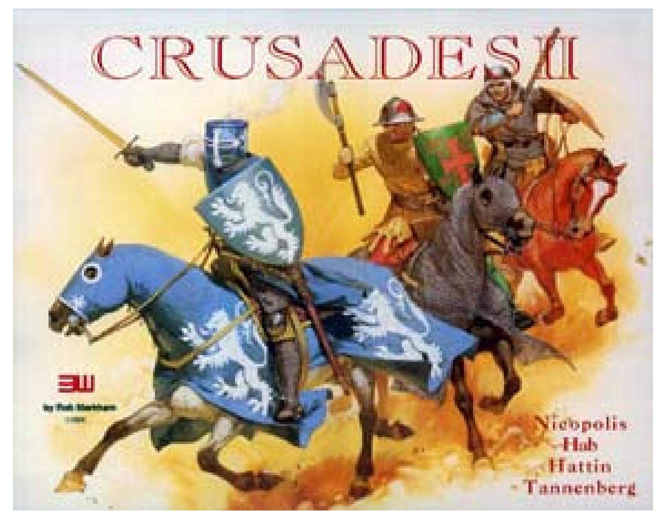
A Shifting World:

- From nation-state conflict to religious, cultural, & ideological conflict
- National borders attenuating
  - Refugee flows increasing and poor migrating
  - Warlord cultures & tribes, interlocking conflicts of sects, ethnics, religions, cults, cultures
- Global alliances becoming depolarized
- Weapons of mass destruction used for primitive ends

THE MIASMA

War on terrorism like warfare in Medieval Europe

- War-making entities not restricted to specific territories
  - Coalitions, tribes, ethnic groups, feudal structures, religious leagues, robber barons, warlords, mercenary bands, commercial organizations
- Shifting centers of power with religious fanaticism, tribal war, ever-mutating chaos
- Fading distinctions between crime & war



THE MIASMA

Since the end of WWII

- More than 200 major armed conflicts
- Mostly ethnic, secessionist, cultural, or religious wars
- Guerilla warfare & terrorism are successful against conventional weapons, which are
  - Too big, unmaneuverable, indiscriminating, fast, & expensive
- Battles replaced by: suicide bombs, improvised explosive devices, car & plane bombs, skirmishes, ambushes, & indiscriminate massacres

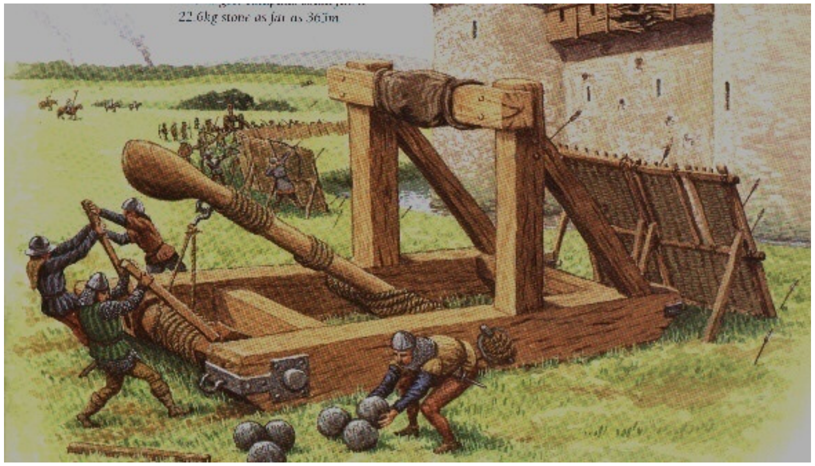
THE MIASMA

In countering terrorists, the fog of war worsens

- Information uncertainty & ignorance, inconsistency & incompleteness
- Decreased command & control
- Enemy dispersed & intermingled with friendly forces & civilian population
- Even advanced conventional weapons insufficiently accurate
- No possibility of formal surrender
  - No fixed enemy bases to surround
  - No lines of communications to sever

NEW TECHNOLOGIES FOR A NEW WAR

- **Historically More varied, complex, and flexible military technologies tend to prevail over simpler, more homogeneous ones**
  - **Example: mechanical artillery (or siege engines, such as the catapult and onager) overwhelmed weapons that were held or thrown by hand**
    - **Significant impact: For first time in history mechanical artillery decoupled weapon power from human muscles and the condition of the combatant: weak or strong, brave or coward, tired or energetic**

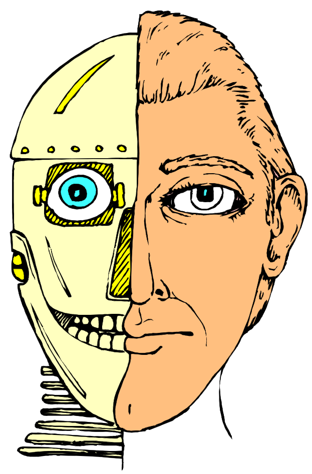


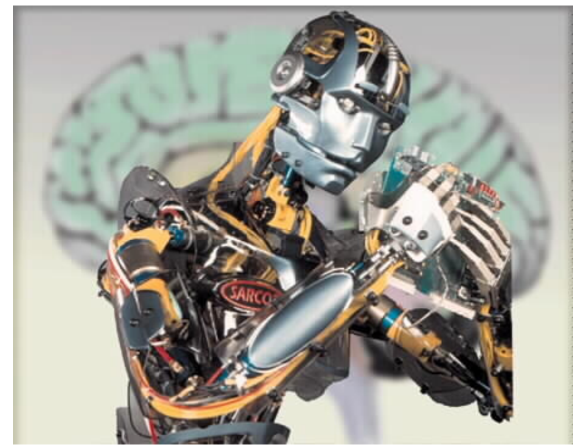
King Archidamas declared that the valor of the soldier was at an end, replaced by the engineer as weapons designer

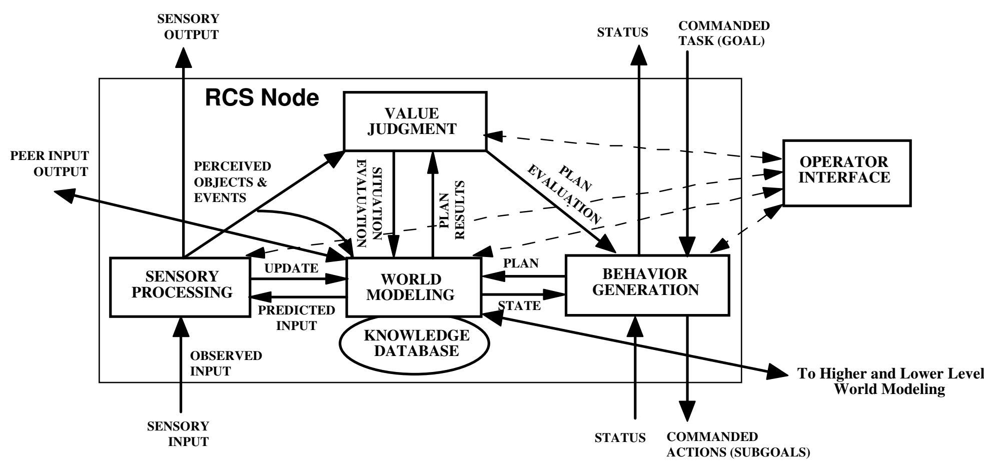
ROBOTICS FOR A NEW WAR

Robotic systems technology can have a comparably fundamental impact:

Just as the catapult replaced human *muscle* in combat, intelligent robots can replace the human *mind*

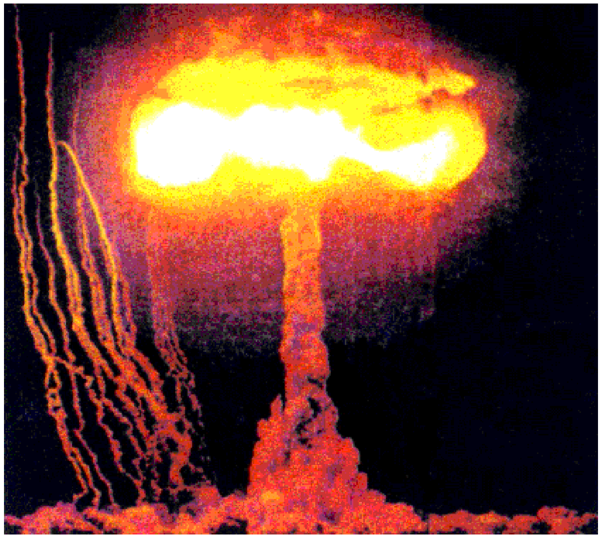






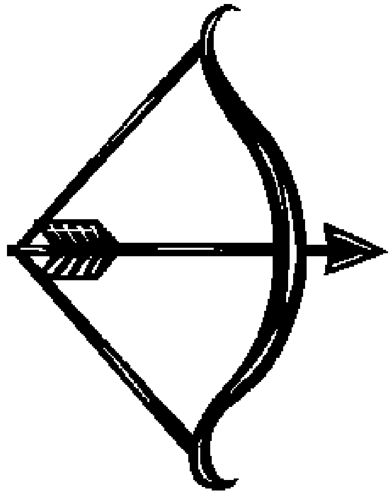
ROBOTICS FOR A NEW WAR

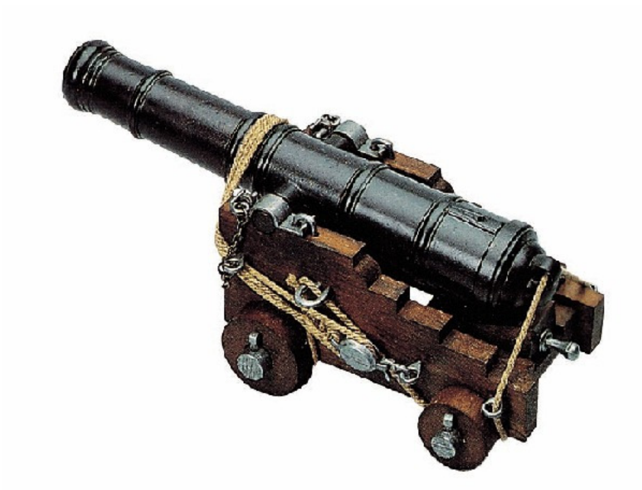
- Historically, evolution of weapons not governed only by rational utility
  - Intertwined with anthropological, sociological, psychological, and cultural factors
- Technology represents a philosophical system affecting the framework for thinking about and conducting war
  - Example: successful years of Mutually Assured Destruction serving as a preventative of nuclear annihilation



ROBOTICS FOR A NEW WAR

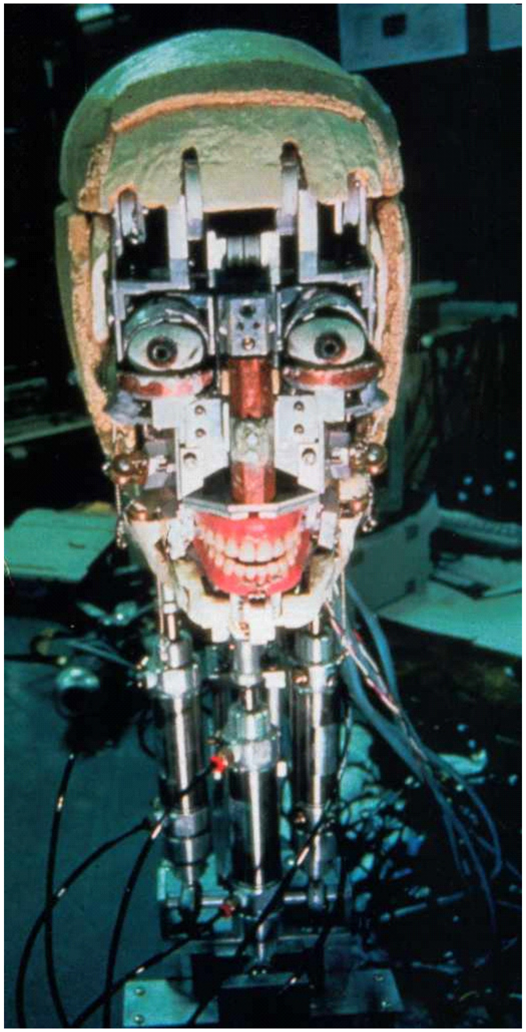
- **Historically, disruptive, transforming technology of warfare also a product of historical and political circumstance and may be rapid or gradual change**
  - **Example: firearms took a long time to barely equal the performance of bows and mechanical artillery; impact of firearms on warfare was evolutionary, not revolutionary**





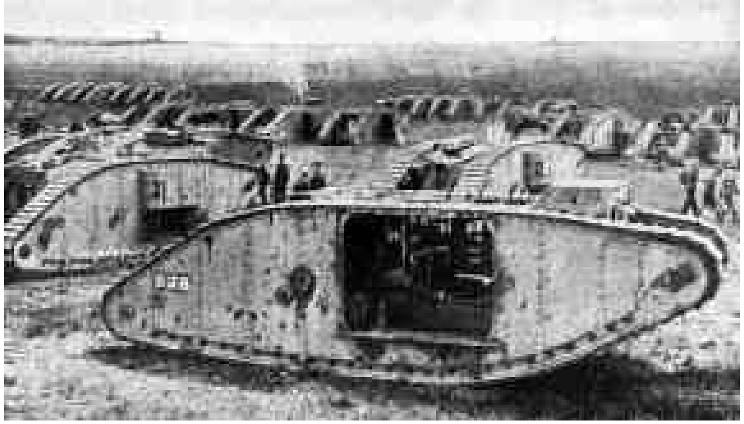
ROBOTICS FOR A NEW WAR

- Historically, superior weapons technology works best in *simpler* environments, overcoming inferior technology
- In *complex* environments, the superior tactician gains the upper hand, even with inferior weapons
- The winning side is often that side which is best able to comprehend and usefully employ the totality of factors in the complex combat environment
- Weapons must be designed to impress the enemy irrationally as well as rationally, to deter and unnerve the enemy



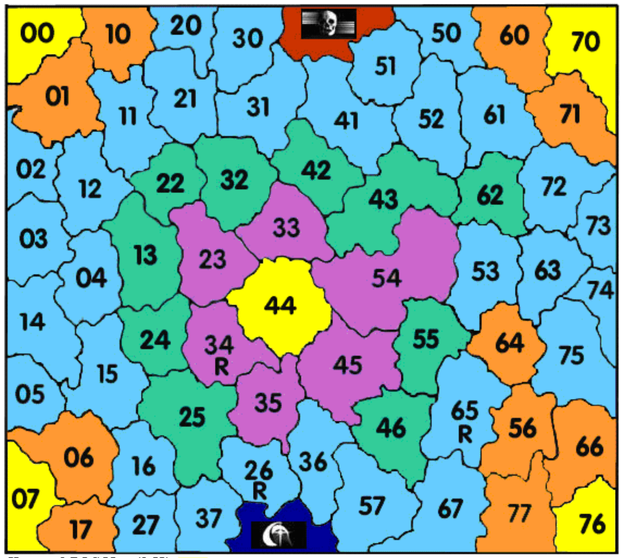
ROBOTICS FOR A NEW WAR

- In the 20th century no war-transforming system ever originated in military doctrinal requirements, including:
- The airplane, tank, jet engine, radar, helicopter, atomic bomb, and computer
- This is true as well for robotic systems
  - Conventional war tactics and strategy nearly unchanged since World War II or earlier
  - Nearing the end of large-scale conventional war
  - Effectiveness of a new weapon no longer depends primarily on inherent superiority, but from its appropriateness for the enemy and situation at hand



ROBOTICS FOR A NEW WAR

- Technological superiority of weapons is meaningless in an absolute sense:
  - Weapons must be appropriate to the enemy and combat environment
  - Bypass the enemy's strengths while exploiting his weakness
  - The essence of asymmetric warfare, which is exploited by terrorists against conventional forces
  - Counter-terrorist forces can also employ asymmetric warfare to their advantage – an opportunity offered by robotic technology
- All else being equal, the combatant who understands the essence of war will prevail and win

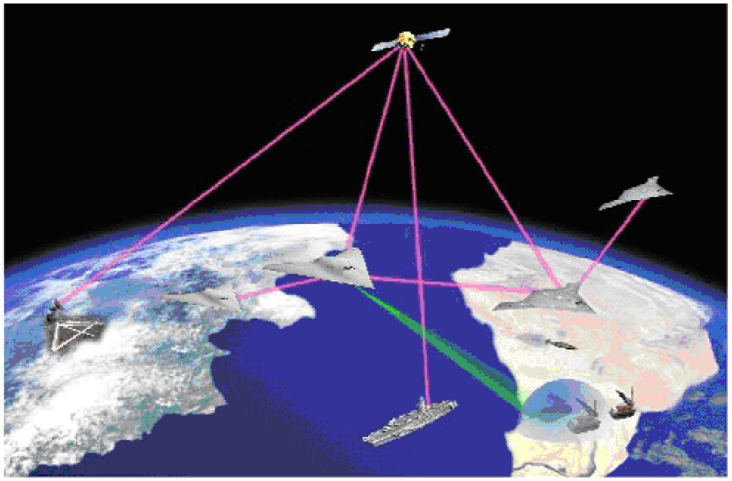


ROBOTICS AS SOLUTIONS

- Robotic systems can:
  - Dispel the fog of war (and terrorism) by reducing the friction and uncertainty of conflict
  - Provide the commander with information on the enemy
  - Help the commander assess tactical or critical situations
  - Decrease uncertainty by improving command and control, directing forces toward the objective while easing the transmission of orders
  - Increase a commander's (or unit's) experience & expertise through virtual environments & exercises
  - Enhance the unity of command by allowing the commander to know more and lead larger, more complex forces

ROBOTICS AS SOLUTIONS

- Intelligent robotic vehicles are asymmetric solutions to problems of:
  - Human casualties
  - Attrition of expensive systems
  - Personnel availability & cost
  - Logistics burdens
  - Functioning with WMD
- Intelligent robotic vehicles can be:
  - Smaller
  - Lighter
  - Stealthier
  - Less expensive
  - Expendable (or more survivable)
  - Fearless and tireless
  - Efficacious with fewer & lower-skilled personnel
  - Beneficiary of U.S. technology



ROBOTICS AS SOLUTIONS

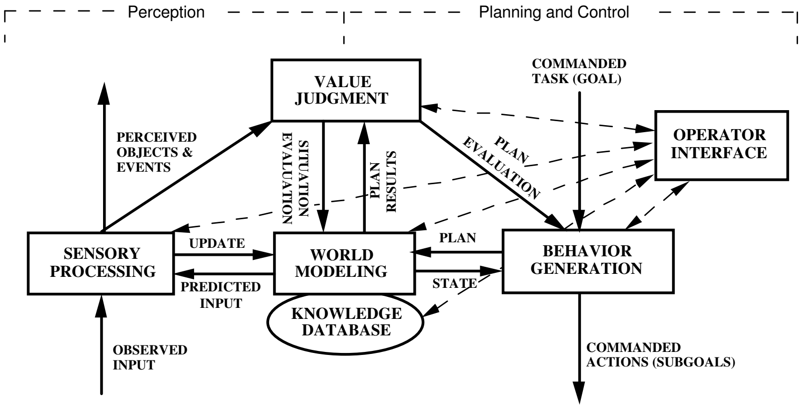
- Asymmetric against terrorists
  - Destruction of robotic vehicles – no human casualties
- Robotic vehicles are NOT excessively:
  - Expensive, fast, indiscriminating, bulky, unmaneuverable, or powerful
- Forces using robotic vehicles can:
  - Avoid tails which are too large and teeth which are too small
  - Operate against WMD
  - Perform fearlessly against skirmishes, ambushes, suicide and car bombings, and IED
- Robotic vehicles can be accurate to target enemy dispersed and intermingled with friendly forces and civilian population
  - Cheap enough to risk

ROBOTICS AS SOLUTIONS

- Robots are mandatory for homeland security and to counter terrorist threats
  - Mass freight
  - Mass transit
  - Massive structures
    - Bridges
    - Tunnels
    - Buildings
    - Factories
    - Power Plants
    - National Monuments
    - Etc.
  - Mass crossings over extensive borders

ROBOTICS AS SOLUTIONS

- Complexity in space & time – dynamic variety in the threat – can be countered with variety generated by intelligent control systems employing extensive sensor networks (on mobile robotic platforms & unattended)
- Reactive, deliberative, & reflexive intelligent systems can "connect the dots" for situational awareness and respond rapidly in crises
- Suggest actions to decision-makers
- Take actions as allowed by decision-makers

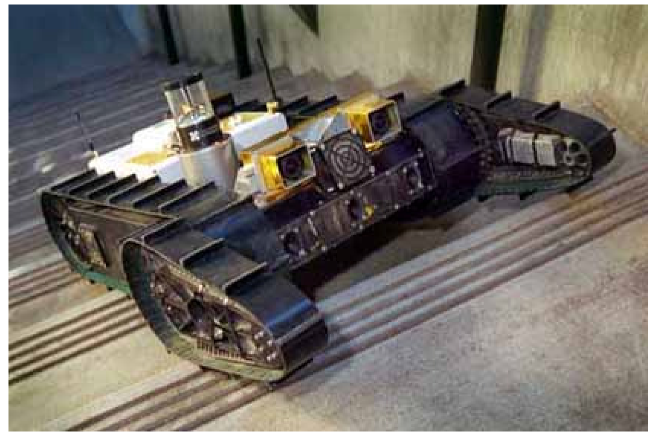


ROBOTICS AS SOLUTIONS

- Robotic systems can provide a new framework and philosophy for homeland security and counter-terrorism
- Leading to conceptual breakthroughs in tactics, operations, and goals
- Doing things differently, as well as better, allowing the commander to comprehend the totality of tactical factors in complex environments
- Integrated with legacy systems while remaining independent and flexible
- Increase effectiveness while suitably diminishing efficiency (e.g., swarm robotic vehicles)
  - (Success in war often means deliberately diminishing efficiency to enhance effectiveness)
- Accommodate rivers of information

ROBOTICS AS SOLUTIONS

- **Overwhelming the enemy with mass is now a losing strategy – we must overwhelm him with quantity, variety, and precision – not mass**
- **Numerous, networked, distributed, small sensors and weapons mounted on low-cost, intelligent, robotic platforms will function and survive**



ROBOTICS AS SOLUTIONS

- An intelligent system architecture can serve as an over-arching framework for the nation's homeland security
- Connecting unattended sensors, robotic security platforms, human intelligence, communications intelligence, databases, world models, manned checkpoints, and command centers
- Monitoring the nation's critical infrastructure
- Encompassing modules for risk perception and risk mitigation
- Suggesting courses of action to human controllers,
  - Or implementing emergency responses autonomously
- "Connecting the dots"
- Responding appropriately to the emerging threat

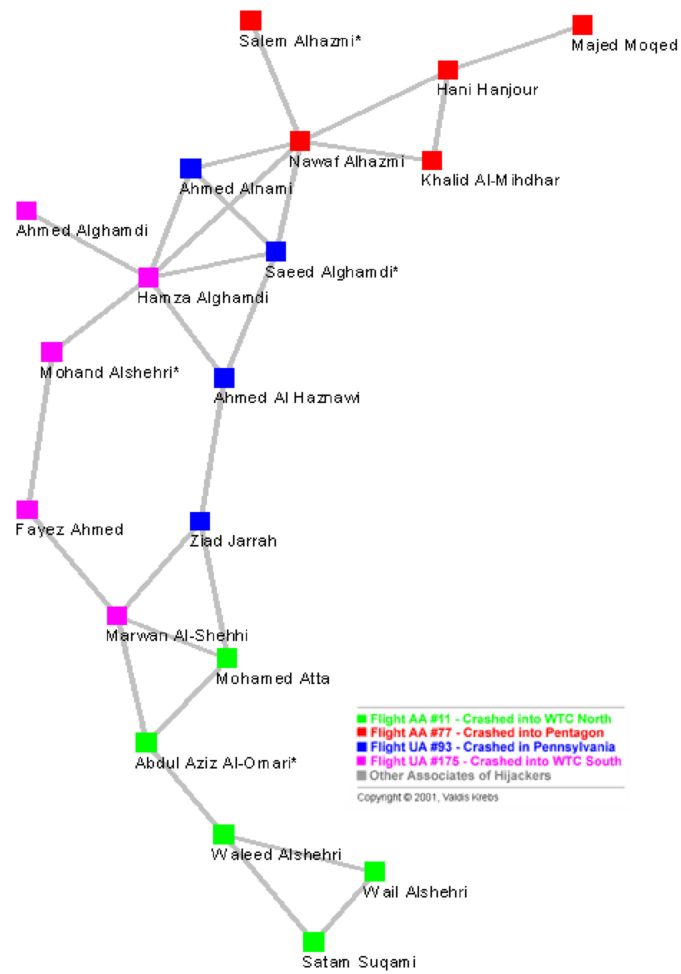

(AP PHOTO)

ROBOTICS AS SOLUTIONS

- **Technological superiority is meaningless in an absolute sense:** ***weapons must be appropriate to the enemy and circumstances***
- **Robotic systems, which are adaptable, are ideal for the ever-transforming terrorist threat,** ***bypassing their strengths while exploiting their weaknesses***

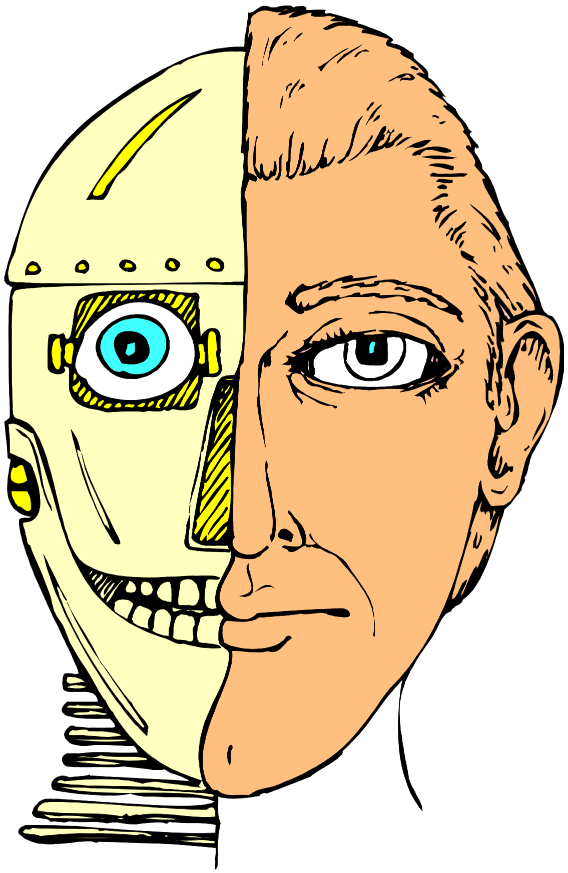
COUNTER-TERORRISM: BOTTOM LINE FOR ROBOTICS SYSTEMS

- **The terrorist network has been very successful using asymmetric warfare *against us***
- **Robotic systems will give us the means to use asymmetric warfare *against the terrorist network***



HUMANOID AND LEGGED ROBOTS

- **Four groups employed in DARPA study for prognostication and judgment:**
  - **Expert Panel**
  - **Expert (developer) survey population**
  - **User survey population**
  - **Researchers in the literature**



HUMANOID AND LEGGED ROBOTS

- To augment foot soldier and be able to:
  - See and perceive
  - Hear and understand
  - Climb obstacles, ladder
  - Crawl and jump
  - Run up and down stairs
  - Recover from stumbles
  - Recover from falls
  - Understand situations
  - Distinguish friend-foe
  - Shoot when appropriate
  - Require no more space or logistics support than human soldier
- These behaviors are now outside the state of the technology

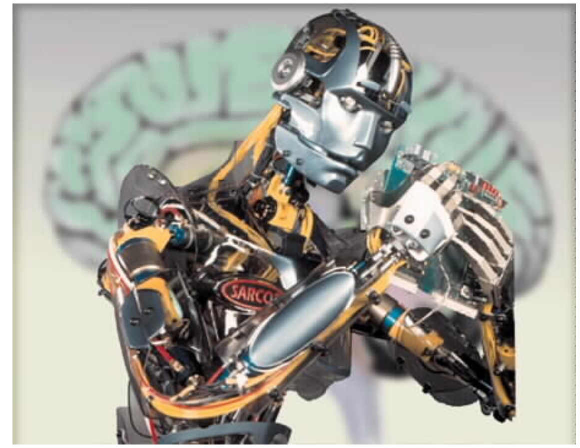
PHOTOS BY KAREL PRINSLOO—ASSOCIATED PRESS

HUMANOID AND LEGGED ROBOTS

- U.S. falling behind Japanese and even Europeans in funding humanoid robot development
- Hexapod robots inappropriate as large robots
- Quadruped and hybrid robots (e.g., Centaur) can be militarily useful
- Humanoid robots militarily valuable by 2015
- Humanoid robots as capable as soldiers by 2035
- 4D/RCS control architecture suitable for supervised intelligent autonomous humanoid robots
- Advent of humanoid robots will have major military and civil societal impacts and advance scientific understanding human physiology and psychology

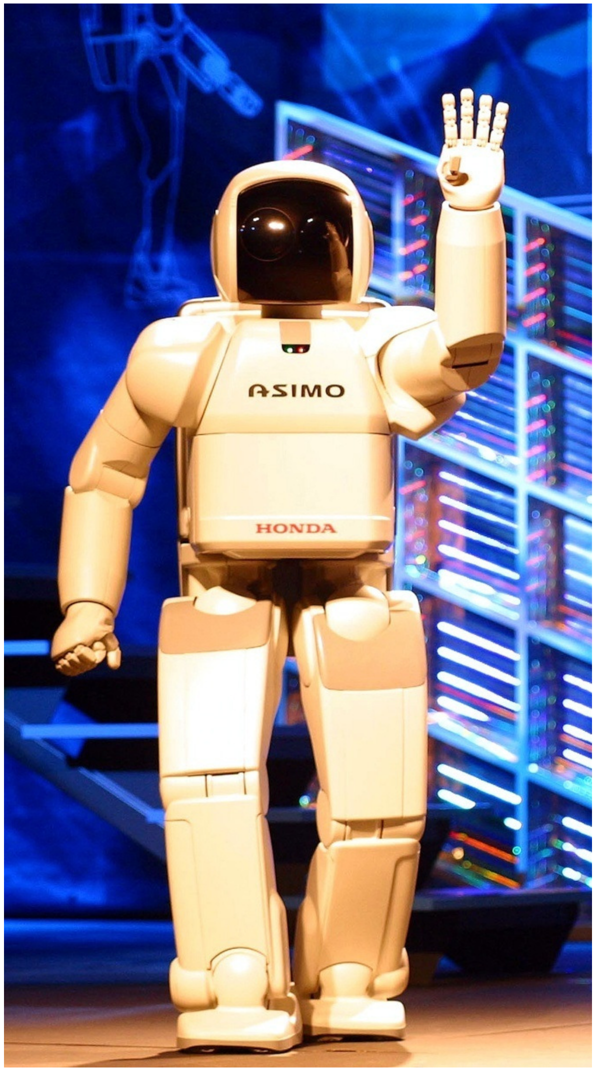
HUMANOID AND LEGGED ROBOTS

- Near-term technological advances could enable humanoid and quadruped robots to walk, run, and jump with a level of strength, dexterity, and endurance that equals or exceeds human and animal capabilities
- These technologies may also enable robots with near human levels of perception, situation assessment, decision making, planning, and manipulation of tools and weapons in tactical environments



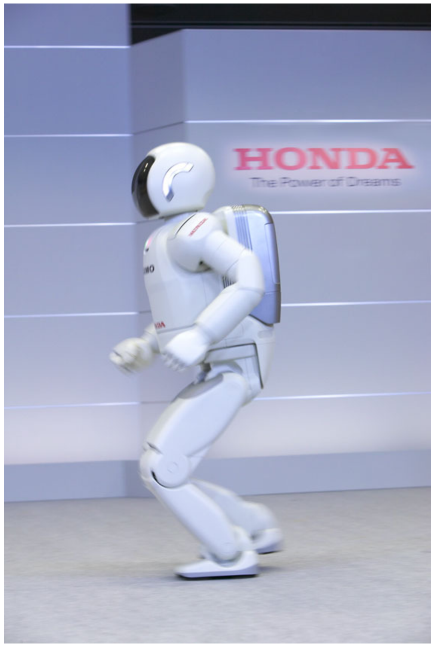
HUMANOID AND LEGGED ROBOTS

- Expected technological advances include:
  - Orders of magnitude growth in raw computational power
  - New technologies for sensing and perceiving the environment
  - Advances in the representation of geometric and symbolic knowledge
  - Advances in simulation, modeling, and graphics
  - Merging of virtual and real world environments
  - New approaches to real-time planning and intelligent control
  - Advances in efficiency, responsiveness, and strength-to-weight ratio of actuators



HUMANOID AND LEGGED ROBOTS

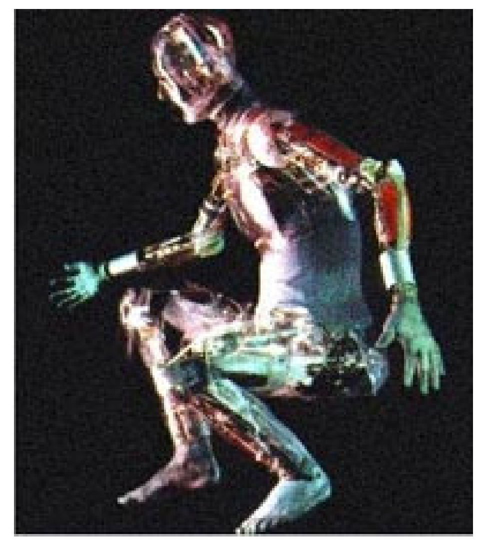
- Assuming adequate funding and program focus: militarily useful biped and quadruped robots are technologically feasible within current decade
  - By 2015: humanoid robots could achieve a degree of agility and intelligence that would enable a variety of tactical behavior on the battlefield
  - By 2025: cost and reliability could improve to the point that the cost and logistics burden of a humanoid robot will be less than or equal to that of a human soldier
  - Before 2035: humanoid robots could be as capable, efficient, and reliable as human foot soldiers in most battlefield situations




HUMANOID AND LEGGED ROBOTS

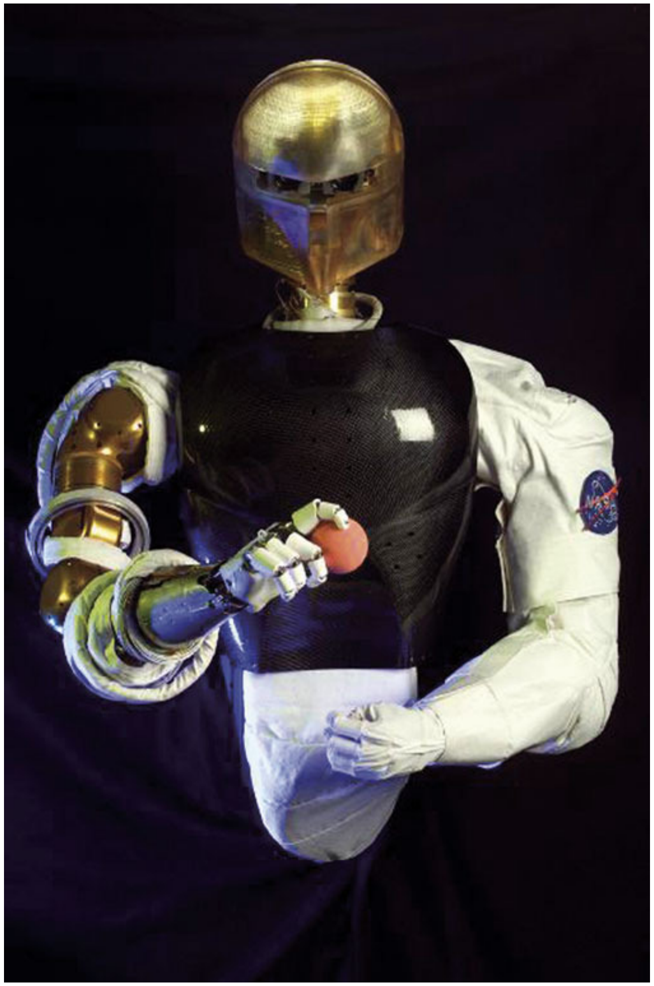
- **Humanoid robot key issues:**
  - Lack of enabling technologies for developing militarily useful humanoid robots (e.g., adaptable bipedal leg control)
  - Satisfactory humanoid technology by 2012
  - Most promising missions: RSTA & MOUT
  - Significant impact on military operations by 2024
  - Hybrid legged robots (e.g., Centaur) more useful for military than pure bipedal humanoid
  - Biped most difficult legged robot to develop
  - Propulsion (energy source) most pressing humanoid R&D need, then leg control
  - Semi-autonomy sufficient for most missions
  - Experts' expected unit cost of military humanoid: $400K - $1 million

Korean Robots



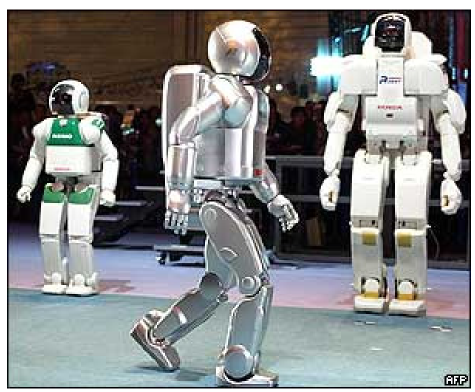
HUMANOID AND LEGGED ROBOTS

- Humanoid robot key issues:
  - Primary missions: countermine & EOD (followed by RSTA)
  - Significant military worth, but not ubiquitous, in 21st century
  - Quadruped robots favored over humanoid
  - Major issue: technology readiness (followed by safety)
  - Favor somewhat greater autonomy than experts
  - Humanoid robots should be fielded – the sooner the better



HUMANOID AND LEGGED ROBOTS

- **EOD MISSION NEEDS STATEMENT**
  - **NOTIONAL CONCEPT #5-03: *HUMANOID ROBOT***
  - **STATEMENT OF NEED:** ***A need exists for a robotic platform that is capable of climbing narrow stairs, climbing ladders, opening doors/hatches, and self-loading itself for transport.*** There is currently no capability to examine devices placed in locations that require climbing, such as water towers, ships' holds, or roofs. The humanoid robot would be capable of climbing both ship and land-based ladders. A humanoid robot would alleviate a need for the robot to be light for transportation, since it would be able to stow itself into an EOD response vehicle. A humanoid robot would also be capable of emplacing a disrupter tool or x-ray rather than the current methodology of mounting the disrupter on the tracked or wheeled robot.
  - **THREAT:** All IEDs and UXOs both foreign and domestic.
  - **INADEQUACIES OF CURRENT SYSTEMS:** Currently the services use tracked or wheeled robots. The current systems are heavy, weighing several hundred, if not thousands, of pounds, and are not capable of traversing all types of terrain or climbing ladder. The weight of these robots is important because personnel are expected to load the robot into a transport vehicle. The tracked and wheeled robots also move slowly and are expensive to operate. They have limited capability to emplace and aim a disrupter and no capability if the device is on a tower or roof.

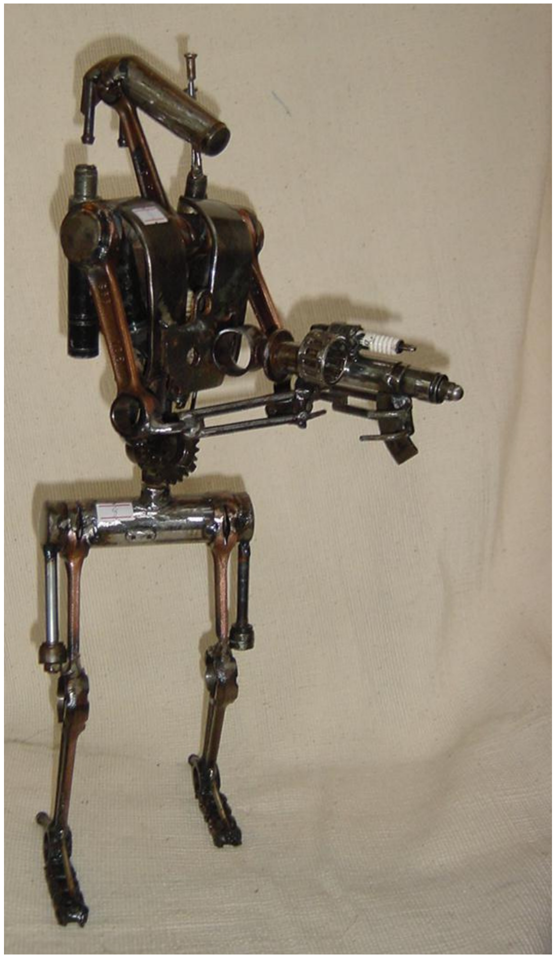


HUMANOID AND LEGGED ROBOTS

- **EOD MISSION NEEDS STATEMENT (Continued)**
  - **PROPOSED APPROACH:** This effort should examine if any COTS humanoid robots currently available that can be transitioned to EOD use. The pursued technology should leverage the "Land Warrior" type of control mechanism. Ideally, the hardened robot should be capable of a 3 foot jump/fall from a hovering helicopter onto soft soil. The robots gripper mechanisms should be capable of grasping the components of all current disrupters for assembly and they should have operator feedback sensitivity. The robot should have visual and auditory feedback capability. The robot should also be capable of carrying the EOD tools or X-ray down to the suspect item. The robot must be capable of being decontaminated. The robot must be able to self right itself should it fall or become knocked over. It should also have the capability of running a self diagnostic/prognostic. The robot should be able to operate in the temperature range of -10F -- + 100F for a minimum of 2 hours.
  - **CURRENT EXAMPLES OF THIS TECHNOLOGY:** Four known examples of this technology are: Sony SDR-4X, Honda Asimo, Fujitsu HOAP-1, and Dr. Robot (manufacturer unknown)
  - **POC:** LTC Bob Klimczak, U.S. Army EOD Technical Detachment, 2008 Stump Neck Rd., Indian Head, MD 20640. Phone 301 744-6820. e-mail robert.klimczak@us.army.mil

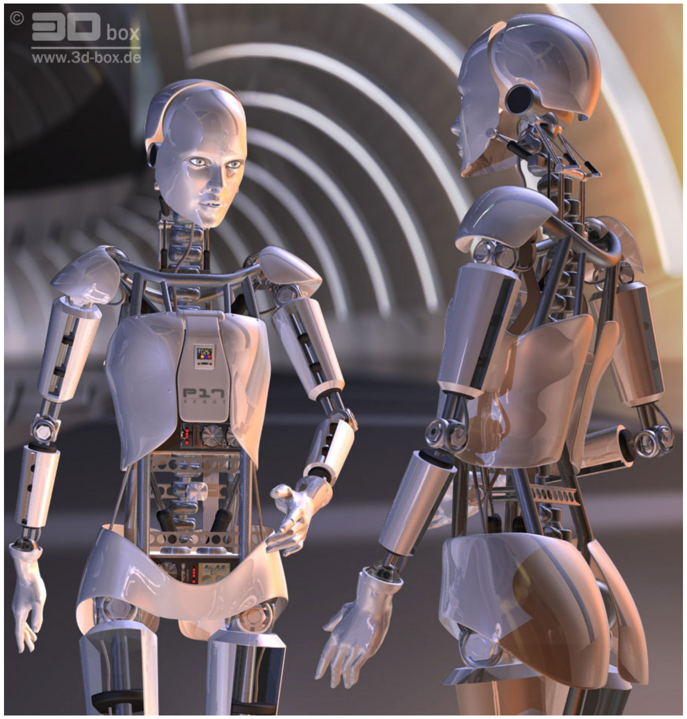
HUMANOID AND LEGGED ROBOTS

- Recent Progress in Legged and Bipedal Humanoid Robot Technology
  - Teleoperation and telepresence feasible in near-term & militarily useful
  - Tools being developed for optimal gait control
    - Genetic algorithms, neural networks, expert systems, vision-based walking, many kinds of control algorithms
  - Research to allow humanoid robots to learn complex tasks in uncertain environments without the need for programmers to foresee every contingency
    - Methods for intelligent control and robot cognition improving
  - Humanoid robots becoming more lifelike in movement and ability to interact with humans



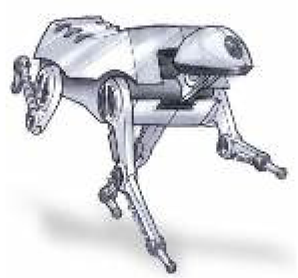
HUMANOID AND LEGGED ROBOTS

- Much more progress is needed for humanoid robots to perform a variety of useful military missions
- State of humanoid technology in 2007 is equivalent to the state of automotive technology in 1907
  - Not discouraging, given rapid automotive progress in 20th century
  - 2007 technological infrastructure much more advanced than 1907 counterpart
  - With sufficient user demand, humanoid robot technology can be elevated to competence like Model T Ford (239 cars sold in 1908; 1 million cars sold in 1927)
  - WWI accelerated automotive technology – war on terrorists can accelerate humanoid and legged robot technology



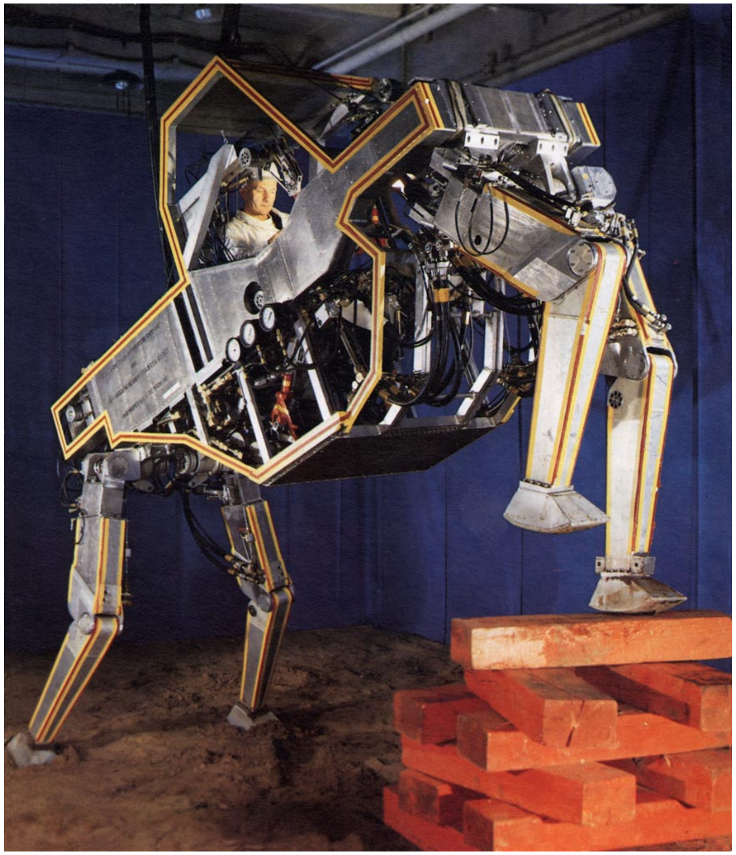
HUMANOID AND LEGGED ROBOTS

- Technical challenges
  - Energetics and Dynamics
  - Sensing and Perception
  - World Modeling
  - Knowledge Representation
  - Real-time Planning
  - Intelligent Control
  - Architecture for System Integration
  - Software Development
  - Computational power



HUMANOID AND LEGGED ROBOTS

- Energetics and Dynamics
  - Actuator efficiency, responsiveness, strength-to-weight ratio
- Japanese humanoids use electric motors, gears, and batteries
  - This is a dead end approach

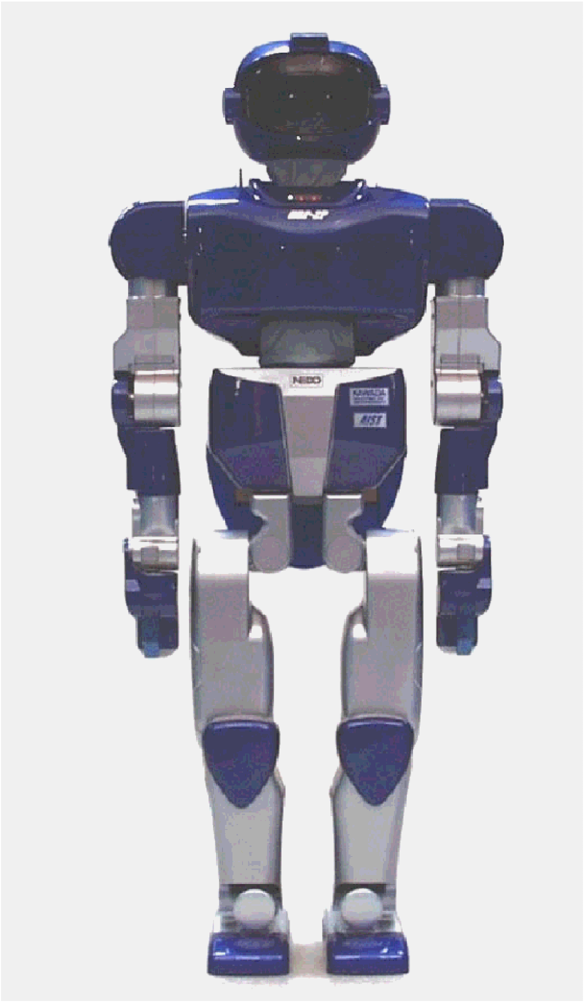


HUMANOID AND LEGGED ROBOTS

- Energetics is the biggest single problem for legged locomotion
  - Walking, running, recovering from stumbling requires combination of strength, speed, and dynamics not achievable with current actuator technology
  - Batteries have insufficient energy density
  - Electric motors have insufficient strength to weight ratio for both low-end torque and high-speed response
  - Gearing produces impedance mismatch
  - Hydraulics are too inefficient

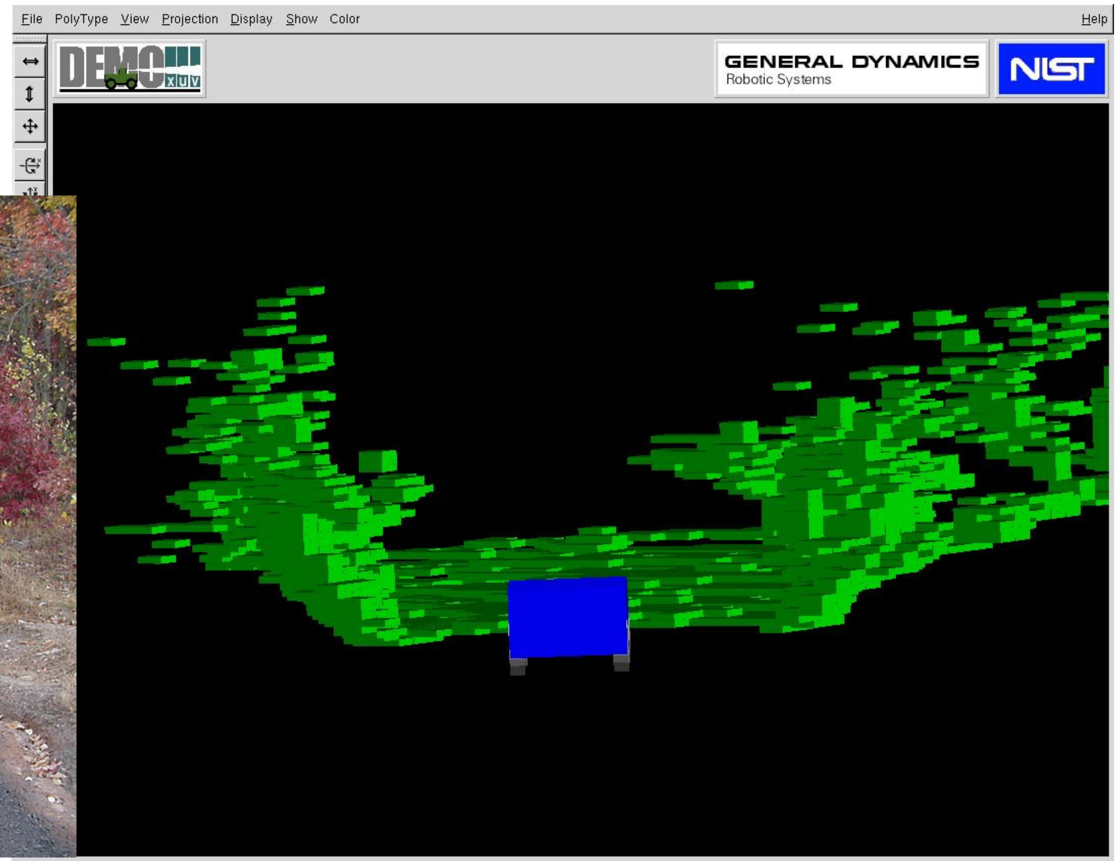
HUMANOID AND LEGGED ROBOTS

- Need Improved Sensors
  - LADAR
  - FLIR
  - Stereo
  - Image flow
  - Inertial navigation systems (INS)
  - Global positioning systems (GPS)
  - RADAR
  - Tactile, force, acceleration
  - Acoustic



HUMANOID AND LEGGED ROBOTS

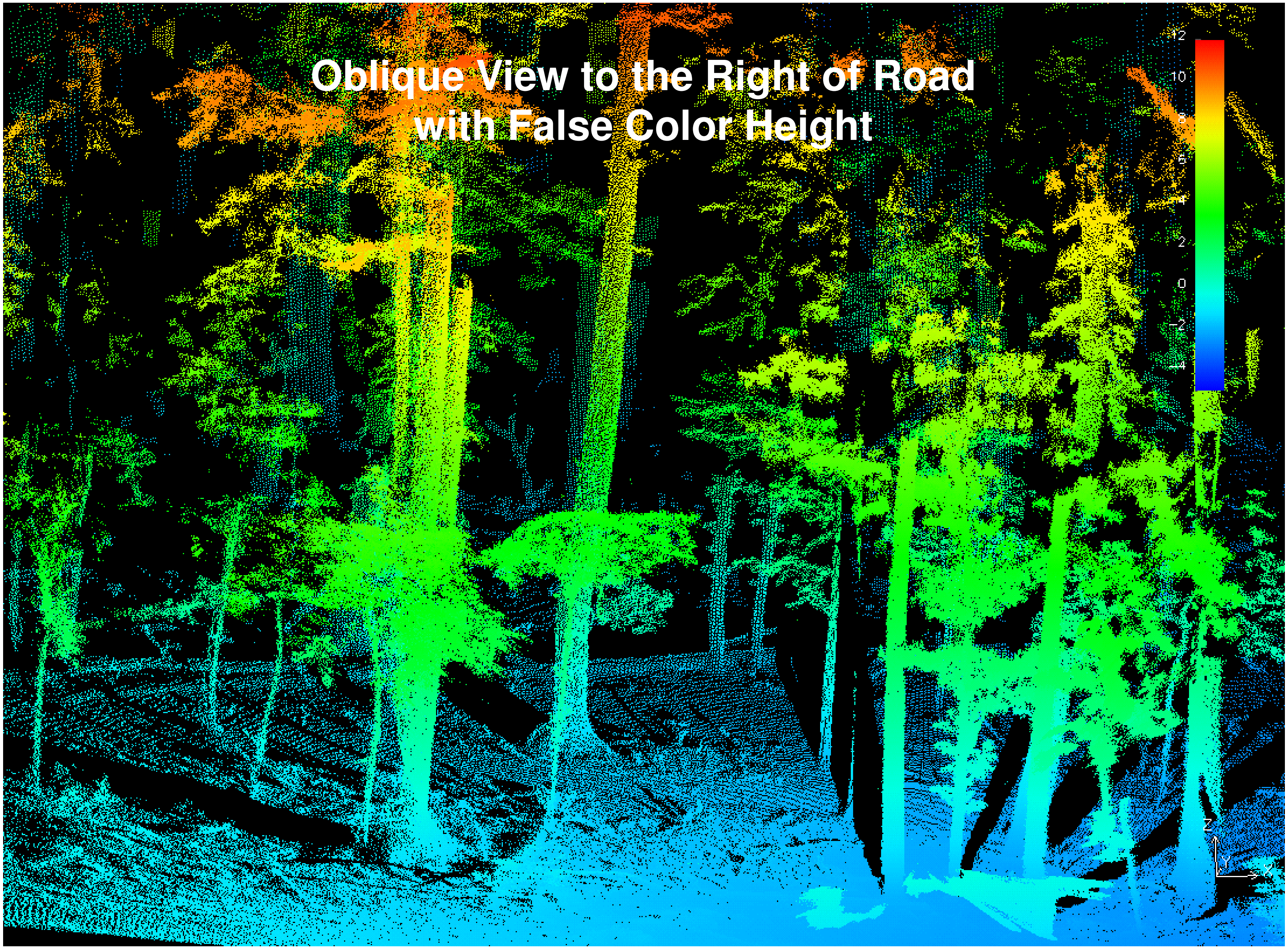
Ladar Range Image



Color Image

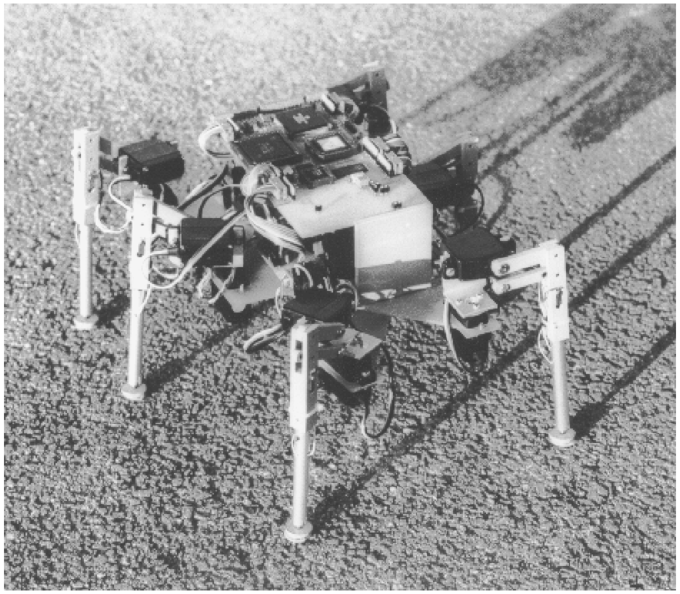
HUMANOID AND LEGGED ROBOTS

High-Resolution Ladar Image: Road Through The Woods


Oblique View to the Right of Road
with False Color Height
12
10
8
6
4
2
0
−2
−4

HUMANOID AND LEGGED ROBOTS

- Within 5 years:
  - Manipulation: load, aim, and shoot a rifle; unlock a door with a key; collect environmental samples; disable explosives; cut the pant leg of a wounded soldier and apply appropriate pressure to a wound
  - Perception and cognition: locate and map suitable foot placement
  - Dynamics: compute posture and balance
  - Legs: carry loads of practical size and weight over uneven terrain

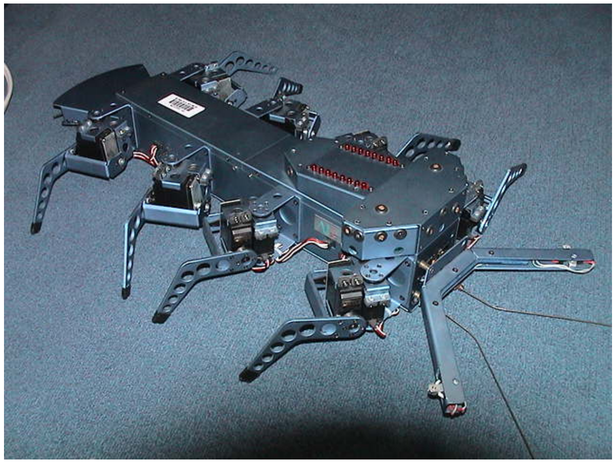


HUMANOID AND LEGGED ROBOTS

- Within 10 years:
  - Manipulation: pick up and carry a wounded soldier to safety; give injections and IVs to the wounded; apply telemedicine intervention; change a tire
  - Perception and cognition: detect, classify, and track moving objects, including humans and vehicles; interact safely with humans
  - Dynamics: run, jump, and crawl; fall safely and get up
  - Legs: operate in an outdoor urban environment with tactical posture and gait

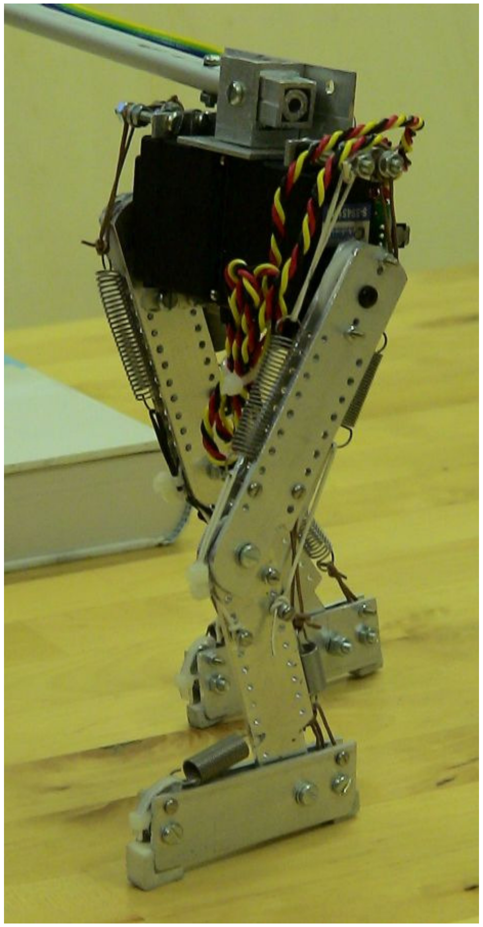
HUMANOID AND LEGGED ROBOTS

- Within 15 years:
  - Manipulation: rescue victims from rubble and wreckage; suture wounds
  - Perception and cognition: analyze many tactical and other situations, solve problems, and devise solutions
  - Dynamics: climb, rappel, and parachute
  - Legs: operate in an indoor environment with stairs and halls filled with rubble, and outdoors in jungle and mountain terrain



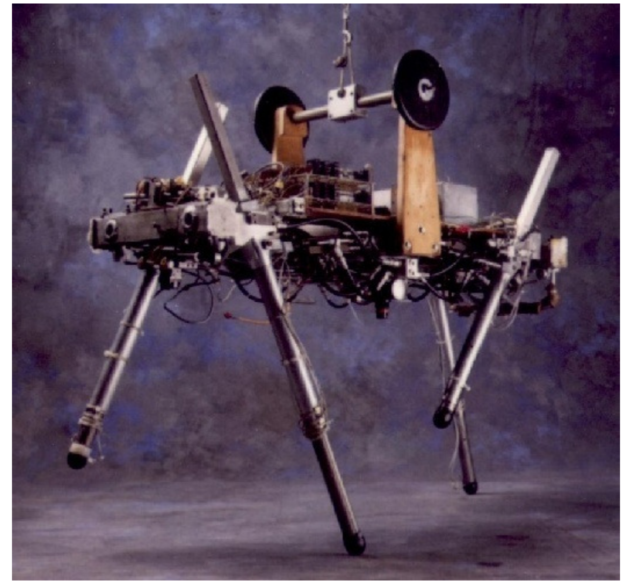
HUMANOID AND LEGGED ROBOTS

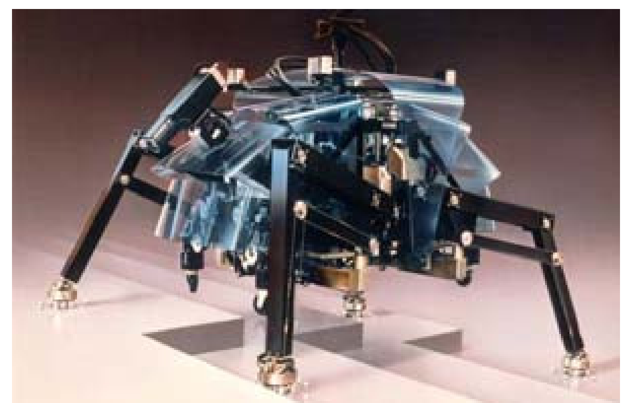
- Example 5-year biped leg motion criteria
- Biped robot weighing no more than 100 kg and standing no more than 2 meters tall can demonstrate ability to:
  1. Run 100 m in 15 seconds
  2. Run 120 m high hurdles in 25 seconds
  3. Run up 3 flights of stairs in 20 seconds
  4. Run down 3 flights of stairs in 15 seconds
  5. Carry load of 100 kg a distance of 10 km in 2 hours
  6. Fall and get back up in 5 seconds
  7. Climb a 10 meter ladder in 30 seconds



HUMANOID AND LEGGED ROBOTS

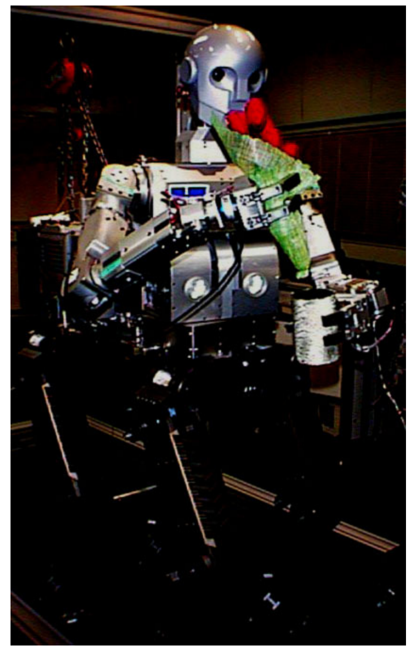
- Example 5-year quadruped or hybrid leg locomotion criteria
- Quadruped or hybrid robot weighing no more than 300 kg and standing no more than 2 meters tall will demonstrate ability to:
  1. Run 100 m in 10 seconds
  2. Run 120 m high hurdles in 20 seconds
  3. Carry load of 300 kg a distance of 10 km in 2 hours
  4. Fall and get back up in 10 seconds

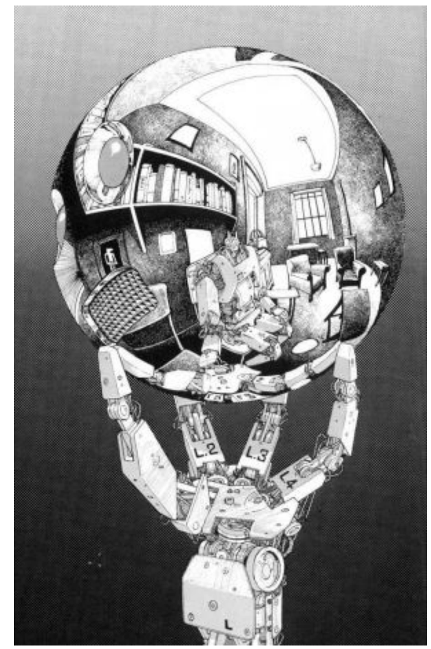




HUMANOID AND LEGGED ROBOTS

- Example hand dexterity decision criteria
- Two arms and a head designed for a biped robot weighing
- no more than 100 kg will demonstrate the ability to:
  1. Disassemble a live mine
  2. Render harmless a live mine
  3. Open a door with a key
  4. Open a wrapped package without disturbing it
  5. Remove a bomb from a garbage dumpster



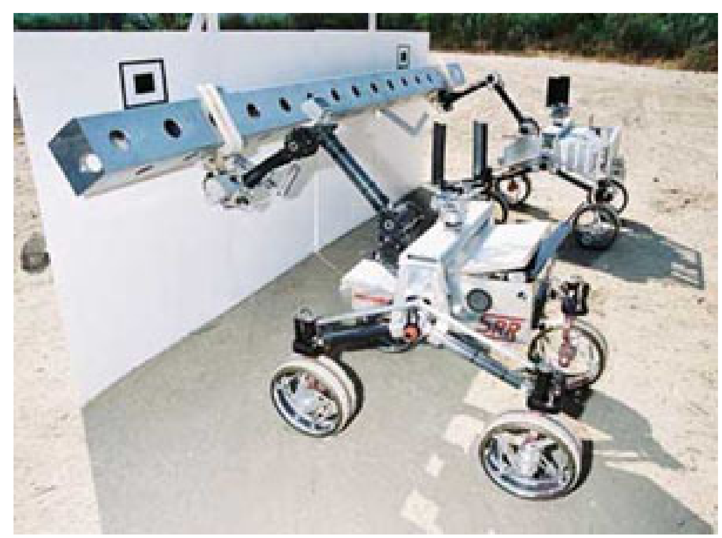


COMMERCIALIZATION OF MILITARY ROBOTICS

- Agriculture robots
  - Spray crops
  - Inspect crops
  - Farm hydroponically
    Plow/plant/harvest
  - Milk cows
  - Pick fruit/vegetables

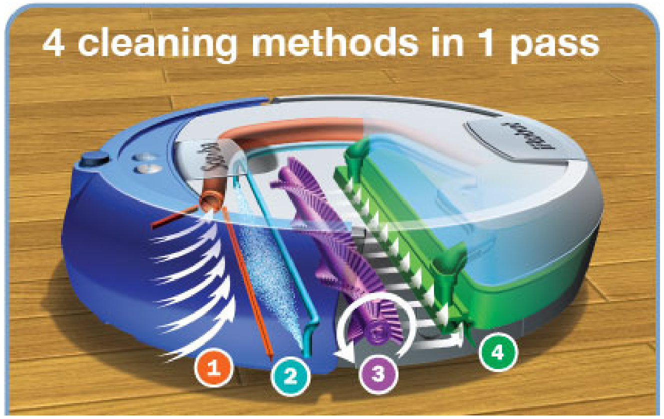
COMMERCIALIZATION OF MILITARY ROBOTICS

- Construction robots
  - Digging
  - Site preparation
  - Pipe laying
  - Crane operations
  - Assembly operations
  - Brick laying
  - Concrete work
  - Building construction
  - Road construction/repair
  - Bridge construction, repair, and maintenance



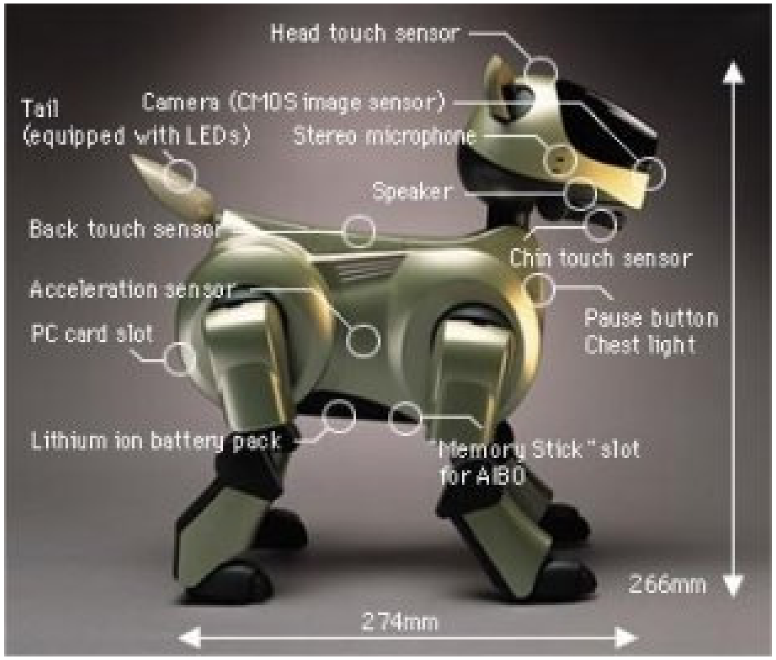
COMMERCIALIZATION OF MILITARY ROBOTICS

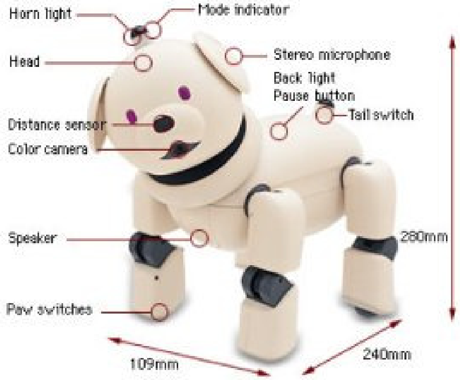
- Household robots
  - Vacuuming
  - Floor cleaning/washing
  - Security
  - Lawn mowing
  - Maid/butler
  - Elder care



COMMERCIALIZATION OF MILITARY ROBOTICS

- Toys and entertainment robots
  - Dolls and pets
  - Movie special effects/stunts
  - Theme parks
  - Robo-wars/fighters
  - Educational
  - Pornographic



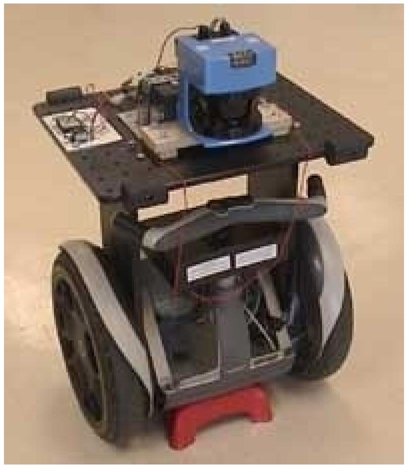


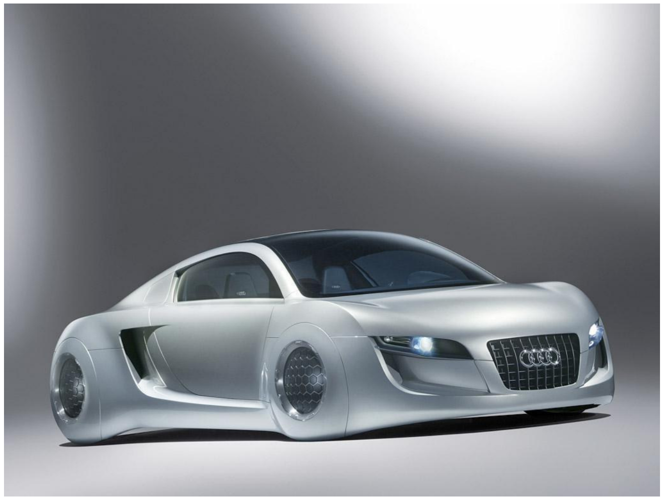
COMMERCIALIZATION OF MILITARY ROBOTICS

- Medical and healthcare robots
  - Medical procedures/surgery
  - Medical logistics
  - Wheelchair
  - Exercise/rehabilitation
  - Nursing care

COMMERCIALIZATION OF MILITARY ROBOTICS

- Transportation robots
  - Cars, trucks, buses
  - Segway-type vehicle
  - Golf carts

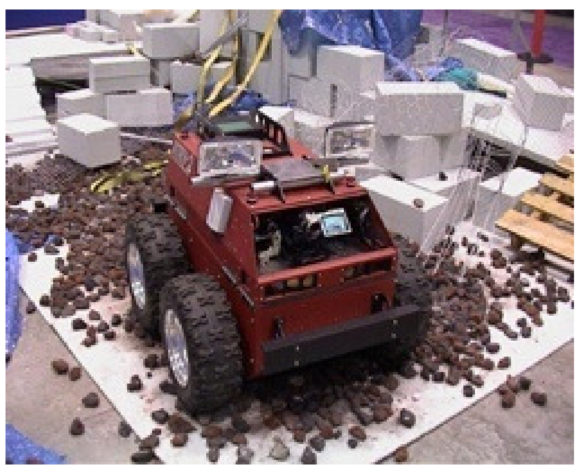




COMMERCIALIZATION OF MILITARY ROBOTICS

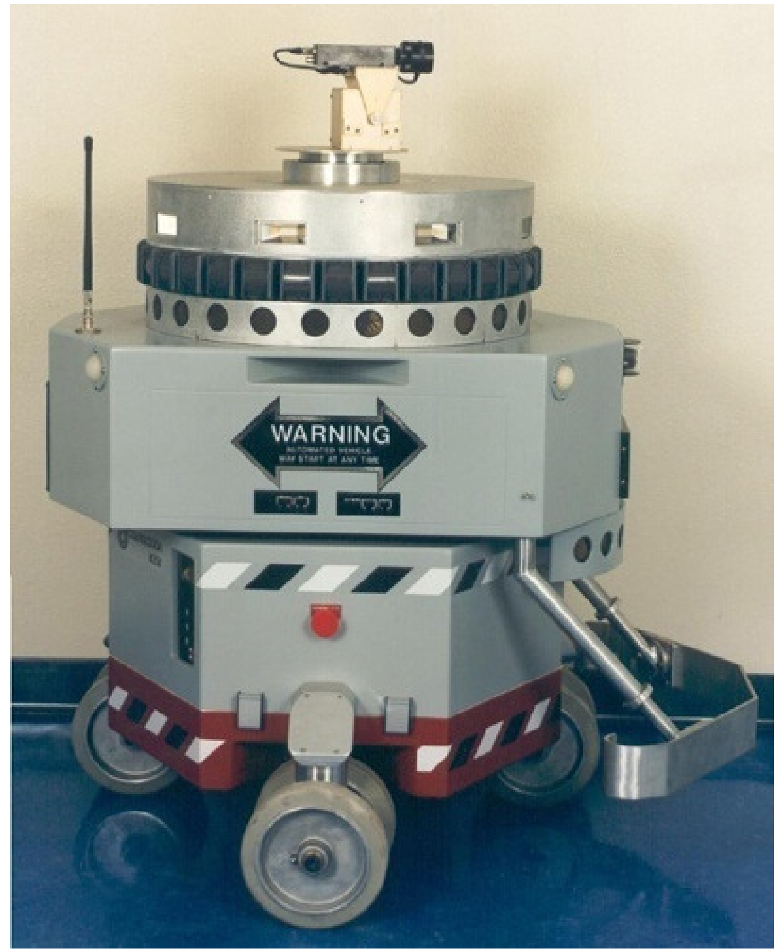
- Industrial service robots
  - Security
  - Fire fighting
  - Search & rescue
  - Pumping case
  - Maintenance and cleaning

Urban Search & Rescue



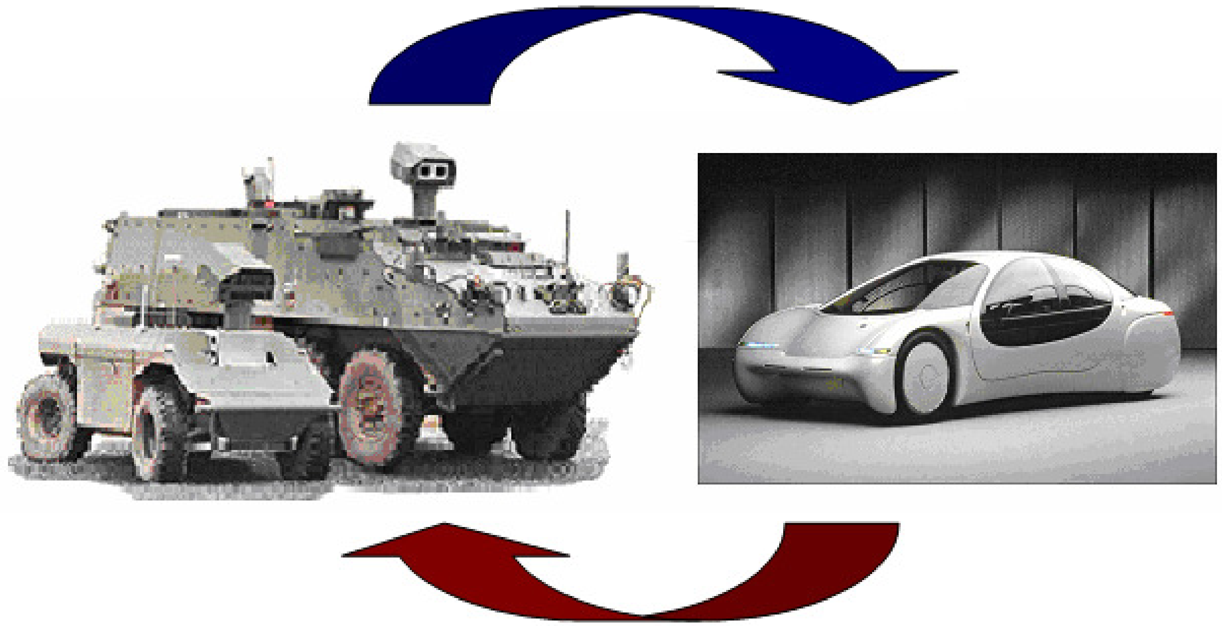
COMMERCIALIZATION OF MILITARY ROBOTICS

- Office and facility robots
  - Security
  - Window cleaning
  - Mail sorting/delivery
  - Maintenance/cleaning
  - Receptionist



COMMERCIALIZATION OF MILITARY ROBOTICS

- Cars, trucks, buses
  - Autonomous civilian vehicles will be a major area of commercialization
  - The process has begun

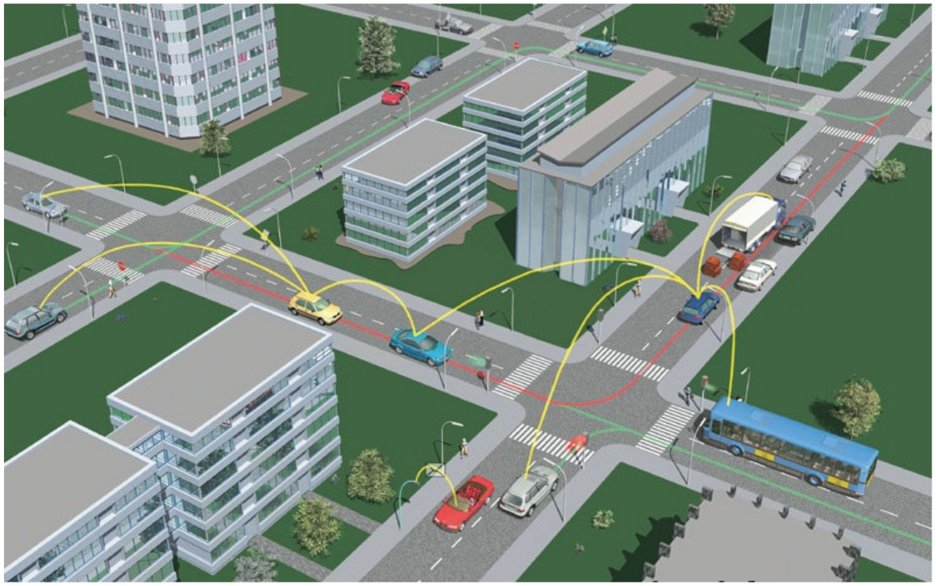


COMMERCIALIZATION OF MILITARY ROBOTICS

- Department of Defense (DOD) and Department of Transportation (DOT) both supporting development of intelligent vehicles
- DOD deploying a variety of autonomous intelligent vehicles (robots)
  - To reduce human casualties on the battlefield
  - Increase the global combat efficiency and effectiveness of the U.S. military against conventional and unconventional forces
- DOT supports intelligent vehicle technology
  - To reduce human casualties on the nation's highways
  - Increase the efficiency and effectiveness of the U.S. transportation system

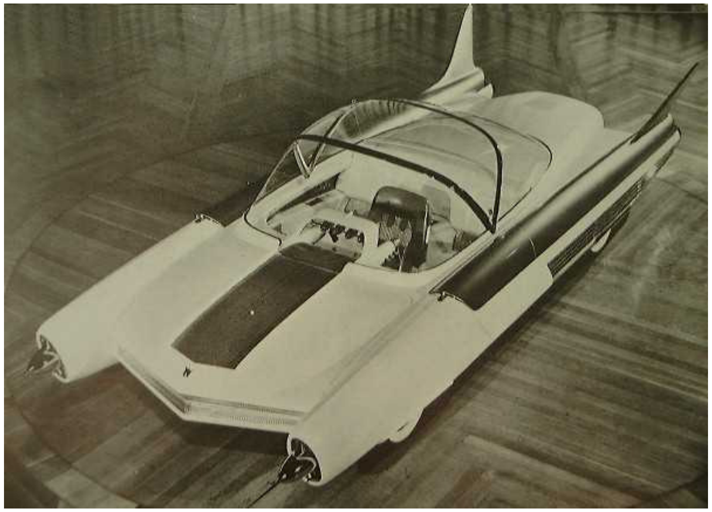
COMMERCIALIZATION OF MILITARY ROBOTICS

- DOD's rapid progress in intelligent vehicle technology can directly benefit the commercial development of intelligent cars, trucks, and buses
  - Reduce time and expense for the automotive industry
- Technology transferred from DOT and commercial sector to DOD and DOD contractors will reduce the cost and increase the availability of commercial-off-the-shelf (COTS) intelligent vehicle systems and components for military services



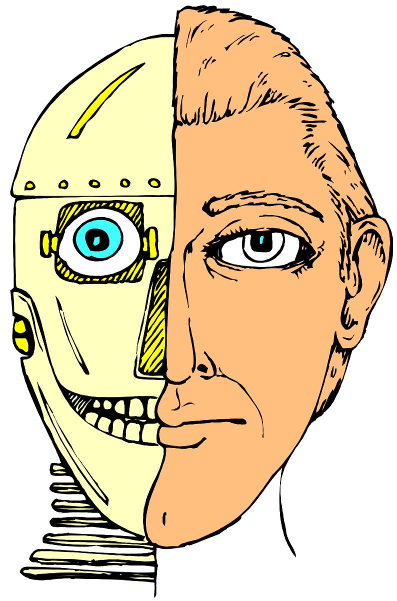
COMMERCIALIZATION OF MILITARY ROBOTICS

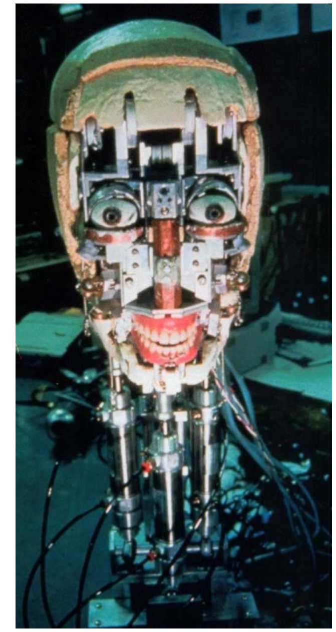
- Benefit of **mutual technology transfer**, between the military and commercial sectors, exemplified by computer technology
  - Expensive military computer technology became **faster, better, cheaper** – and **ubiquitous** – after **commercialization**
- A **formal process** for **sharing and leveraging** intelligent vehicle technology between **DOD** (and its stakeholders) and **DOT** (and its stakeholders)
  - Will facilitate advent of intelligent vehicles
- Intelligent Vehicle Technology:
  - Quickly emerging disruptive technology offering enormous potential benefits for the military and civil sectors alike

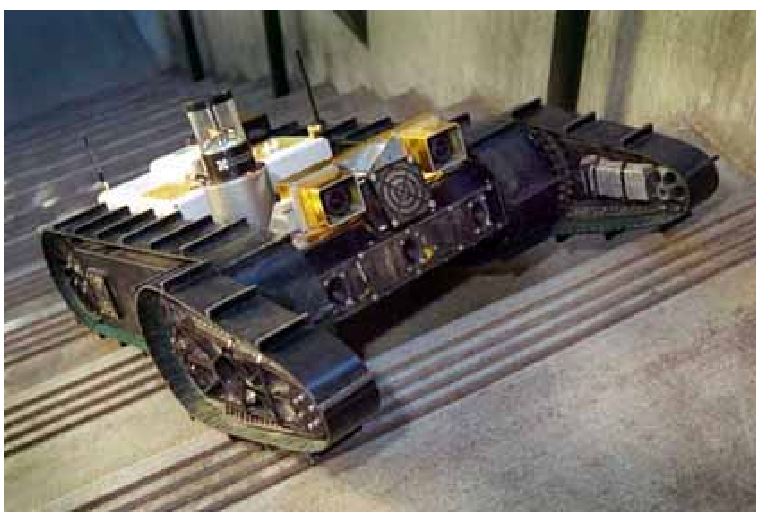


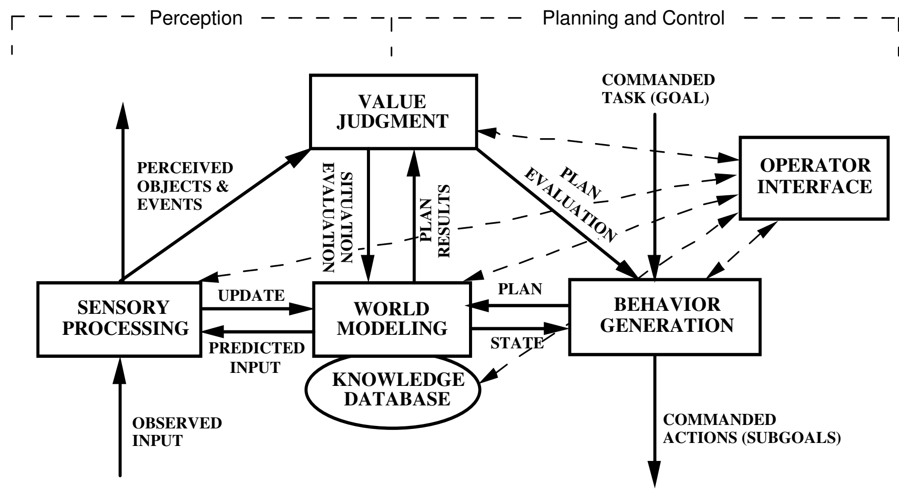
DOD INTELLIGENT VEHICLE TECHNOLOGIES

- **Advanced intelligent vehicle technology which DOD can transfer to DOT includes:**
  - **Control Systems**
  - **Sensor Systems**
  - **Mobility Systems**
  - **Interface Systems**



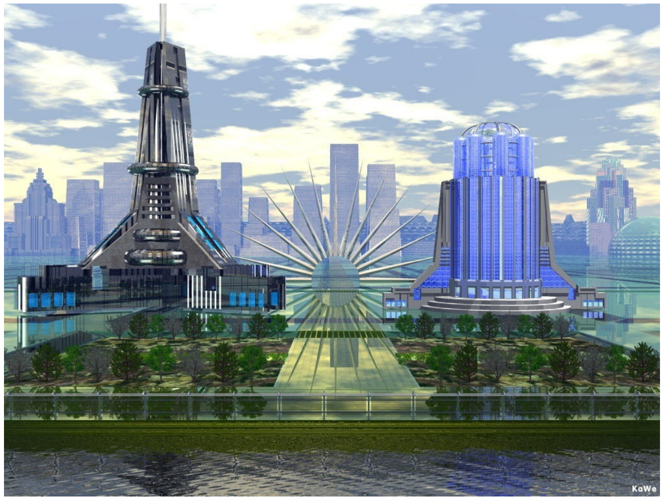


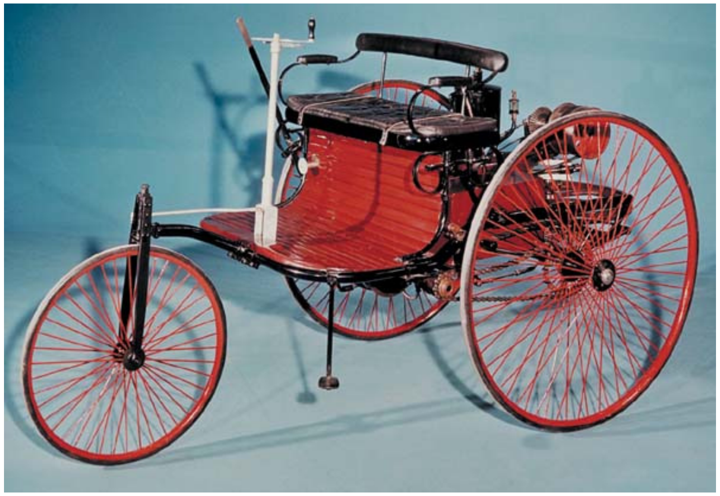




DOT VISION FOR INTELLIGENT VEHICLES

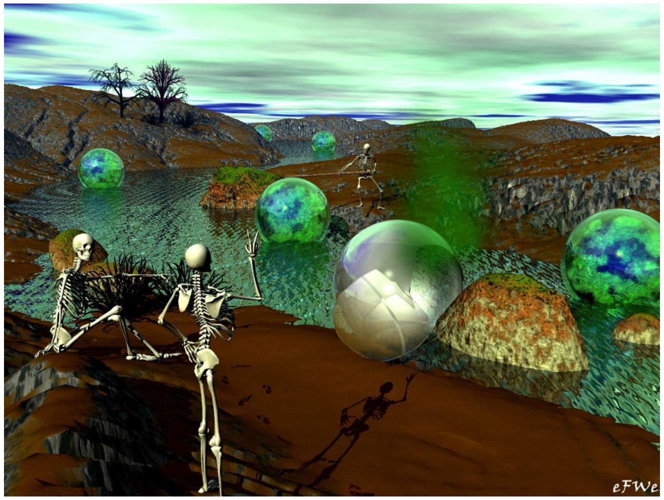
- **A system involving roads, vehicles, and drivers, where drivers:**
  - **Operate in a significantly safer environment**
  - **Enjoy greater mobility and efficiency as a result of vehicle-based autonomous and infrastructure-cooperative *driving assistance* features**





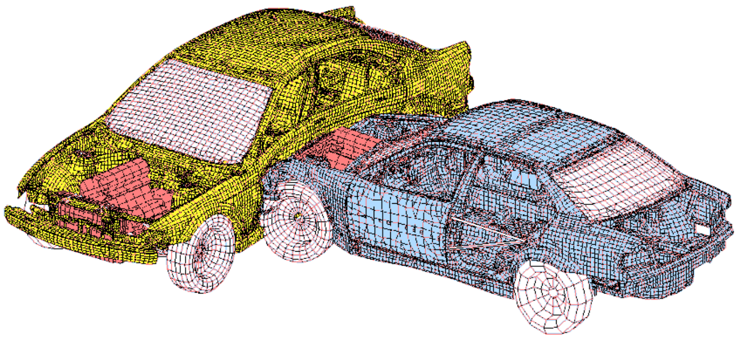
DOT MOTIVATION

- Can significantly reduce motor vehicle crashes
- Each year more than 41,000 Americans die as a result of about 6 million crashes
  - Equivalent of 115 each day, or one every 13 minutes
- Impact of highway injuries is horrendous
  - More than 3.2 million Americans per year, with crash survivors often sustaining multiple injuries and requiring long hospitalizations
- Crashes cost the U.S. economy more than $230 billion a year
  - Consume a greater share of national health care costs than any other cause of illness or injury
- New technology offers potential safety solutions but poses new problems
  - Some in-vehicle technology may become a dangerous distraction to drivers



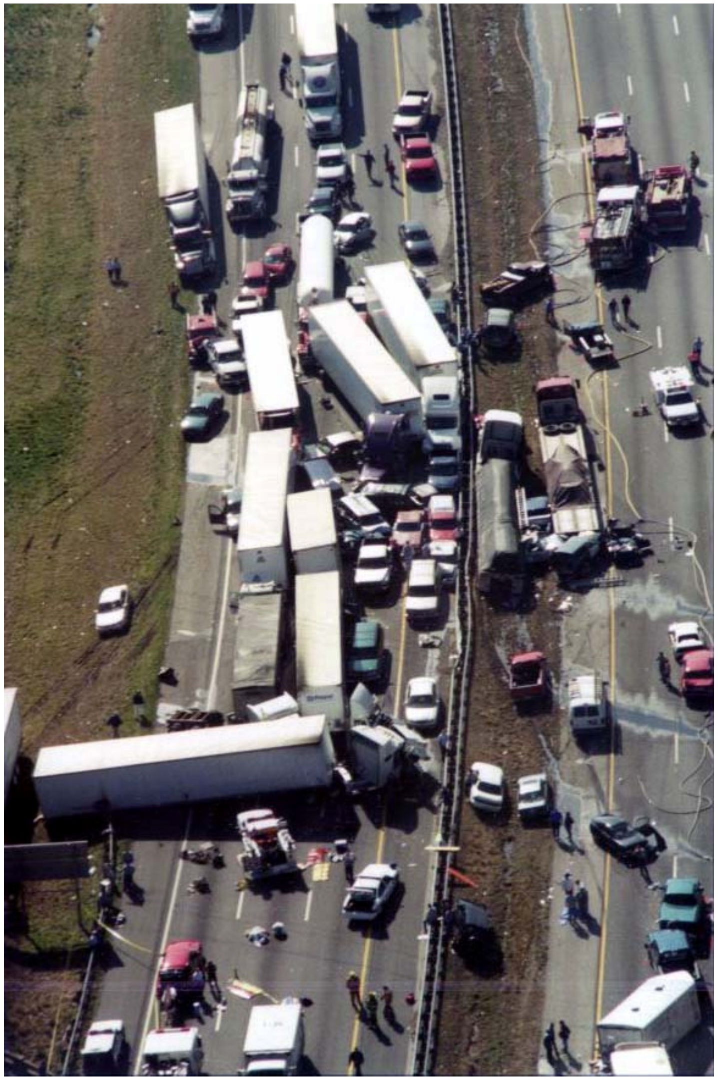
DOT MOTIVATION

- NHTSA estimates that driver inattention, from all sources, causes **20 to 30 percent** of the **6.3 million accidents** per year
- Driver error remains the leading cause of crashes
  - Cited in more than 90 percent of police crash reports
- Intelligent vehicle mission is to reduce the number and severity of crashes through driver assistance systems
  - Assume *partial control* of vehicles to avoid collisions
- Focus on *preventing* crashes, by helping drivers avoid hazardous mistakes, is a significant new direction for DOT safety programs
  - Previously primary focus was on crash *mitigation* (i.e., alleviating the severity of crash-related injury to persons and property)



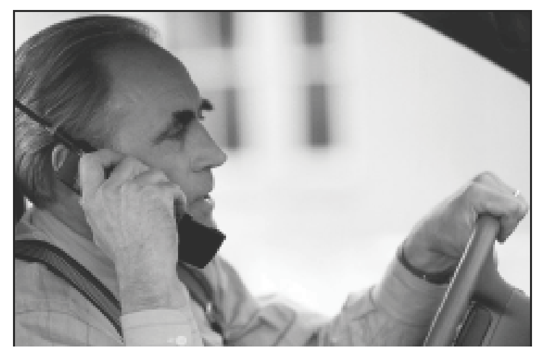
DOT VISION: DRIVER ASSISTANCE

- Current DOT intelligent vehicle vision does not encompass fully-autonomous vehicles
  - Driver assistance systems only
- Driver assistance systems warn drivers of danger or, in more advanced versions, intervene to prevent or mitigate accidents (e.g., intermittent automated braking or steering)
  - Can save many lives
- But the technology transfer between DOD and DOT should include consideration of the technical, economical, and social issues concerning ultimate autonomy for cars, trucks, and buses
  - As the military intends for combat vehicles



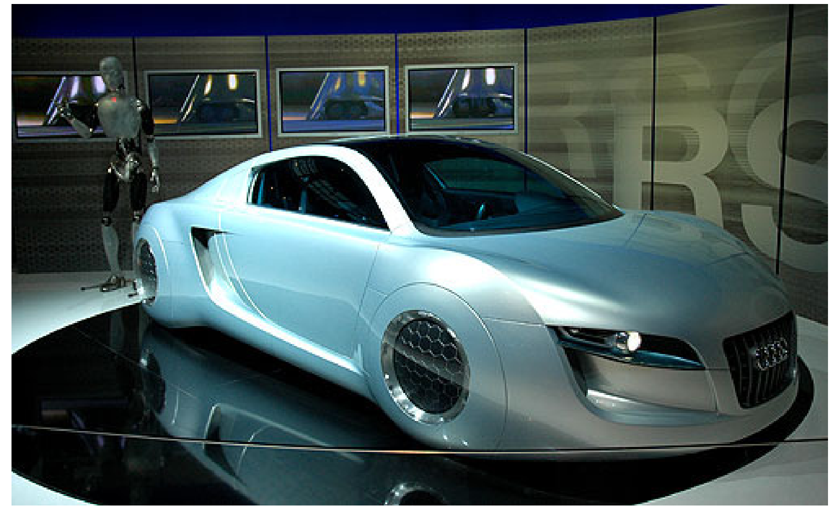
AN AUTONOMY SCENARIO

- Commuter enters car at home
  - Tells it where he wants to go
  - It takes him to his destination (while he reads, talks on the phone, works on the computer, sleeps, or watches videos)
  - Parks itself after dropping him off
  - After work (or a night out), commuter summons vehicle with phone
- “Built-in chauffeur” will be safer and more efficient than a human driver
- Will benefit millions of baby boomers who are becoming elderly and will lose driving privileges
- Handicapped of all ages will gain the freedom to travel in their own cars without the debilitating dependence on others



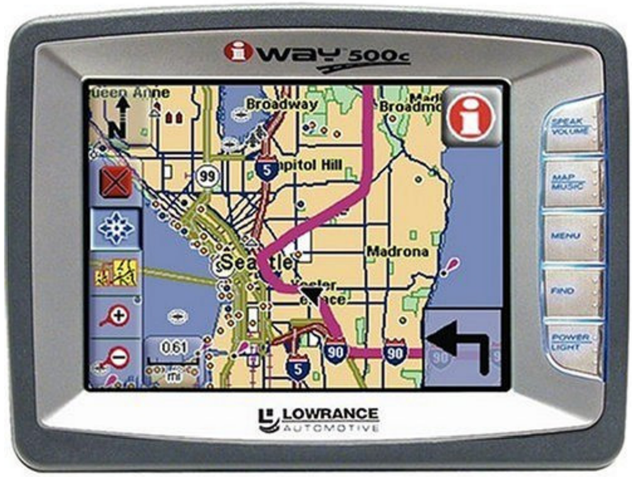
ITS PROGRESS

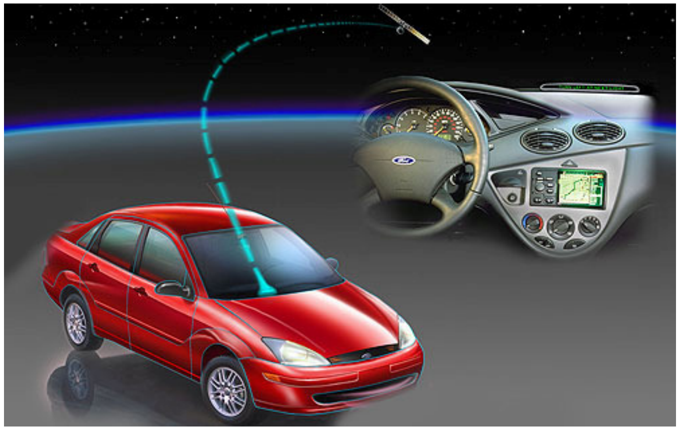
- Since the 1990 initiation of the DOT's Intelligent Transportation System (ITS) Program
  - Remarkable progress in commercializing advanced technology in vehicles and transportation system
  - Some of the technology, like the Global Positioning System (GPS) and infrared sensors, originated with the DOD
- Much current and near-term commercially-feasible intelligent vehicle technology did not exist at the start of ITS in 1990



EXAMPLE ITS COMMERCIALIZED TECHNOLOGY

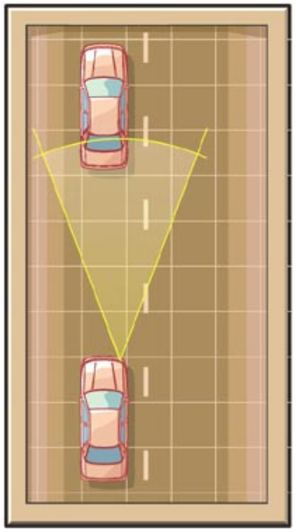
- GPS Navigation
  - Lost drivers are unsafe drivers
  - Automated crash notification ("Mayday") system senses airbag deployment, knows GPS location, and calls for help via satellite phone link
  - Real-time information on traffic conditions displayed on navigation map
- Fleet management system
  - Trucks, buses, taxis, police and emergency vehicles, hazardous waste transporters, etc. tracked and routed by control center
- Adaptive cruise control
  - Maintains vehicle speed consistent with selected safe distance from vehicle in front
- Crash warning and automated crash avoidance
  - Senses objects and may automatically respond with brake and steering
- Back-up object detection
  - Avoids backing into bicycle or cat; helps with parallel parking

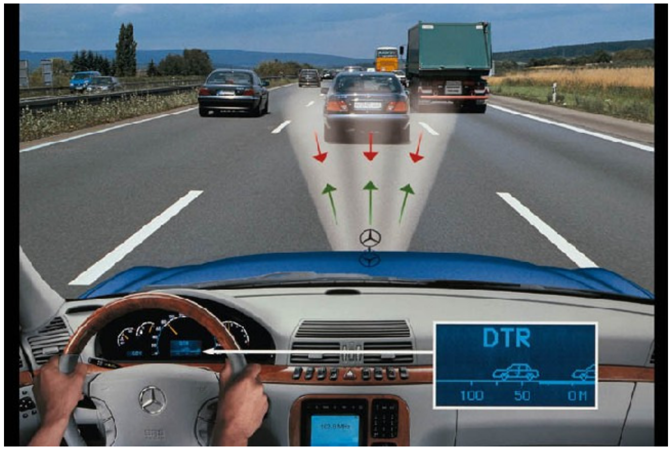


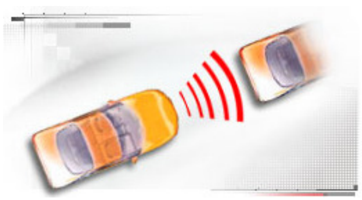


EXAMPLE ITS COMMERCIALIZED TECHNOLOGY

- Lane change warning
  - Senses oncoming vehicles in adjacent lane
- Automated lane tracking
  - Senses lane markers and may have automated steering
- Driver distraction and drowsiness detection and mitigation
  - Senses driver's eyes, head position, or steering
- Head-up displays
  - Projections onto windshield
- Road-departure crash warning
  - Senses movement across lane markers or vehicle movement
- Rollover prevention
  - Senses vehicle stability and attitude
- Haptic driver warning cues
  - Provides touch feedback to driver of danger signals

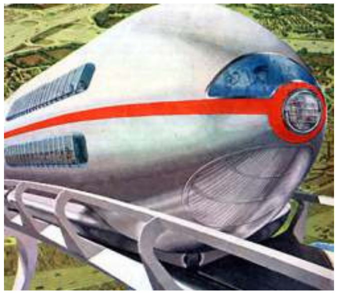


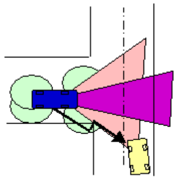




EXAMPLE ITS COMMERCIALIZED TECHNOLOGY

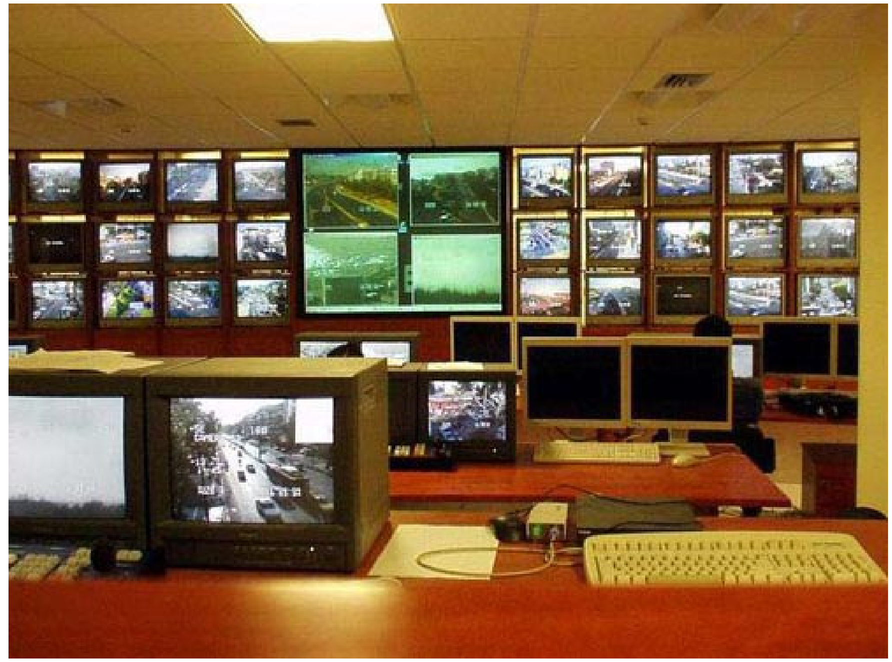
- **Automated bus systems**
  - Semi-autonomous or autonomous buses on fixed bus lanes
- **Intersection collision countermeasures (vehicles and pedestrians)**
  - Senses and communicates among infrastructure/vehicles at intersections
- **Night vision**
  - Sensing to allow drivers or vehicle to detect objects at night
- **Travel and service information**
  - Available or transmitted to numerous sources (on buses and trains, home television, radio, Internet, public kiosks)
- **Electronic weighing and inspection**
  - Senses commercial vehicles in motion, enables electronic issuing and monitoring of permits, or tracking containers throughout multi-modal shipment





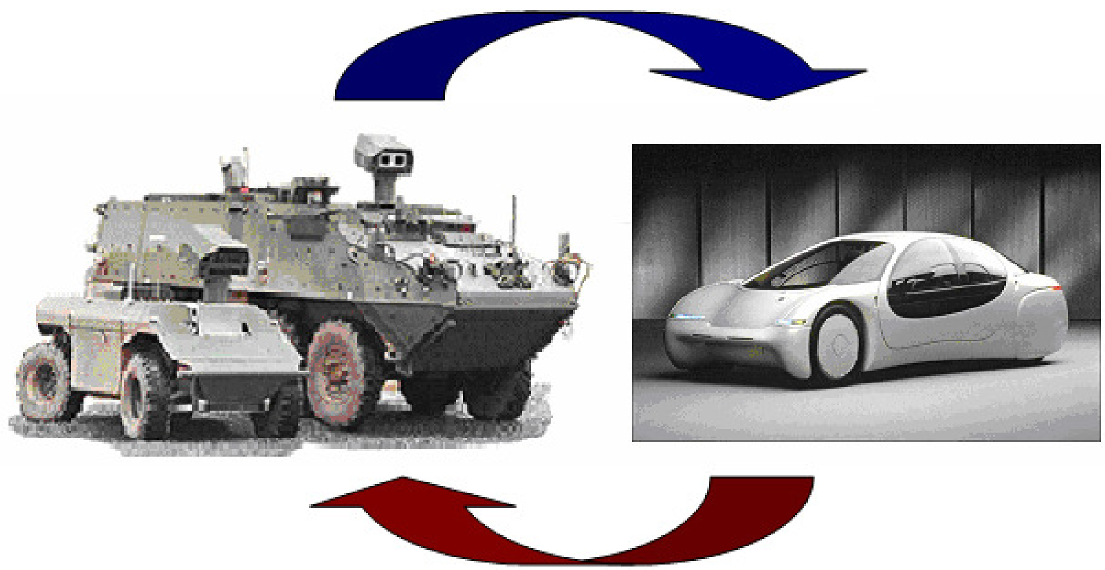
EXAMPLE ITS COMMERCIALIZED TECHNOLOGY

- Traffic management systems
  - Monitor current conditions and adjust lane usage, speed limits, traffic signals, and roadway ramp access based on actual traffic conditions rather than historical patterns
- Public transit enhancements
  - Smart cards, real-time displays of service status, and systems for dynamic ride sharing
- Toll collection
  - Automatic, electronic collection of tolls, transit fares, and other transportation user fees



INTELLIGENT VEHICLE TECHNOLOGY TRANSFER (IVTT) PROCESS

Sponsored By: DOD Space and Naval Warfare Systems Command
Supported By: Office of the Secretary of Defense, Director of Defense Research & Engineering (Office of Technology); DOT Intelligent Transportation System Joint Program Office; Department of Commerce, National Institute of Standards & Technology (Intelligent Systems Division); Army Tank Automotive Research, Development, and Engineering Center

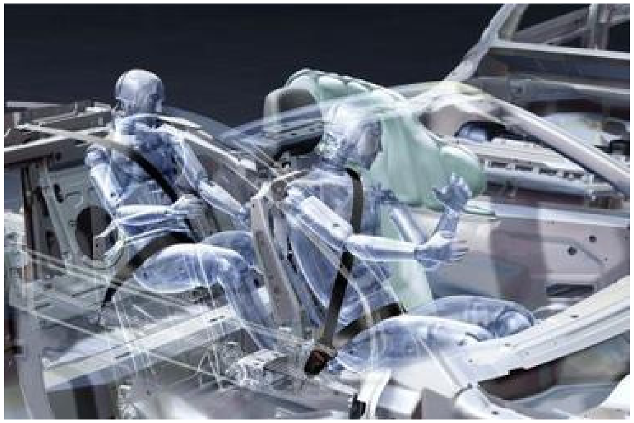


PURPOSE OF THE IVTT

- To save lives
  - On the battlefield
  - On the roads and highways
- To save money
  - On systems and infrastructure
- To ease the emergence of a transformational (disruptive) technology
  - Which will impact military tactics, strategy, and doctrine
  - Which will impact the automotive industry and society in general
  - Which will lead to new systems and enterprise

OBJECTIVE OF THE IVTT

- Establish an intelligent vehicle technology transfer program
  - Among DOD and its stakeholders (government agencies, laboratories, industry, academia)
  - Among DOT and its stakeholders (government agencies, laboratories, industry, academia)
  - Among other agencies (NASA, DOE)
- Solicit ideas and approaches for the technology transfer program
- Determine key issues
- Develop a core constituency of participants

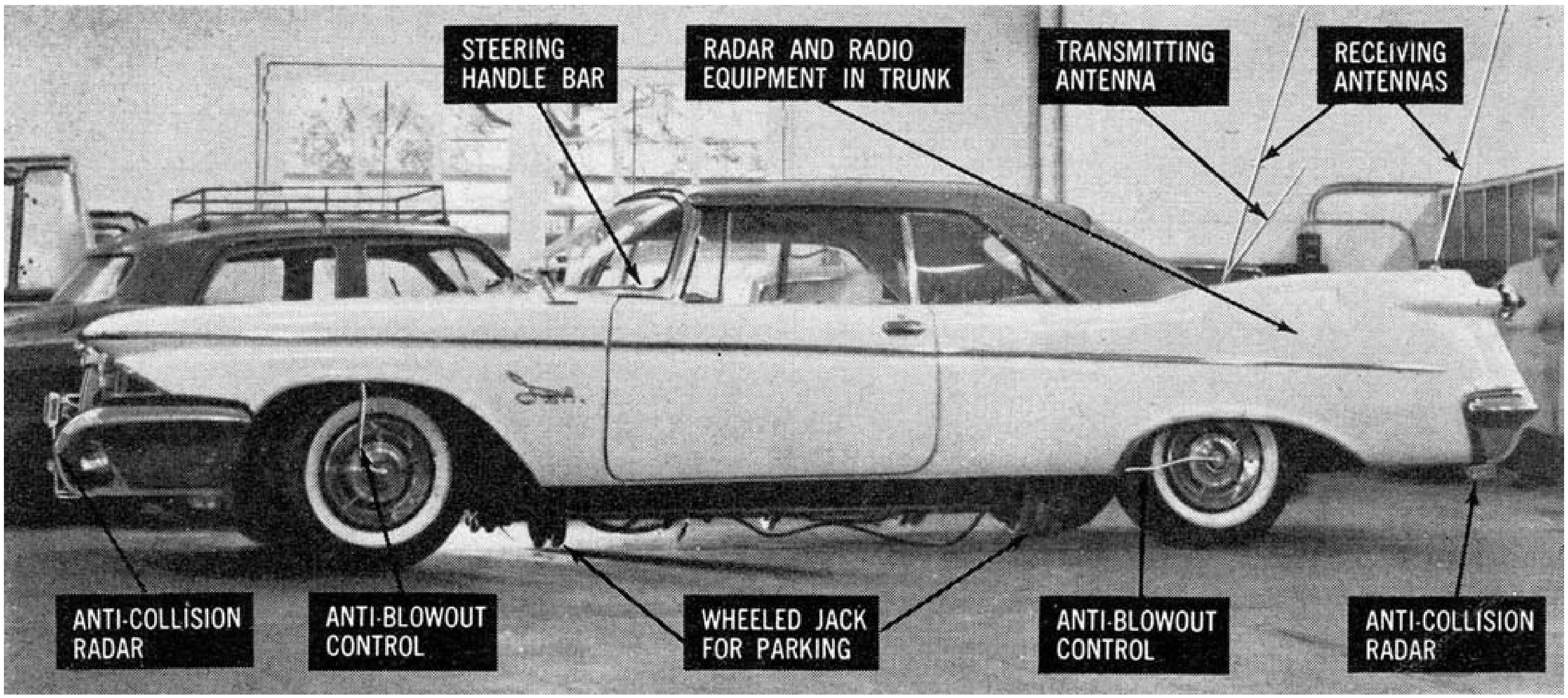


IVTT ROADMAP

- ***"The biggest return on investment will be the accelerated development and deployment of crash-avoidance technology."***
  - **Dr. Jeffrey Runge, Administrator, National Highway Traffic Safety Administration, 18 January 2005**
- **Vehicle safety technology trend**
  - **Immediately preceding the crash (example: crash avoidance by warning the driver of an imminent crash or automatically steering or braking the vehicle and closing windows and sunroof; anti-lock brakes and vehicle stabilization systems (e.g., anti-roll))**
  - **During the crash (example: crash mitigation by deploying airbags and roll-bars, and locking seatbelts)**
  - **Immediately following the crash (example: GPS-based Mayday signal to alert responders of the crash and its location)**

IVTT ROADMAP

Intelligent vehicles are the ultimate crash avoidance technology



In the early 1960's, a Belgian mechanic showed this 1960 Imperial with crash-avoidance radar, tire-pressure monitoring, among other features, including remote-start

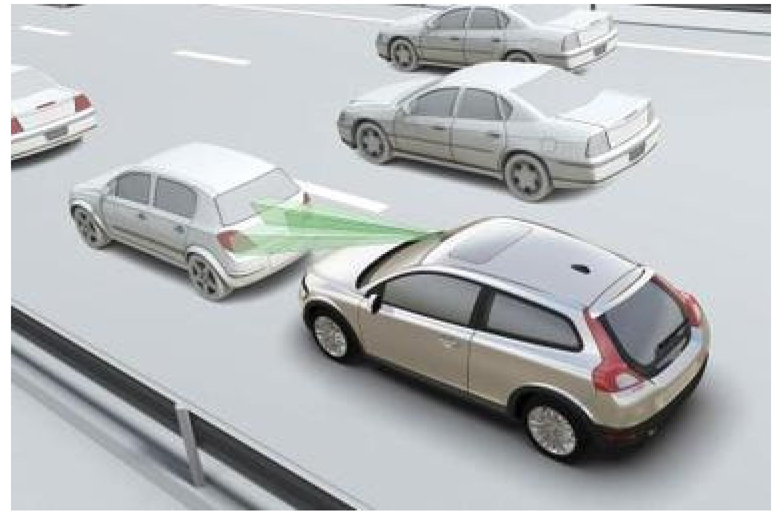
IVTT ROADMAP

- There was an initial effort by the Steering Committee to draft vision and mission statements for the IVTT:
  - Vision Statement: To be the international champion for the transformational technology needed to develop and use intelligent vehicles for military and civil applications
  - Mission Statement: To serve as a central knowledge base for intelligent vehicle technology; to provide forums for the transfer of technology between military and civil developers and users; and to advocate and facilitate the technological and economical feasibility of intelligent vehicles
  - It was the consensus of the committee that the IVTT process be proactive, transparent, and accessible to a spectrum of participants

The Cyclone, a 1959 show car, had a crash avoidance system. Radar-sensing technology provided the driver with information on an object ahead, including distance to the object and stopping distance. When a sensor in the console detected rain, it automatically put up the one-piece bubble top.

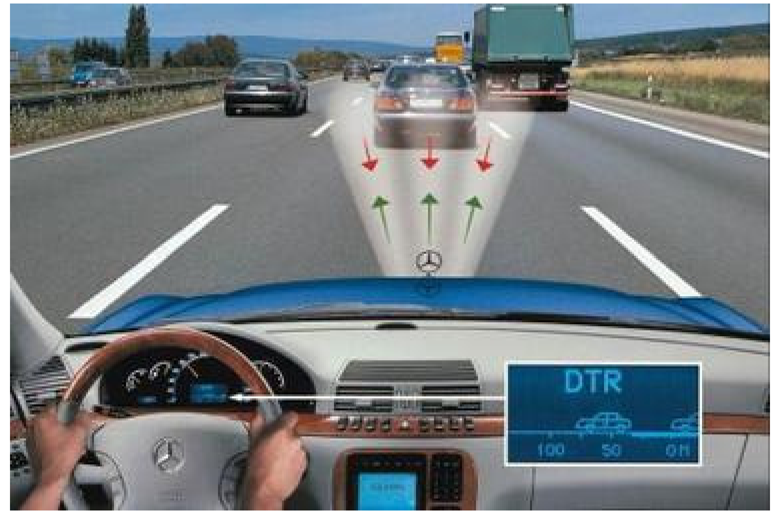
IVTT ROADMAP

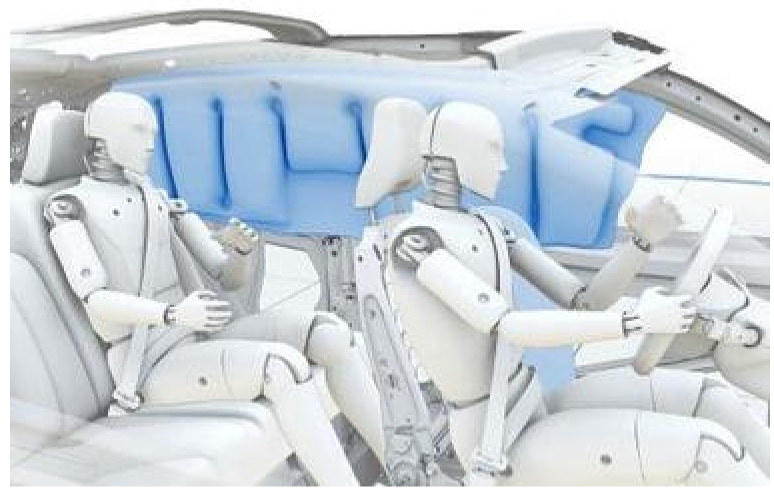
- A key forum and core mechanism for technology transfer and the dissemination of knowledge about intelligent vehicles will be a website to be hosted by SPAWAR
- The committee suggested some of the functions and contents of the website, including:
  - Background (e.g., definitions and descriptions of intelligent vehicles)
  - Vision and mission statements
  - Glossary of terms/acronyms
  - Technology white papers, overviews, and reviews
  - Relevant government programs (information and links)



IVTT ROADMAP

- Website continued:
  - Available technology from developers and vendors (government, academia, and industry)
  - Technology that user needs and wants
  - Technology gap analyses and descriptions of technology push and pull
  - Matchmaking between those having technology and those needing technology
  - Directory (contact information) of vendors, OEMs, R&D labs, and users
  - WWW.IVTT.ORG
    - In early development





IVTT ROADMAP

- Website (continued)
  - Information on standards, testing facilities, and metrics
  - Newsletter (posted and emailed)
  - Journal (digital and perhaps paper)
  - Credit card processing ability
  - Success stories
  - Links to professional societies, tech transfer sites, government agencies, academia, corporations
  - Different levels of access for different categories of members, participants, or website visitors
  - Unrestricted public access (including foreign) to at least portions of the website
  - Membership with fee and no fee
  - Advertising (classified, banner, links)
  - Survey tool for regular feedback from developers, users, and other stakeholders (including the public)
  - Serve as broadcast medium for critical capabilities and technologies
  - Issues to be considered: restrictions due to classified or proprietary information and export controls

IVTT ROADMAP

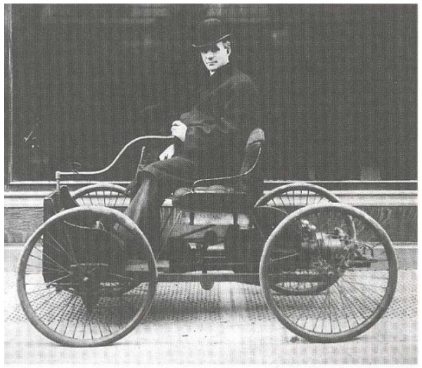
- The Steering Committee discussed establishing functionally-focused Working Groups for key activities and issues for IVTT, including:
  - Programs (government, academia, and industry)
  - Technology (e.g., systems, subsystems, and technology relevant to IVTT)
  - Technology Transfer Forums (e.g., website, publications, conferences and workshops)
  - Interfaces (e.g., with members, government and commercial organizations, professional societies, academia)
  - Public Relations (e.g., press, media, public)
  - Legal Issues (e.g., national security, intellectual property, liability)

1897 Daimler

IVTT ROADMAP

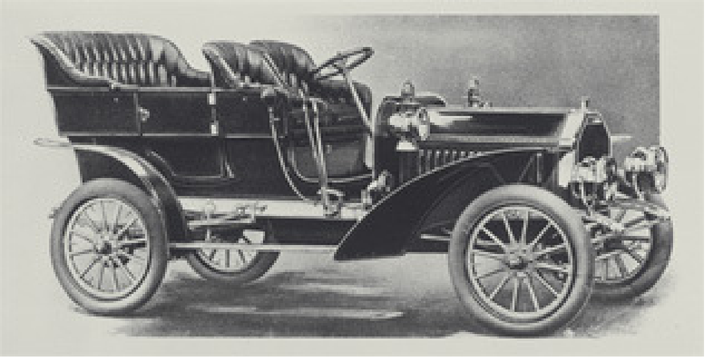
- The Steering Committee agreed to try to hold conferences, workshops, and Steering Committee meetings in conjunction with other relevant professional gatherings (as practical), such as:
  - AUVSI
  - IEEE
  - SAE World Congress
  - TRB (Transportation Research Board)

First Car: 1886 Benz Patent Motor Car (single-cylinder four-stroke engine)



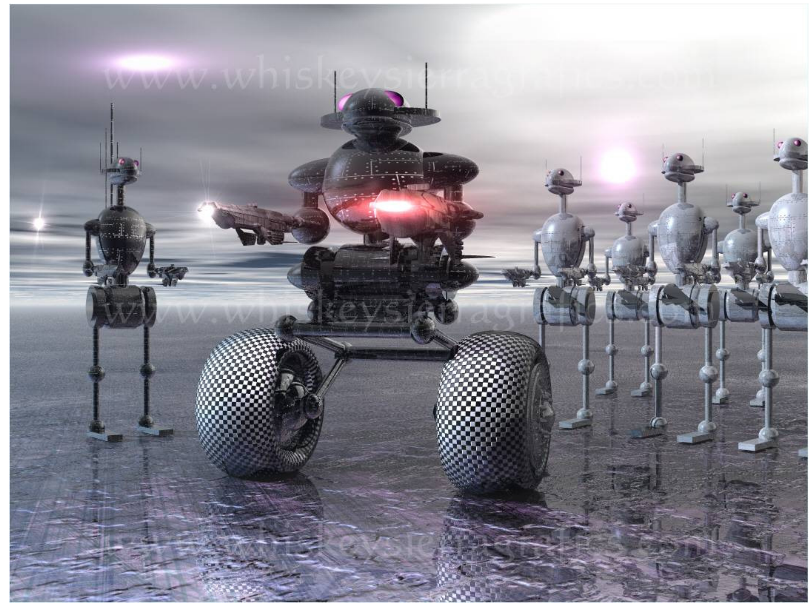
IMPACTS OF INTELLIGENT VEHICLES

- First order impacts: linear extrapolation – faster, better, cheaper
- Second and third order impacts: non-linear, more difficult to forecast
- Analogy: The automobile in 1907
  - Faster, better, cheaper than horse and buggy
  - Then industrial changes: rise of automotive industry, oil industry, road & bridge construction, etc.
  - Then social changes: clothing, rise of suburbs, family structure (teenage drivers, dating), increasing wealth and personal mobility
  - Then geopolitical changes: oil cartels, foreign policy, religious conflict, wars, environmental degradation and global warming



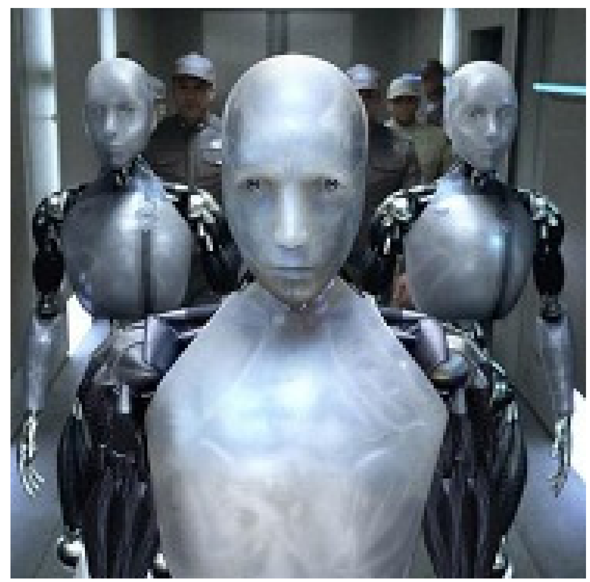
POTENTIAL IMPACTS OF MILITARY ROBOTICS

- **Between now and the end of the 21st century**
  - **Robotics – military and civilian – will become ubiquitous in peace and war**
  - **There will be almost no human combatants on the battlefield**
- **Robots will generate $12 trillion in annual U.S. revenue (2007 dollars) – approximately the U.S. GDP in 2007**



POSTULATED IMPACTS OF MILITARY ROBOTICS

- Between now and the end of the 21st century
  - A code of moral behavior for intelligent robots will be developed
  - Isaac Asimov's Three Laws are insufficient (especially for military)
    - A robot may not injure a human being or, through inaction, allow a human being to come to harm
    - A robot must obey orders given it by human beings except where such orders would conflict with the First Law
    - A robot must protect its own existence as long as such protection does not conflict with the First or Second Law

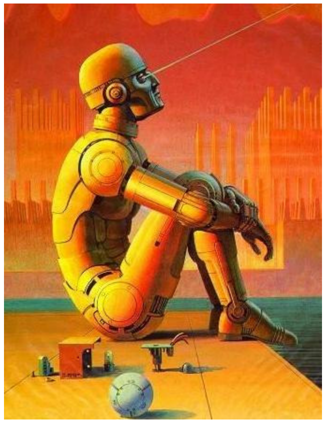


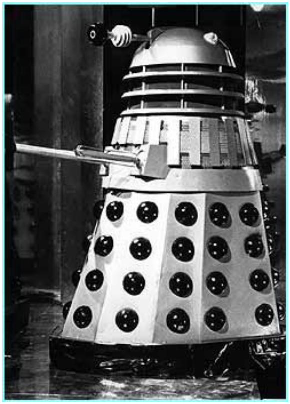
POSTULATED IMPACTS OF MILITARY ROBOTICS

- Tactical
- Strategic
- Doctrine
- Organizational
- Political
- Cultural
- Psycho-social
- Economical



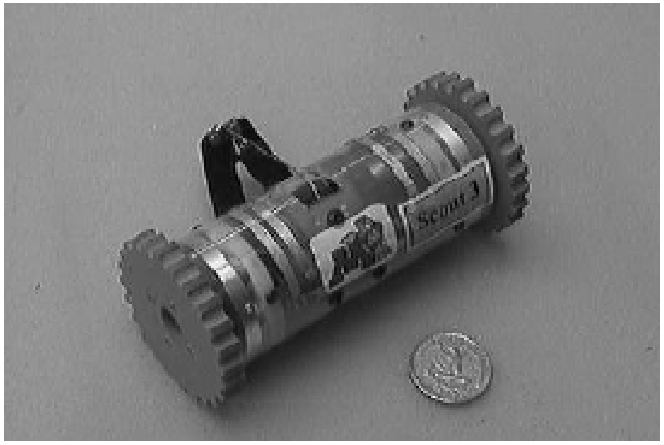






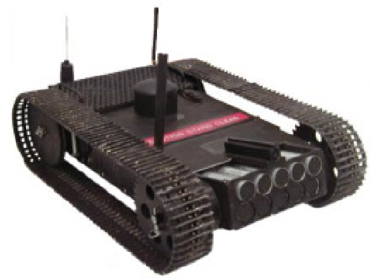
POSTULATED IMPACTS OF MILITARY ROBOTICS

- First order impacts usually linear extrapolation: **faster, better, cheaper**
  - Greater accuracy for RSTA and weapons
  - Greater flexibility for forces
  - Fewer casualties
  - Faster deployment
  - Lower cost systems
- Second and third order impacts usually non-linear, more difficult to forecast
  - Changes in organization, composition, and structure of forces (examples)
    - Smaller
    - More rapidly deployed
    - Mixed forces (air, ground, sea)



POSTULATED IMPACTS OF MILITARY ROBOTICS

- Second order impacts (Cont.)
  - Changes in tactics
    - Highly dynamic, very aggressive, 3-dimensional battlespace
    - Overwhelming collective (like the Borg: "resistance is futile")
    - Offensive defense
    - Non-nuclear deterrent
  - Changes in personnel
    - Fewer people, different skills
    - Training *by* and *of* robots
    - Reduced training time and costs
    - Recruiting changes (e.g., quantity and quality; age and sex; physical ability; terms of enlistment)



Combat Robotics: Postulated Impacts

- Third order impacts
  - More intervention?
  - More humane?
  - More hubris?
  - More peace?
  - More war?