Future Autonomous Systems Overview

Autonomy Working Group

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Autonomous Systems Working Group Charter

- Autonomous systems are here today. How do we envision autonomous systems of the future?

- Our purpose is to explore the 'what ifs' of future autonomous systems'.
  - 10+ years from now what are the emerging applications / autonomous platform of interest?
  - What are common needs/requirements across different autonomous platforms?
  - What advances in materials, devices, sensors, computation and communication technologies, architecture, algorithms, security/trust are required to realize these future autonomous systems?
  - What research/develop to we need to start today to enable this future vision?

- Note: Focus on technology (not policy or ethical/moral issues)

Members

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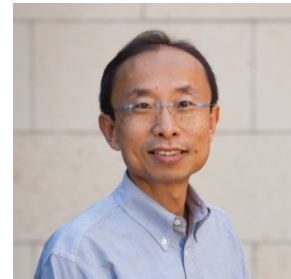Naresh Shanbhag
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Autonomy and Intelligent Systems

- **Description:** Systems that are aware and interact with their environment. DARPA defines intelligent systems as "systems that know what they're doing" and exhibit the following abilities:
  - will be able to infer and reason, using substantial amounts of appropriately represented knowledge
  - will learn from their experiences and improve their performance over time
  - will be capable of explaining themselves and taking naturally expressed direction from humans
  - will be aware of themselves and able to reflect on their own behavior
  - will be able to respond robustly to surprises and explore in a very general way
  - will be able to interact/interface with humans, if in the loop, using the same language as the human nervous system

- **Attributes of Autonomy and Intelligent Systems** include, but not limited to:
  - Energy efficiency (esp. for untethered and energy constrained systems)
  - Decision Making
    - Perception and awareness, Recognition, Learning, Planning, Knowledge representation, Reasoning
  - Speed/Latency
  - Trust
  - Minimum number of sensors
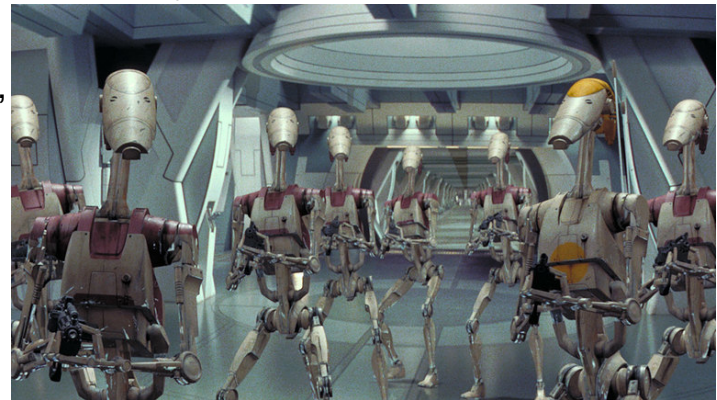
What research is required today to enable future autonomous systems with these characteristics?

Future Autonomous Systems

- Missions
  - Replace humans (in certain tasks)
    - Unattended exploration (e.g., space, undersea, hazardous environment)
    - Unattended monitoring (situational awareness)
  - Assist humans
    - Overcome handicaps
    - Repetitive tasks
    - Requires robust human-machine interface
  - Augment/Enhance human capabilities
    - Requires robust human-machine interface
- Inspiration
  - Biology/nature inspired (biological organisms)
  - Science fiction inspired
    - Example: book called *Lock In:* Humans have robots that interact for them
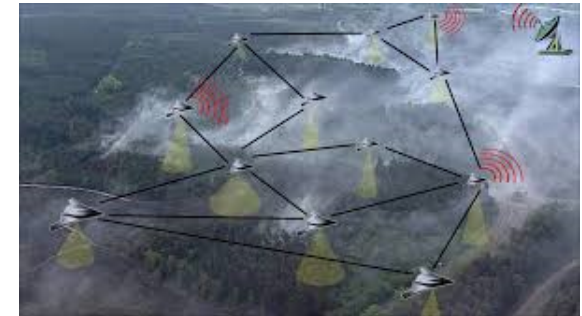
Types of Autonomous Systems

- UXVs
  - Unmanned X Vehicles where X = undersea (UUVs), on sea, on land (driverless cars), in air (UAV), in space
    - Emphasis on mobility in various environments
   - Need for energy efficient locomotion and navigation

- Robots
  - perception, planning and decision making
  - mobile manipulation
  - enhance human capabilities

Autonomous Systems – Swarms

- Swarms: Collection of autonomous systems with distributed communication and control
  - Biological inspiration from ant colonies and bird flocking behaviors
  - Human teams and organizations need good communication and decision making capabilities
  - Advantage of robot teams: efficient convoying and V2V, faster search and rescue operations, wider ISR coverage
- Distributed computing and communications between individual agents and high-level human control
- Robustness: adaptation, learning, and reconfigurability
- How to make whole greater than sum of parts?

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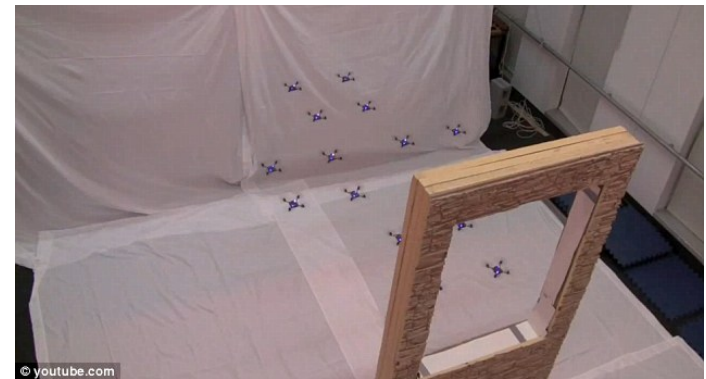
Future Autonomous System 'Desire-ments' (1)

- **Enhanced Situational Awareness**
  - *Intelligent (cognitive), Adaptive (*Reconfigurable) multi-function/multi-mode sensors**
    - In-sensor processors
    - Coordinated use of multiple sensor modalities
  - *Autonomous Operation and Decision making (ability to recognize and react to different and changing scenarios)*
  - Supports operation in cluttered/contested/denied environments

- **Energy efficient communications/networking**
  - Supports collaboration of autonomous systems and human-autonomous systems collaboration

- **Energy Efficient, Intelligent Processors**
  - Scalable, reconfigurable processing (information extraction) architecture
  - Distributed sensor/compute/actuation networks
  - Real-time embedded machine learning
  - 'Cognitive' including advanced neural (and related) computing

Future Autonomous Systems: Energy Efficient, Cost Effective Sensing, Information Extraction and Actuation

Future Autonomous System 'Desire-ments' (2)

- **Seamless, natural Human-Machine Interfaces (HMI)**

- **Security (System, Hardware, Cyber, Processing)**

- **Algorithms**
  - *Advanced Reasoners*:
    - A capability to choose the best algorithms for the mission including low-power learning, reasoning, and decision making.
  - *Adaptive Sensor Resource Management*
    - Algorithms for efficient utilization of multiple sensors and effectors.
  - *Adaptive Mission Management*
    - Capability to plan, task and adapt across systems during mission execution.

- **Lower C-SWAP (Cost, Size, Weight and Power)**
  - *Energy efficient circuits/algorithm/architectures/cognitive processing*
  - Higher levels of integration (functional density)
  - Critical for size and energy constrained platforms

Future Autonomous Systems: Energy Efficient, Cost Effective Sensing, Information Extraction and Actuation

Questions to Consider:

- How to characterize levels of autonomy?
  - Quantify intelligent characteristics and behavior
- How to compare with human performance?
  - Divide responsibility between humans and machines
  - Ability to override and switch control
- What are fundamental limits to autonomy?
  - Energy limits: (decisions/unit of energy)?
  - Tradeoff between functionality and power
  - Robustness versus energy
- What is proper balance between autonomy, safety and security?
  - Is it possible to make guarantees for verification and validation
- How to plan technology roadmap for autonomous systems?
  - Mapping application level requirements with nanotechnology development

Enabling Technologies (Computing)

- Recent Advances in Machine Learning
  - Deep learning and convolutional neural networks
  - Reinforcement learning (AlphaGo)
- Event-Based Computation
  - New sensors and computing paradigms based upon temporal events (spikes).
  - Using time to encode information rather than levels or multiple bits.
- Probabilistic Algorithms and Programming
  - Bayesian inference in hardware
  - Exploiting noise and variability in computation
- Neuromorphic Computing
  - How to use limited precision and analog hardware
  - Mimic SWAP benefits of biological computation in silicon and other computing fabrics
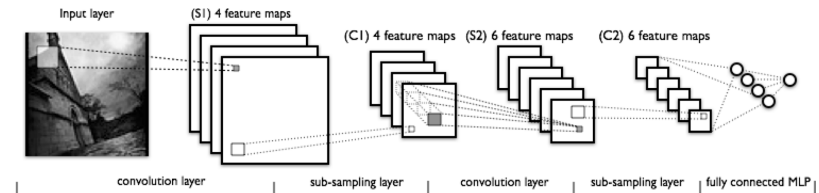
Nanotechnology Foundation

- **Nano-materials and Devices**
  - New materials/devices including topological materials
  - Alternate- and multi-state variables/devices
  - Bio-inspired and soft materials/ electronics

- **Integration**
  - Multi-material stacking
  - Advanced Interconnects/connectivity (Local, semi-global and global: Wired and wireless)
  - Thermal solutions

- **Nanofunctions/Nanofabrics**
  - Need to define basic building blocks to support:
    - Stochastic/Statistical Information processing
    - Real-time neuromorphic processing
    - Reconfigurable Circuits/Sensors
    - New Circuits/systems for augmenting situational awareness
    - New Circuits/systems for enhancing human – machine interface

Need to explore new materials, device and circuit concepts/ architectures that address 'desire-ments' and enable next generation autonomous systems

Backup

Common Requirements

- Energy efficient computing (or information extraction) and communication

- Size and weight

- Safety, Privacy, Security

- Nanotechnology can have tremendous impact on autonomous systems
  - Reduce size, weight, power

Autonomous systems enhancing human capability- examples.

1) Human being walking around and they have systems that help them better navigate an environment.
   - What is needed for autonomous systems to replicate human in above capabilities
   - Seamless integration between robot/PDA and human.
   - Enough autonomy on these systems that they could take over certain situations or run independently

2) Book: Locked In – virus attacks that causes humans to not be able interact. Humans have robots that interact for them..
   - You could imagine this applied to people with real illness that prohibit mobility
   - Sounds more like human-machine interface

3) One of the challenges of bio-inspired computing is that it cannot reach the same accuracy as traditional computing
   - Could machines eventually do human computational tasks? Studies on human intelligence?
   - Recent Alpha Go beating world champ in the game of go. Much more complicated than chess
   - What level of on-board intelligence is required?

4) One can trust a machine to aggregate date. One can not trust a human to take tons of data and aggregate by hand.
   - Need to find the right match between human and machine
   - Balance between human's native ability to process information and the kinds of information humans can process vs. what machines can process

What is being done today (in DoD)?

- ONR LOCUST (Low-Cost UAV Swarming Technology) program uses drones, that can be controlled via a line-of-sight radio link or operate autonomously according to a predetermined path.

- ONR CARACaS (Control Architecture for Robotic Agent Command and Sensing) - a "swarming" system that employs multiple unmanned boats working together to escort ships, patrol harbors or confront adversaries.
  - autonomous swarming capability combines artificial intelligence, machine perception and distributed data

- DARPA CODE (Collaborative Operations in Denied Environment program seeks to make improvements in collaborative autonomy In which multiple UAS can work together under the direction of one operator. One advanced function under collaborative autonomy is the identification and engagement of targets with limited supervision from operators
  - new algorithms and software

- DARPA ALIAS (Aircrew Labor In-Cockpit Automation System) The objective of DARPA's ALIAS program is to develop and insert new levels of automation into existing military and commercial aircraft to enable those aircraft to operate with reduced onboard crew. ALIAS seeks to leverage advances in autonomy that reduce pilot workload, augment mission performance, and improve aircraft safety and reliability

- DARPA UPSIDE and NEOVISION: Beyond CMOS computation platforms. Using statistical computing and brain inspired architectures as a means to leap-frog over the current limitation of von Neumann based, CMOS computation platforms. Gaining comparable performance while operating at 3 orders of magnitude improvement in power efficiency.

More questions to consider:

- What are requirements for next generation nanofunctions/fabrics to support autonomous systems?

- From compute perspective, what are options for advanced computing approaches/architectures
  - Apply computer vision to sensors and sensors systems for autonomous systems, information extraction?
  - Apply neuromorphic computing to autonomous systems? How?

- What are the right models of computation and architectures to map the application level requirements with the opportunities and behaviors of emerging nanotechnology devices

- There are directions that seem like they would not be ideal for autonomous systems, but improved technology could make them ideal

- What hardware/software algorithms are needed to make future autonomous systems?

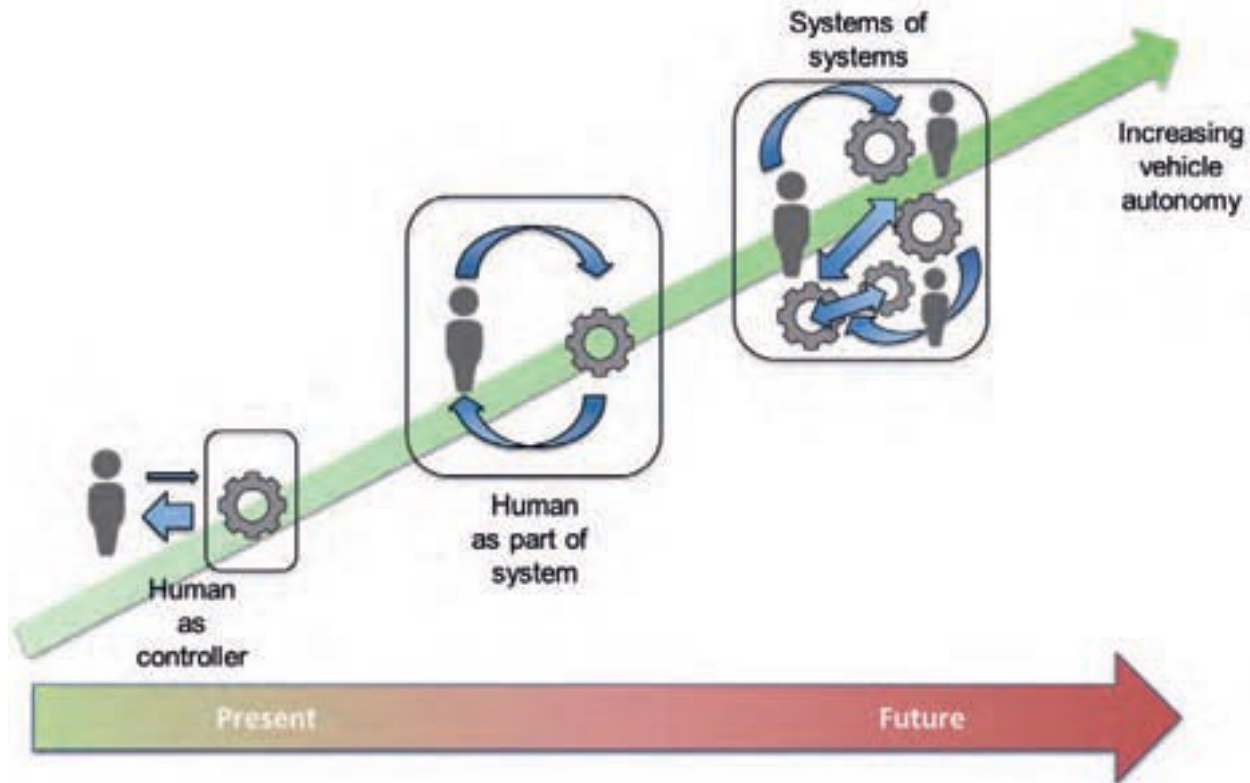# Platform Autonomy: *State-of-the-Art and Future Perspectives from an S&T Point of View*

- Autonomy from an unmanned system point of view describes the capability of a platform to accomplish a pre-defined mission with or without further human interaction and/or super-vision. The degree of autonomy of the unmanned system depends on the vehicles' own abilities of sensing, analyzing, communicating, planning, decision-making, and acting (altogether forming the intelligence of the system), ranging from semi-autonomy to full-auton-omy and autonomous collaboration.

- US National Institute of Standards and Technology (NIST) defines a fully autonomous system as being cap-able of accomplishing its assigned mission, within a de-fined scope, without human intervention while adapt-ing to operational and environmental conditions. Furthermore, it defines a semi-autonomous system as being capable of performing autonomous operations with various levels of human interaction

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Contextual autonomous capability (ALFUS Model)

Environmental Difficulties
- static: terrain, soil
- urban, rural, climate
- operational: threats, decoy

Mission Complexity
- subtasks, decisions
- organization
- performance
- situational awareness
- knowledge requirements

Independence from Human Control
- supervisory control, trust
- experience, skills
- % of decisions/time
- operator to UMS ratio and comm. types

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Evolution of Vehicle Autonomy

Systems of systems

Increasing vehicle autonomy

Human as part of system

Human as controller

Present

Future

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Key Autonomy Issues and Implications for Platform / Vehicle Aspects.

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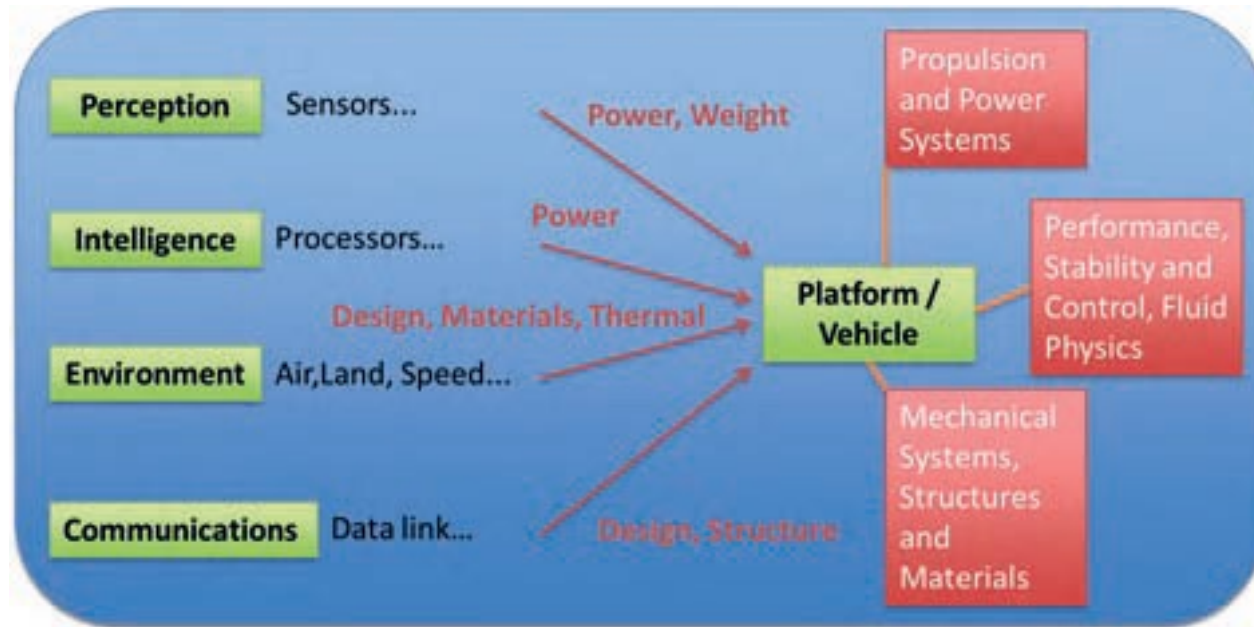
UxV Autonomy – The Future

- In the future, more and more UxV autonomy will be required to increase effectivity and to lower the workload and endangerment of humans.
  - Today, there is a man-machine interaction, wherein the human retains the main parts of command and control. The UxV performs the commanded actions based on automated routines and sends a stream of information back, which is processed at the GCS and supports the derivation of command updates.
  - The next step will be a system wherein human and machine work together as a team. They act together to achieve an objective, of course, still determined by the human part. They share information and the UxV will act more independently while the human retains direction but does less monitoring and control. Technology is gradually shifting in this direction.
  - A second large step into the future would be a -system-of-systems approach, wherein humans and UxV work together as a group performing a joint task. Direction will still remain with the human, but the role will be similar to a commander of a unit. The UxV will act with a high degree of autonomy combined with highly complex communication. As an example, this could be a group of UCAV fighting -together with some conventionally piloted aircraft and supported by ground, air, or space-based ISR assets. The operational future includes autonomous collaboration amongst different systems sharing -required information for mutual situational awareness. This stage implies a large number of issues, which are not all of a technical nature and will not be achieved in the near future. The understanding of the potential of autonomous collaboration is still in its infancy.
- Increasing the autonomy of UxVs requires an increase of on-board capabilities for
  - Situational awareness;
  - Fast decision-making and response to dynamic situations and environments; and
  - Communication (speed, multi party, electronic counter-measures, etc.).
- Technically, this means a demand for <u>highly enhanced on-board sensing and processing capabilities</u> and potentially for <u>larger data link bandwidth to cope with multi party communication</u>. Vehicle -design will have to accommodate more and larger/heavier components and a significantly increased power demand. This will necessarily lead to larger and heavier ve-hicles, where limitations exist for space and airborne vehicles. Also, the requirements for safety, reliability and low vulnerability will likely increase for more auton-omously acting and more complex and costly UxV. This will aggravate the issues with verification and validation as well as certification. A tradeoff will have to be made between benefits from increased vehicle autonomy and competing design, cost and certification implications.
- Progress in the direction of human-machine teams or systems of systems raises additional issues of:
  - Shared situational perception and assessment;
  - Mutual understanding of behaviour (human and machine).
- Inducing problems with modelling/simulation and pre-dictability of such scenarios being totally unresolved today. Fully autonomous systems, completely independent from human directions, are unlikely to be realized in the foreseeable future.

UxV Autonomy - Conclusions

- Unmanned platforms are becoming increasingly more important.
  - Today:
    - UxVs feature a high degree of automation which enables a semi-autonomous operation, while 'intelligence' and de-cision-making is retained by the human operator.
    - Applies to air, space, land and maritime unmanned systems
  - Future:
    - Artificial Intelligence has to be transferred to the unmanned platform to increase the autonomous capabil-ities.
    - A higher degree of autonomy is required for smart decision-making (to avoid potential threats).
    - Additional equipment for sensing, data processing, communications and power generation/power storage is needed for this purpose, with the drawback of increasing the size and mass and complexity of the unmanned platform.
    - Moreover, the stability and control characteristics of the platform need to be precisely predicted to provide the required data for autonomous operations.

Extracted from: https://www.japcc.org/wp-content/uploads/JAPCC_Journal_Edtion-20.pdf

From Intel 'Technology and Computing Requirements for Self-Driving Cars' (2014)

- Reality: current IVI (in-vehicle-infotainment) systems do not offer the requisite processing abilities for autonomous vehicles. *Tomorrow's cars will require a level of computing not currently available in any of today's automobiles*, though already widely used in advanced computers.

- **Sensors, cameras, and more**
  - To enable next-generation ADAS (advanced driver assistance systems) - and ultimately self-driving vehicles - cars will need numerous sensors to gather the necessary information about the driver's constantly changing surroundings and the ability to "fuse" the data (~1gb/sec) from these various sensors in order to make safe decisions.
    - The sensors will be part of a larger constellation of technologies that include light detection and ranging (lidar), radar, advanced camera technologies, and GPS, among others.

Enabling self-driving cars:
The top 5 requirements

- **1. Greater computing power**
  - Approximately 1 GB of data will need to be processed each second in the car's real-time operating system.
  - This data will need to be analyzed quickly enough that the vehicle can react to changes in its surroundings in less than a second.
  - The car's 'brain' will demand new levels of compute to figure out when, how hard, and how fast to brake based on analysis of a range of variables, from the vehicle's speed to the road conditions to surrounding traffic. It will successfully gauge the flow of traffic to merge onto a freeway and account for the unpredictable behavior of pedestrians, bicyclists, and other cars while in the city. And that is just the beginning.
- **2. A reliable supply chain**
- **3. A centralized approach**
  - Currently, new technologies added to the car often come with their own computer and software. Such a situation has spawned a distributed-computing approach that accommodates this growing ecosystem of embedded control units (ECUs).
  - With each new addition, the complexity and cost increase, as do the challenges for the automaker to manage so many disparate systems.
  - As the industry moves toward autonomous vehicles, such a strategy will no longer be supportable and automakers will see many benefits in returning to a more centralized model to enable self-driving cars.
- **4. A small, low-power solution**
  - The processors in tomorrow's cars must deliver increasing computing power, however they also must do so as efficiently as possible → they will have to use semiconductors, which both provide very high processing capabilities and use very little power.
- **5. Security and privacy**

- **Conclusion**
  - For self-driving vehicles, it remains critical that the growing volumes of data transmitted to, from, and within the vehicle are safe.
  - The vehicle will need to rely on its data and the source of that data to make quick, accurate decisions—and to prevent, identify, and isolate malicious threats. This underscores the need to move the automobile's compute architecture from a decentralized approach with numerous discrete technologies to one that relies on a more homogeneous system.

From Intel 'Technology and Computing Requirements for Self-Driving Cars' (2014)

From 'Autonomous Systems' John Hopkins APL Technical Digest, 2005

- Challenges
  - Interaction with open physical world to accomplish complex tasks
  - Unreliable communications links
  - Sensing/Perception (obstacles)
  - Intelligent control (intelligent planning, reactive control, behavior coordination, limited human control)
- Technology Needs/Challenges
  - Intelligent Sensors
  - Real time Machine Learning
  - Human Machine Interface
  - Coordinate peer autonomous systems operation (swarming)
  - Ad hoc sensor/control networking
  - Distributed computing
  - Energy efficiency
  - Alogrithms
  - Need cross domain solution

Gov't perspective

- How autonomous should we be from a government perspective?
  - In department of defense we already have machine than can best humans. Ex. missile systems can best pilot

  - Are autonomous weapon systems allowed to a certain degree?
  - Dan Raddack - working group should focus more on technical capabilities than ethical questions
  - CY – not from an ethical standpoint, but from a technical standpoint is this on the roadmap
  - Dan Radack – Will see what kinds of conclusion may be there after the workshop
  - Dan Lee – focus on the technologies/fundamental research to guide the uses of the applications

Potential Discussion Topics (from CCC Charter)

1. **Application and Platform Requirements**: identify metrics and platform requirements of applications of the future:
   1. What are the emerging applications for this platform and their characteristics?
   2. What should be the target requirements on throughput, energy, latency, reliability, security?
   3. Are there other more meaningful platform/application-specific metrics one could consider?

2. **Alternative Computational Models and Architectures**: identify models of computation and architecture options for the platform:
   1. What are alternative models of computing such as brain-inspired, communication/information (Shannon)-inspired, approximate, probabilistic, and other models?
   2. What are the limits on energy, throughput, robustness, and latency of emerging architectural frameworks including currently deployed ones?
   3. What might be appropriate programming models for emerging architectures?
   4. Articulate challenges in computer-aided design methodology, testability, and verification of complex systems designed using the alternative models.

3. **Beyond CMOS Nanotechnologies** – identify the opportunities and challenges afforded by emerging materials and device technologies to meet the requirements of emerging applications and platforms:
   1. What is the potential for 1D and 2D materials such as carbon nanotube, graphene, MoS_2, $MoTe_2$, black phosphorus in designing alternative computing platforms?
   2. Identify the new memory technologies, their statistical behavior, and limits on storage capacity, energy and latency.
   3. Potential for using spin and ferroelectrics to realize new architectures.
   4. What are the challenges in fine-grain monolithic integration of memory, logic, and other device technologies to achieve true 3D integration?