

White Paper: Robotic Cognition/Sensors versus Mobility Trade-Off

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Frequently the desire for hunting-dog type robotic platforms is mentioned by Army leaders. A dog moves freely over rough terrain with minimal guidance from its master such as illustrated in Figure 1 below. A canine uses its eyes, tactile sensing, and brain to carefully place limbs for mobility. Animals also dually use the same cognitive and sensing capacities for route planning. The seemingly effortless movement of animals is the result of intrinsic mobility COMBINED with route planning. The biological tradespace (constrained by food energy) overwhelmingly shows a preference for preview sensing, cognition, and overlapping mechanism function. Brains burn a huge amount of energy – nearly 20 times more than muscle tissue by mass. Figure 2 gives some impression of how a dog allocates its limited resources. The cerebellum is largely responsible for motor control, but it is highly cross linked with the cortex (planning) as well. Neither operates in isolation.

This paper hypothesizes that achieving a breakthrough off road capability (i.e. hypermobility) for an automotive platform will require the use of sensing and cognition. Purely passive mechanical systems have failed to yield significant improvements in mobility since the 1950s. The cost of sensors and computers purely for extreme mobility will be negated in the future by commercial sector investments for self driving vehicles. Automotive industry projections estimate the cost premium for a fully self-driving car feature will drop from the \$120,000 (Google’s current autonomous vehicle) to \$7000 for a commercial luxury car by 2020^{1,2}. Self driving vehicles already out-perform humans for on-road performance because they can monitor more data more quickly and continuously. Using sensors and computing for mobility, a ground platform should be able to outperform a vehicle with a dismounted spotter. A future Soldier should be able to aim a vehicle at a boulder-laden field and just stomp on the accelerator pedal.



Figure 1. U.S. Air Force Staff Sgt. Brent Olson, a military dog handler and Blek, a military working dog, clear caves during a mission with U.S. Army Soldiers from Charlie Company, 3rd Battalion, 187th Infantry Regiment, 3rd Brigade, 101st Airborne Division, in the Zirat Mountain Area, Waza Kwah District, Paktika province, Afghanistan, July 7.

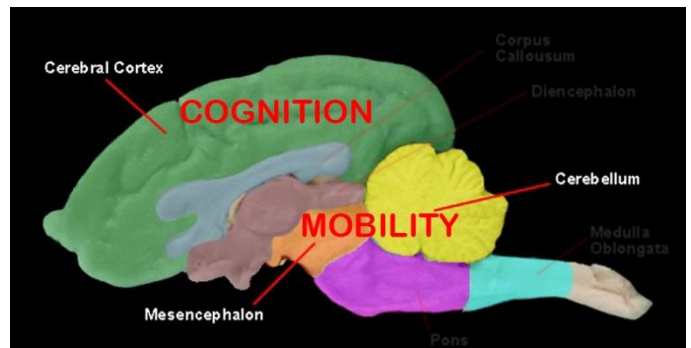


Figure 2. Canine gross brain anatomy. The cerebral cortex handles memory, perception, attention, awareness, language, and consciousness. The cerebellum coordinates voluntary movements such as posture, balance, and coordination, resulting in smooth, balanced muscular activity. Source: Wikiversity³.

¹ IHS Automotive. (2014). *Emerging Technologies: Autonomous Cars—Not If, But When*.

² Anderson, J. M., Kalra, N., Stanley, K. D., Sorensen, P., Samaras, C., & Oluwatola, O. A. (2014). *Autonomous Vehicle Technology: A Guide for Policymaker*. RAND Corporation.

³ *Gross Regions of Central Nervous System*. (n.d.). Retrieved Jul 9, 2014, from http://en.wikiversity.org/wiki/Gross_regions_of_central_nervous_system

Mobility Definitions/ Goals

A simple definition of combat mobility is that it is the ability to move freely and rapidly over the terrain of interest to accomplish varied combat objectives⁴. An updated definition is proposed: maximizing the total set of options, including the derived set of future options, to move freely and rapidly to accomplish varied combat objectives. The new definition is an adaptation of recent work by Wissner-Gross⁵ on the goal of animal intelligence, where it is theorized that intelligence seeks to maximize the number of available option. Wissner-Gross calls this entropic-force animal intelligence, which is pictorially illustrated in Figure 3. An example is that in the game of chess is that it is advantageous to always make moves that keep the most options open for successive future moves, which is a method that has beat many human chess players.

Terrestrial mobility may be further broken into the following taxonomy: Vector mobility is the ability to move in a desired direction over the ground with little deviation from the desired path. Path mobility is ability to reach a desired point by changing the path to move around obstacles usually due to restricted vector mobility in localized terrain. Cooperative mobility is mobility derived from entities collaborating to achieve movement. For example, cooperative mobility may entail robots cooperatively lifting themselves over obstacles, or sharing information to help the collective better use path mobility. Figure 4 illustrates graphically the effect of no-go regions due to a lack of vector mobility over obstacles and its impact on combat mobility. As ground pressure increases, so does the percentage of no-go terrain (terrain over which a combat platform is immobile). The total entropic combat options are the sum of all available options on the battlefield. This may be quantified by representing the terrain by resistances that represent the total operational area, speed over terrain, etc. The total entropy is calculated by summing the inverse of the resistances, including all future positions.

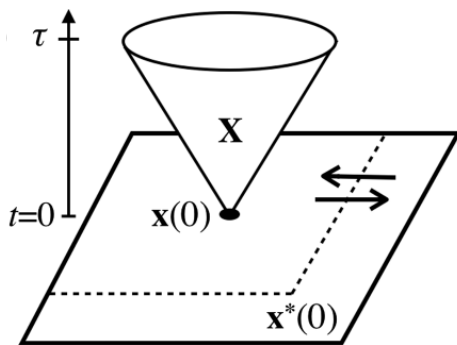


Figure 3. Schematic depiction of entropic combat options. Shown is a macroposition X with horizon time τ , consisting of path microstates $x(t)$ that share a common initial system state $x(0)$ with initial environment state $x^*(0)$.

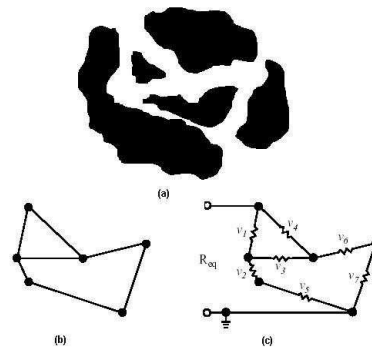


Figure 4. Diagram of battlefield mobility chokepoints as an electrical diagram. The military aspects of terrain is a study of its resistance: both the natural resistance the terrain affords, as well as how well the terrain supports enhancing its natural resistance through the emplacement of weapon systems. Adapted from Glinton⁶.

⁴ Hornback, P. (March-April 1998). The Wheel Versus Track Dilemma. *ARMOR* , 33-34.

⁵ Wissner-Gross, A. D., & Freer, C. E. (2013). Causal entropic forces. *Physical review letters*, 110(16), 168702.

⁶ Glinton, R., Owens, S., Giampapa, J., & Sycara, K. (2004, July). Terrain-Based Information Fusion and Inference. *Proceedings of the Seventh International Conference on Information Fusion* , 338-345.

Active Modality Examples

Active modalities involve some sort of feedback loop and computation. The computation may include using time history data and making future predictions. The sensory input for active systems can come from instantaneous contact sensing or preview sensing which senses upcoming terrain. It may be argued that human-in-the-loop is a form of an active modality.

Figure 5 provides an excellent illustration of the exponential capability enhancement of going to an active system. Figure 5 depicts 2009 testing on an uparmored HMMWV with an active suspension (714 pound weight cost). The figure is exemplary of a number of metrics in the report (reference not provided to protect company proprietary information). Another study⁷ on a standard HMMWV with active and preview suspensions is shown in Figure 6 below. For the nonpreview controllers, more than a twofold increase in ride comfort over passive suspension was obtained. With preview control, the ride comfort was improved threefold. This resulted in an increased drivable speed for rough terrain.

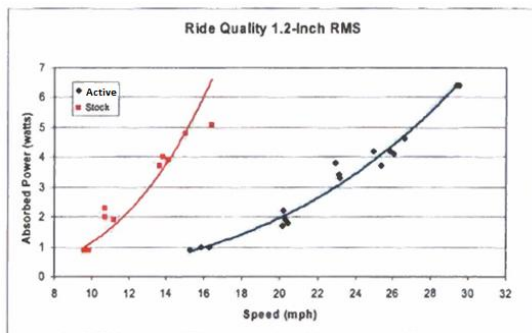


Figure 5. Up-armored HMMWV absorbed power on 1.2-inch RMS. Both vehicles achieved 6 Watts: The stock vehicle achieved this at 16 mph, and the active system achieved it at 29 mph. The testing was done in 2009.

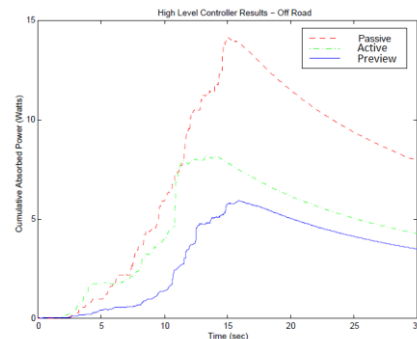


Figure 6. Standard HMMWV absorbed power with preview, active, and passive suspensions (asphalt with six standard, hard rubber speed bumps). Source: Donahue⁷.

Another example of an active mobility modality is powered articulation. TARDEC experimented with cybernetically coupled articulated M113s in 1970 as shown in Figure 7. A single M113 could climb an 18-inch-high obstacle, but the two articulated M113s could climb a 5-foot wall⁸. The goals for the articulated vehicle included: climbing vertical obstacles up to 5 feet tall, crossing open 10-foot-wide trenches, climbing 60-percent slopes; entering, crossing, and exiting waterways. Figure 8 shows that at the commonly used power absorption level of 6 watts in the vertical direction at the drivers' seat, the coupled units could be driven 50 percent faster

⁷ Donahue, M. D., & Hedrick, J. K. (1997). Implementation of an Active Suspension, Preview Controller for Improved Ride Comfort. *Proceedings of the 1997 IEEE International Conference on Control Applications* (pp. 860 - 865). Hartford, CT: IEEE.

⁸ Dasch, J. M., & Gorsich, D. J. (2012). *The TARDEC Story Sixty-Five Years of Innovation*. US Army Research, Development, and Engineering Command.

than the single unit in rigid mode (length effect) and twice as fast in a limited pitch freedom mode (combined length and damping effects)⁹.



Figure 7. 1975 Cybernetically Coupled M113s. Source: Dasch⁸.

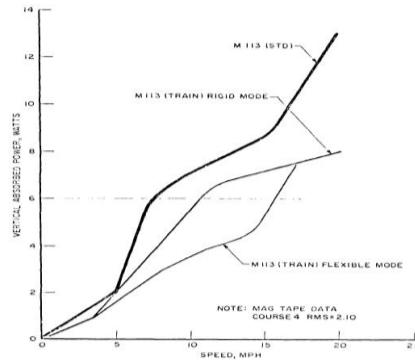


Figure 8. Coupled M113 absorbed power versus speed comparison of an active (flexible mode) and passive (rigid and stock modes) articulated vehicle. Source: Kamm⁹.

Historical Off Road Mobility Innovation

Burstall/Hill are credited for building the first powered vehicle with all driven wheels in 1824 (Figure 9). The first accepted all-mechanical four wheel drive vehicle was built by Spyker in 1903 in Amsterdam (Figure 10). The 1903 Spyker featured permanent four-wheel drive and four-wheel brakes. The first workable tracked vehicle was patented in 1894 by Holt (Figure 11). A mechanical legged platform was patented by Rygg in 1893 (Figure 12).

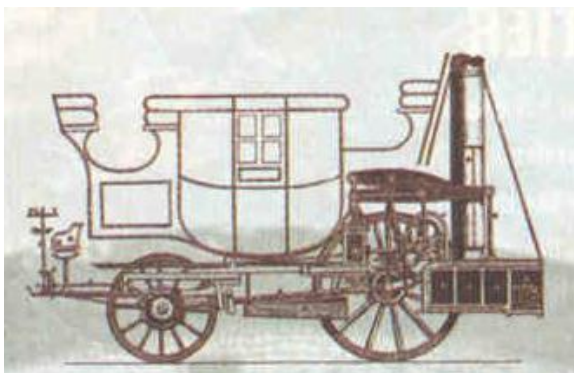


Figure 9. In 1824, Timothy Burstall and John Hill built this steam-powered four-wheel drive coach in England, featuring front wheel brakes and a walking beam engine. Source: 4x4 History¹⁰.

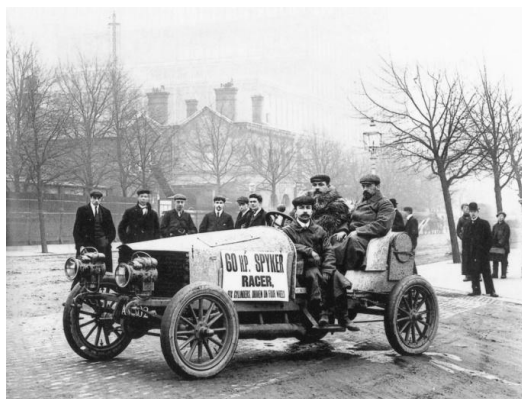


Figure 10. 1903 Spyker. It was the first car with a six-cylinder engine as well as permanent four-wheel drive and four-wheel brakes. Source: Serious Wheels¹¹.

⁹ Kamm, I. O., & Beck, R. R. (Jun 2-6, 1975). The Performance of the Coupled M-113 Armored Personnel Carriers. *ISTVS 5th International Conference Proceedings, I1*. Detroit, MI.

¹⁰ 4x4 History - Where It All Began . (n.d.). Retrieved Jul 9, 2014, from <http://www.dog-walker.us/4x4/4x4-204.htm>

¹¹ Serious Wheels. (n.d.). Retrieved Jul 9, 2014, from <http://www.seriouswheels.com/cars/top-1903-Spyker-60-HP.htm>

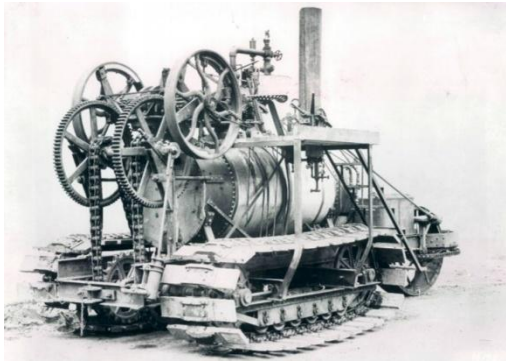


Figure 11. Holt steam driven crawler tractor circa 1890. Source: wikimedia¹².

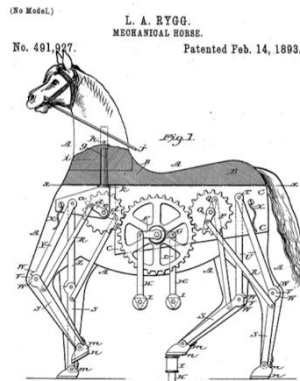


Figure 12. In 1893, Rygg filed for a patent for a mechanical horse. Source: A Brief History of Mechanical Horses¹³.

Such early introductions of off-road technologies are not surprising since the first application was for agricultural “traction engines”. There were very few improved roads at the dawn of motorized transit. The U.S Army's first use of trucks in a military operation was in the "Punitive Expedition" in pursuit of "Pancho" Villa into the mountains of northern Mexico in 1916¹⁴. The first large scale use of motor vehicles in warfare occurred during "The Great War," starting in 1916. Early on, the British used a number of GMC model 15 trucks, similar to those used in pursuit of Pancho Villa. GMC developed the improved model 16, ¾-ton truck and released it in 1916.

Figure 13 plots notable achievements in off road mobility. There is a pattern of adoption going from agricultural or military and then to commercial transportation for nearly all the innovations. The bulk of real innovation occurred between 1890 and 1910. While clearly subject to the opinion of the author, nearly all significant improvements since the 1960s are attributable to the availability of sensing and computing assets.

¹² Retrieved Jul 9, 2014, from http://commons.wikimedia.org/wiki/File:Holt_steam_driven_crawler_tractor_circa_1890.JPG

¹³ *A Brief History of Mechanical Horses*. (2012, Sep 28). Retrieved Jul 9, 2014, from <http://www.theatlantic.com/technology/archive/2012/09/a-brief-history-of-mechanical-horses/262942/>

¹⁴ *The Early Days of Motorized Military Vehicles*. (n.d.). Retrieved Jul 7, 2014, from [military.com: http://www.military.com/veteran-jobs/career-advice/military-transition/gm-military-history-motorized-vehicles.html](http://www.military.com/veteran-jobs/career-advice/military-transition/gm-military-history-motorized-vehicles.html)

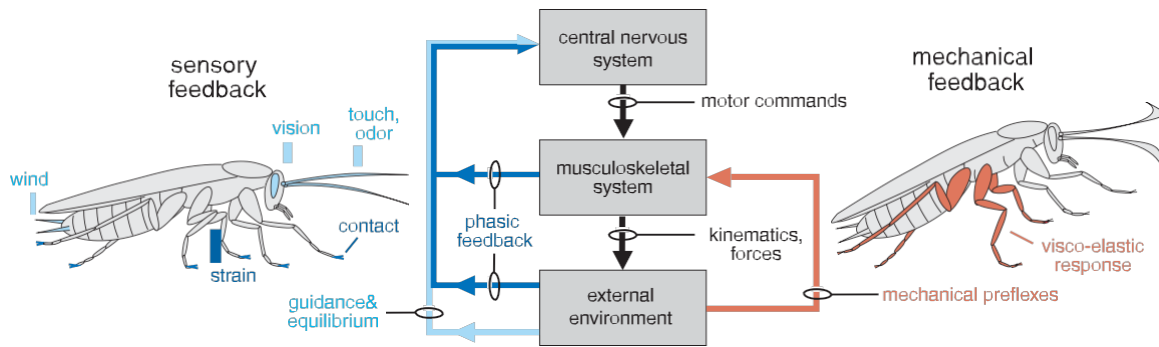


Figure 14. Both neural and mechanical feedback play roles in controlling locomotion. Although depicted here for a cockroach, the diagram represents a general model for locomotor control. The external environment is sensed by multiple modalities and fed back to the central nervous system. The nervous system processes the sensory feedback (blue) and modifies the motor commands. In parallel, viscoelastic mechanical reflexes (red) act rapidly to resist perturbations. Source: Dickinson¹⁵.

Figure 15 illustrates graphically the idea of fractal mobility as an overlapping progression through physical length scales to sensor/cognition based modalities that collectively contribute to locomotion for ground robots. Smaller length scales have a higher frequency at a constant speed and thus may need a faster feedback mechanism. An excellent example of combining the different elements of fractal mobility is the NASA rover platform ATHLETE (shown at the right in Figure 15). ATHLETE uses a hybrid modality of mobility where it rolls on wheels for medium terrain features and then uses legged movement over extreme terrain. A mobility means that is not discussed in this paper or shown in the diagram because it is not continuous is the ability to get unstuck.



Figure 15. Fractal elements of mobility are length scale dependent. Moving beyond the physical ground-engagement space you enter the pure cognitive space (path planning, cooperation, and networked knowledge).

¹⁵ Dickinson, M. H. (2000). How animals move: an integrative view. *Science*, 288.5463, 100-106.

Physical mobility modalities may be either active or passive at any scale. Active mechanisms are characterized as having a feedback mechanism and actuator. When the effective range of sensing is reduced to zero, this is called contact sensing. Contact sensing examples are traction control or a passive suspension. Passive methods are purely mechanically reactive to input forces with no memory or computation. Moving to an active mechanism allows performance gains where passive systems have reached their physical limits.

Foundationally, the terrain interface must provide force to support the body and provide a reaction forces for movement. The terrain interface modality is usually passively handled using grousers, paddles, or tread patterns and seeks to enhance the soil's ability to resist peeling away when force is applied to it. The purpose of all subsequent layers of mobility are to realize acceptable reactive forces with the terrain. Soil motion below the interface is also a key item to consider as it greatly affects performance. This layer could be made active by having lugs or trackpads that extend autonomously when a soft terrain is sensed.

The next scale is the rolling modality, which has no biological equivalent in nature. In nature, entire bodies use rolling as a locomotion mechanism but no known mechanism is able to spin part of its body relative to another to achieve locomotion (aside from flagella bacteria). The main reason wheels have not evolved in nature is they only perform well in limited range of natural circumstances or on prepared surfaces. Only about half the Earth's landmass is accessible to wheeled and tracked vehicles, yet legged animals can go almost everywhere on foot. The clear advantage of rolling systems is to achieve both energy efficiency and speed by eliminating continual accelerations and decelerations of an organism's limbs. LaBarbera¹⁶ provides an excellent detailed discussion why animals do not have wheels. In order to make this layer active, the entire modality could switch, such as morphing from wheels to tracks or maybe tracks to screws (Figure 16 below).

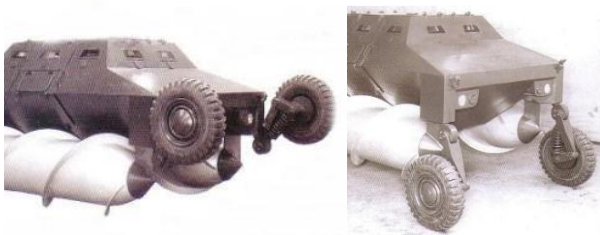


Figure 16. Chrysler 1965 screw vehicle model equipped with retractable wheels. Source: Amphibious Vehicles¹⁷.

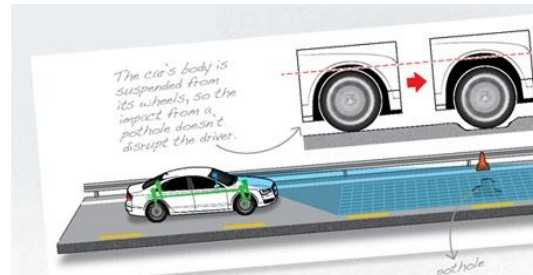


Figure 17. Audi's predictive suspension can spot obstacles up to 65 feet in front of the vehicle so each wheel can individually drop or rise to counteract obstacles¹⁸.

The suspension length scale is typically a mechanical system of springs and shock absorbers that connect the wheels or legs to the chassis of a wheeled vehicle. Suspensions handle medium sized terrain features like potholes, washboard areas, small rocks, etc. Active suspension systems use active actuators and a feedback loop to greatly enhance purely reactive mechanical suspensions. A distinct advantage of active suspensions is the ability to optimize vertical travel as well as bounce, roll, pitch and warp modes simultaneously. A preview

¹⁶ LaBarbera, M. (1983). Why the Wheels Won't Go. *The American Naturalist*, 395-408.

¹⁷ *Amphibious Vehicles*. (n.d.). Retrieved Jul 9, 2014, from http://www.amphibiousvehicle.net/amphi/Ch_Ch.html

system, which scans ahead of the vehicle, allows cuing the suspension to “step” over obstacles or potholes, such as the BMW predictive suspension¹⁸ shown in Figure 17.

The last physical engagement mechanism of mobility is macro-feature kinematics to move over large terrain features (large rocks, etc). There are a number of mechanisms that fall into this category, including articulations between vehicle segments, legs, jumping, etc. While rarely implemented on large ground vehicles, the advantage of this mechanism is that a wheel is unable to climb obstacles when its axle is less than the height of the top of the obstacle. A vehicle with legs or articulation can climb vertical obstacles higher than itself. The front leg can reach to grab the top of the obstacle and then pull the body over. A wheeled or tracked vehicle has to keep its wheels or tracks underneath its chassis at all times or it flips over. With legs, you can manipulate the center of mass advantageously.

Raibert¹⁹ best expresses the value of macro-features: “wheels excel on prepared surfaces such as roads, but perform poorly where the terrain is soft or uneven. One reason legs provide better mobility in rough terrain is that they can use isolated footholds that optimize traction. As a consequence, a legged system can choose among the best footholds in the reachable terrain; a wheel must negotiate the worst terrain. Another advantage of legs is that they provide an active suspension that decouples the path of the body from the paths of the feet. The payload is free to travel smoothly despite pronounced variations in the terrain. A legged system can also step over obstacles.”

The weight burden of active systems is often mitigated in nature because elements generally have multiple functions. Legs act as springs, supporting elements, and actuators at the same time. All running animals, from small insects to large mammals, exhibit a center-of-mass motion that resembles a bouncing ball or a pogo stick as opposed to slow controlled quasi-static motion. Additionally, biological systems use flexible members (springs) for a robust and efficient running gait, to store energy, to provide high mechanical power, and to overcome bandwidth limitations of traditional actuators.

Further biological support for the layered modalities for mobility is provided by looking at the biological time response to a stimulus. Figure 18 shows the phases of response to a mechanical perturbation of a limb. The short latency reflex occurs from 20 to 40 ms depending on the distance to the spinal cord and is generated entirely by the spinal cord. The time from 50 to 100 ms is termed the long latency response and involves both spinal and supraspinal feedback. Activity after 100ms is considered ‘voluntary’, because movement-related muscle related stimulation can be generated at this time from visual or somatosensory stimuli. There are likely lessons here for robotic ground vehicles as well in terms of sensory processing and reaction times.

¹⁸ Chaey, C. (2012, July). Audi's Predictive Suspension Delivers A Smoother Car Ride By Anticipating Potholes. Retrieved from <http://www.fastcompany.com/1839303/audis-predictive-suspension-delivers-smoother-car-ride-anticipating-potholes>

¹⁹ Raibert, M. H. Legged robots. *Communications of the ACM*, 29 (6), 499-514

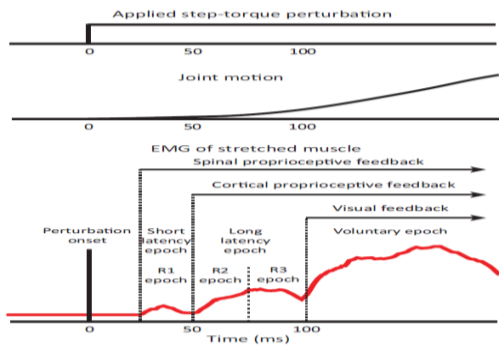


Figure 18. Mechanical step perturbation applied to a joint causes joint motion and a multiphasic electromyographic (EMG) response in stretched muscles. Source: Scott²⁰.

Biological Mobility as a Tradespace

In biological systems, neuronal tissue requires about 20 times more energy than skeletal muscle per unit mass in mammals²¹. Thus, we already know that brains and sensory systems are metabolically very expensive compared to movement systems. Fonseca-Azevedo and Herculano-Houzel²² recently proved for primates that the tradespace between brain size and muscle tissue is bounded by the amount of energy available in the environment. They measured the number of neurons in various primate brains and then took data collected others on the number of hours that these species spend eating. Next, they calculated the maximum number of neurons that each species can afford, given different amounts of feeding time. You can see the results in the results in Figure 19 below. Figure 20 shows the evolution of computing power relative to biological brain size.

“A primate that fed the putative maximum of 10 hours per day could afford a brain of, at most, 113 billion neurons, in which case it could weigh no more than 64 kg; if it fed 8 hours per day, it could afford a brain of no more than 53 billion neurons, but a body no larger than 24 kg; and if it fed 6 hours per day, it could afford up to 23 billion neurons in the brain, but, in that case, its body could weigh only 8 kg.”²²

²⁰ Scott, S. H. (2012). The computational and neural basis of voluntary motor control and planning. *Trends in Cognitive Sciences*, 16 (11).

²¹ Maclver, M., Patankar, N., & Shirgaonkar, A. (2010). *Energy-Information Trade-Offs between Movement and Sensing*. PLOS Computational Biology .

²² Fonseca-Azevedo and Herculano-Houzel. (2012). *Metabolic constraint imposes tradeoff between body size and number of brain neurons in human evolution*. PNAS <http://dx.doi.org/10.1073/pnas.1206390109>

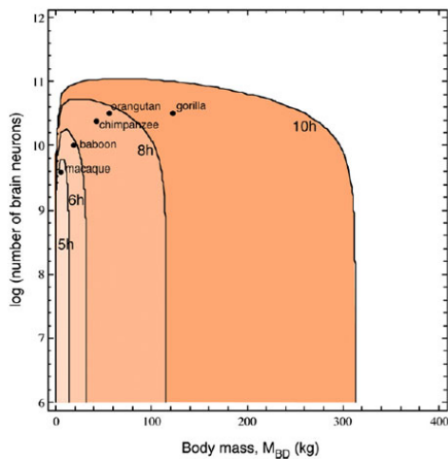


Figure 19. Primate tradespace as limited by the amount of feeding time.

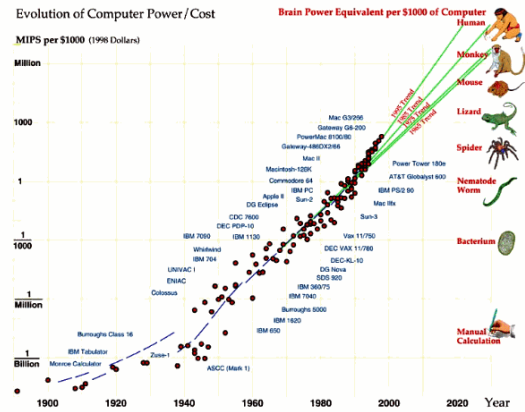


Figure 20. Evolution of Computer Power/Cost²³.

To further illustrate the importance of sensing in nature (beyond mobility), a recent Northwestern University study²¹ in behavioral ecology reveals that certain species trade-off energy and information during various routine activities. For example, for a fixed amount of available energy from food sources, is it better to expend that energy on a larger visual sensing range (via a larger eye and the brain tissue to process signals), or to move the body more so that the effective area that is scanned is similar? MacIver et al found that the increase in prey encounter rate more than counterbalances the additional energy expended in swimming inefficiently. The reduction of swimming efficiency for improved sensing arises because positioning the sensory receptor surface to scan more space per unit time results in an increase in the area of the body pushing through the fluid, increasing wasteful body drag forces. Other studies have also found similar results for bees.

The 1966 TARDEC moose mobility study²⁴ shows that animals avoid questionable terrain. Equally important as the mechanism of mobility is the animal's ability to select paths to purposely avoid or by-pass adverse conditions created by geometric obstacles. Many animals do not expend energy interrogating the terrain (try and get a horse through a puddle). The terrain severity may be unknowable, for example a deep puddle looks the same as a shallow puddle. In fact, the biological solution for many predators is that evolving a mammalian brain which increases the ability to act as a pack or swarm further extends cognition, sensing, and action to an emerging group property. Granted natural selection is known to optimize to a state that is "good enough", the mobility tradespace for the animal kingdom has chosen to dedicate a large amount of resources to sensing and navigation instead of raw mobility.

²³ Moore's Law limit reached. <https://community.emc.com/people/ble/blog/2012/02/21/moores-law-limit-reached>

²⁴ Hanamoto, B., & Martin, L. (Nov 1966). *Locomotion in Nature. Part I: Quadrapeds*. TARDEC.

Sensor and Computing Monetary Cost

The adoption of self-driving vehicle (SDV) technology in commercial automotive will likely be the dominant forcing function that will drive down military autonomous platform costs. Safety and ultra-reliability issues force an unusual technology overlap because while the Military wishes to operate in any environment, commercial automotive wishes to avoid lawsuits and both goals require system robustness. In order to maximize sensing reliability, multiple types of sensors are likely to be involved. Autonomous systems require layers of sensors, including LIDAR, cameras, radar, ultrasonic, accelerometers, gyroscopes, and the traditionally military infrared band. Sensors in combination complement one another and make up for any weaknesses in any one kind of sensor. Military drivers have been augmenting sensing for human drivers (example: night vision/infrared) for decades now. Autonomous systems take things further because they do not fatigue and can fuse more data with a constant attention as compared to a human driver. In fact, for the sensing modality itself, computer data fusion provides an advantage in fusing raw data. The human visual cortex still maintains a huge margin of capability in the area of interpreting the data. The human brain is able to provide context to situations where autonomous vehicles cannot.

Two major business studies on SDVs were published in 2014. IHS Automotive, serving multiple clients, published a study¹ entitled "Emerging Technologies: Autonomous Cars—Not If, But When." Additionally RAND Corporation published a highly detailed study aimed at policymakers². Both studies predict the first human-supervised SDVs will sell commercially by 2020 and IHS estimates an initial cost premium of \$7,000 to 10,000. Within five years, the premium is expected to drop to \$5,500. IHS predicts that 90 percent of cars in the US will be self-driving only by the year 2055. In fact, IHS claims the biggest adoption barrier will be government regulation and legal based more than technology-limited. The IHS projected price premiums versus feature levels are shown in Figure 21 below.

Autonomous function that are needed, with a focus on the cost trends of individual autonomous functions		
Autonomous function	Initial price	Projected price
Speed control: Fixed → Variable	1997ACC: \$3K	'13 ACC: \$0.8K; '30: \$0.3K
Steering within lane	2003 LKA: \$1.5K+	'13 LKA: \$0.6K; '30: \$0.15K
Detect pedestrian & other objects	2010 PDS: \$3K	'13 PDS: \$1K; '30: \$0.25K
Spot, sense & recognize signs	2008 TSR: \$0.8K	'13 TSR: \$0.4K; '30: \$0.1K
Sense & recognize when to break	2003 CMB: \$3K	'13 CMB: \$1K; '20: \$0.3K
Steering to another lane	2016: \$2K	2030: \$0.5K
Always sense accurate position	2018: \$1K	2030: \$0.4K
Determine driving routes	2018: \$1K	2030: \$0.4K
Drive according to traffic laws	2018: \$1K	2030: \$0.4K
Auto Pilot: Traffic Jam-APJ	2013: \$3K	2030: \$0.8K
Auto Pilot: Highway-APH	2017: \$2.5K	2030: \$0.9K
Auto Pilot: Parking-APP	2018: \$2.5K	2030: \$1K
All driving functions; SDC & HDC	2025: \$7-10K	2030: \$5.5K (Sum of above)
All driving functions; SDC only	2030: \$4.5-5K	2035: \$3-4K

Source: IHS © 2014 IHS

Figure 21. IHS Automotive projected initial and projected price for varying levels of autonomy. Note IHS shows fully self driving cars by 2025 (RAND projects 2020). By 2030, manual controls (steering wheel + pedals) will cost more than the solely autonomous vehicle.

Google’s self-driving car provides an excellent snapshot of the state of research-grade SDV technology. Google is using the best performing hardware devices available with a business goal of developing data-driven driving algorithms, not producing commercial vehicles. Chris Urmson at Google has stated their base vehicle has \$150,000 worth of equipment, including a \$70,000 LIDAR²⁵. Ryan Lamm at SWRI points out in the same article “Right now these systems are in the prototype phase, and so the hardware that’s purchased is either a one- or two-off, low-volume price.” The LIDAR is a Velodyne HDL-64E LIDAR uses 64 lasers that provides 1.3 million data points per second and offer a 360-degree field²⁶. Add to that GPS, Streetview, and Google Maps²⁷. All-in-all the platform collects 750 megabytes of sensor data per second. The Google SDV sensors are show in Figure 22.

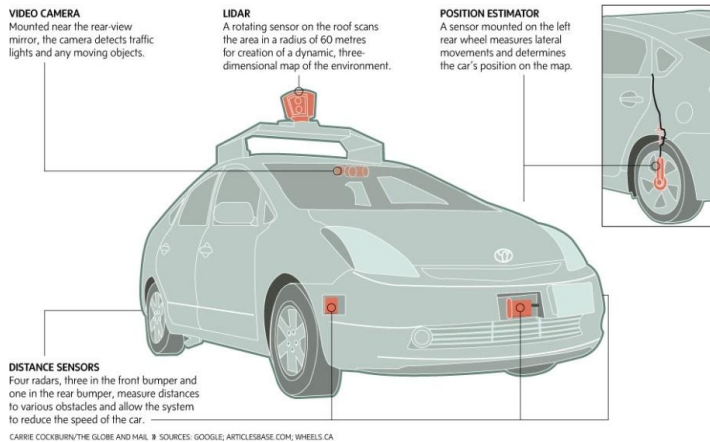


Figure 22. Googles self driving vehicle sensors.

Accordinging David Hall of Velodyne (Google’s LIDAR source), confirmed in a Popular Science article²⁸ that a major automaker recently summoned him to its headquarters to ask whether he could make a ruggedized, standardized automotive component that would wholesale for no more than \$1,000. Hall rebuffed the offer. "If you look at this from a venture capital point of view," he says, "that's just about the stupidest idea anyone's ever come up with." Hall is confident that with enough time and resources, he could engineer a \$1,000 LIDAR unit, but why bother? It would be many more years before a self-driving car is brought to market, prompting LIDAR orders in the hundreds of thousands.

Google’s methodology assumes there is no new specialized infrastructure (embedded markers in roads, vehicle-to-vehicle communications). This is similar to the environment the military will encounter. Google was able to beat drivers on a cone course using autonomous system. The Google SDV has logged over 700,000(Google, Inc., 2014) miles²⁹ with only one known crash. Google released the results³⁰ of a number of studies showing their

²⁵ Driving Down the Cost of Change. (2013, May). Mission Critical: Self-Driving Cars, p. 13.

²⁶ Gross, B. (2013, May 2). Google's Self Driving Car Gathers Nearly 1 GB/Sec. Retrieved from <http://www.linkedin.com/today/post/article/20130502024505-9947747-google-s-self-driving-car-gathers-nearly-1-gb-per-second>

²⁷ Chau, e. a. (2013). Patent No. 8,428,873. Uniited States of America.

²⁸ Fisher, A. (2013, Sept 2013). Inside Google's Quest To Popularize Self-Driving Cars: Robots can already outdrive humans. Now everyone needs to get out of their way. *Popular Science*.

²⁹ Google, Inc. (2014, Apr 28). The latest chapter for the self-driving car: mastering city street driving . Retrieved from <http://googleblog.blogspot.com/2014/04/the-latest-chapter-for-self-driving-car.html>

SDV accelerated and braked significantly more sharply than professional human drivers. Another study showed that the cars' software was much better at maintaining a safe distance from the vehicle ahead than the human drivers were. "We're spending less time in near-collision states," said Urmson. "Our car is driving more smoothly and more safely than our trained professional drivers."

Audi provides an excellent example of how commercial automotive is moving from research vehicles to mass producible technologies. The focus of automotive is to cleanly integrate the technologies into an affordable package. Audi recently has taken the first steps to shrink the rotating Velodyne radar into four one-megapixel cameras running at 30fps in a package the size of a fist³⁰ as shown in Figure 23. Additionally, Audi debuted the first self-driving computing system, called zFAS³¹ in partnership with nVidia that shrinks a trunkfull of server racks on the Google vehicle to a laptop sized system that fits cleanly in the dash as shown in Figure 24. And because the technology, known as zFAS, uses NVIDIA's multicore graphics processing chip technology it can be upgraded as new technology is developed, improving performance and allowing more functions to be added. The zFAS currently uses NVIDIA's Tegra K1 chip, with a quadcore ARM Cortex-A15 CPU running at 2.3GHz and a 192 core GPU.

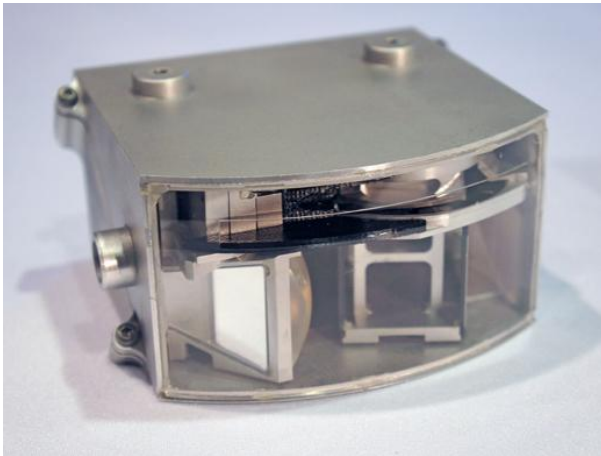


Figure 23. Audi compact LASER sensor. Audi has developed a compact laser sensor, about the size of a fist, for autonomous vehicles.



Figure 24. Audi's zFAS central driving system is based on the nVidia Tegra K1 GPU with 192 cores.

³⁰ Simonite , T. (2013, October 25). Data Shows Google's Robot Cars Are Smoother, Safer Drivers Than You or I. *Computing News*. Retrieved from <http://www.technologyreview.com/news/520746/data-shows-googles-robot-cars-are-smoother-safer-drivers-than-you-or-i/>

³¹ Allen, D. (2014, Jan 8). Audi Shows Off The Brains Of Its Future Self-Driving Cars. *Gizmodo Australia*. Retrieved from <http://www.gizmodo.com.au/2014/01/audis-shows-off-the-brains-of-its-future-self-driving-cars/>

Conclusion

Both hypermobile vehicles and hunting-dog type robotic platforms will require the use of sensing and cognition for vector mobility. The biological tradespace overwhelmingly shows the importance of sensing and cognition even when neuronal tissue requires about 20 times more energy than skeletal muscle. Combining vector mobility with path planning shows the largest promise for maximizing mobility on the battlefield. Further, there are multiple length scales (fractal) that a mobility system must embrace. Historical evidence shows that purely passive mechanisms are mostly mature. Active means (especially preview sensing as opposed to contact sensing) show potential breakthrough mobility performance increases. The cost of sensors and computers will be negated in the future by commercial sector investments for self driving vehicles. The military needs to invest in developing advanced mobility now to change vehicle capabilities on the battlefield in 2025.

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