MOBILE ROBOTS AND WALKING MACHINES

1.0 Background

The notion of a mobile robot, as perceived by the general public, is one aligned with creatures that science-fiction has brought to the big screen, as well as those popularized by the mass-media[1]. In reality though, the ‘real’ mobile robots in use today are of a different morphology due to the implementation constraints imposed by the laws of nature. The design of these systems is always a compromise between many variables that the different engineering disciplines have to optimize, in order to develop a mission-capable, cost-effective and reliable remote device or automaton. To better understand and focus the scope of this section, it is important to understand the topic of design of a mobile/legged machine in terms of its place, applications impact and the true practical and theoretical problems challenging the evolution of robotics morphologies and technologies.

1.1 Introduction

In order to develop any robotic system, whether teleoperated or automated, one has to realize that robotics represents a truly multidisciplinary field, where the different areas of design (mechanical, electrical and software) have to be successfully integrated into a complex system. As such, mechanical design can not be thought of as a totally separate, dominant nor stand-alone discipline, but rather as an activity closely linked with the others. In practical terms this implies that decisions on the robot configuration (locomotor type, passive/active structure, etc.) are not purely mechanical, but heavily influenced and sometimes even dominated by software or electrical requirements.

Having said that in robotics all disciplines are equal, in reality the performance specifications imposed by the task that the robot has to accomplish, usually dictate the importance of each discipline. So if a machine is to accomplish a task, for example access an area through a constrained space, the mechanical design might drive the packaging of all other components; if the sensing requirements are stringent, the type of sensor and support electronics/computers to run the system might dominate the design; if remoteness and duration of autonomous operation are crucial, the type and size of power source and electronic power-management hardware could dominate the overall design.

This chapter will attempt to focus on the mechanical aspects of mobile robot design, without explaining the lengthy and rich process of overall robot design, by concentrating on different mechanical design issues related to generic subsystems found on mobile/legged robots.

1.2 Overall Scope, Nomenclature and Definition

The term mobile robot can be thought of as the most generic description of a robotic system that is able to carry out a set of generic tasks in different locations without

1. whether sci-fi writers influence robot designers or vice-versa, is left to the reader to ponder

being constrained to work from a fixed location, such as is the case in industrial robotic manipulator arms operating within work cells. It is important to realize that mobility can be achieved in a variety of ways, namely through movable platforms using different forms of locomotors, such as wheels, tracks, legs, etc. Hence a mobile robot can be thought of as a platform with a certain characteristic configuration, that is able to transport sensors, tools and/or manipulators to any accessible and desirable location to perform a desired task. The basic diagram depicted in Figure 1, thus attempts to capture the generic nature of a mobile robot, where legs are seen as just one of the many possible forms of locomotors.

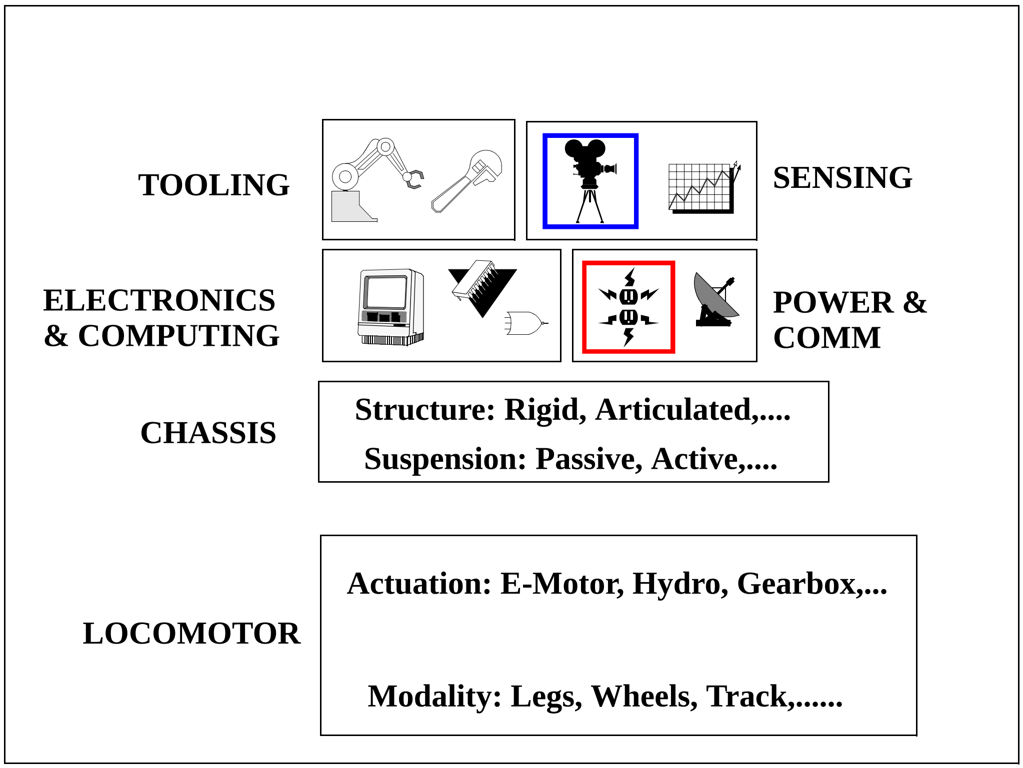


Figure 1: Diagrammatic View of a Mobile Robot System

The definition of a mobile robot should certainly include the ability of the machine to operate with some form of autonomy, based on on-board decision-making without requiring a human operator in the loop. On the other hand, since we are limiting ourselves to more of the mechanical aspects in this chapter, we will not solely investigate truly autonomous platform designs, but rather any and all remote (whether teleoperated, supervisory-operated or autonomous) platforms, since mechanical design transcends definitions of autonomy - a well-designed mobile platform can be robotized and even made autonomous - the goal of this chapter is to illustrate the most important and interesting aspects of mobile robot/platform design.

This chapter will be limited to exploring the theoretical and practical mechanical design aspects of the chassis and locomotor components of a mobile robot, without dwelling on the details of the power and communications, electronics and computing and tooling and sensing systems. The idea is to limit ourselves to those components that are responsible for the mobility of a robotic system, and the different configurations developed for specific environments and applications, as manifested in the chassis or structure of the system that houses the remaining components of any robotic system.

Figure 2: Locomotion modalities found in mobile robots

Typical examples for different mobile robot locomotor modalities, i.e. legs, wheels, tracks, and hybrids (locomotor with other or combinatorial mobility features) can be seen in Figure 2. Legged vehicles can usually have one, two or more legs (usually 1, 2, 4, 6 or 8), such as mono-, bi- and quadru-ped or insect-like walkers. Wheeled vehicles can come in configurations of single-, three- and multi-wheeled systems, with two or more wheels actively driven and the others idling, while steering using angular heading changes (ackerman steering) or skid-steer driving (akin to a tank). Tracked vehicles usually have a two-sided continuous belt/chain loop wrapped over idler and driver pulleys, allowing the vehicle to drive in a skid-steer fashion while using a large contact area on the ground for ground support and traction[1]. Hybrid locomotors come in many varieties, including vehicles with omni-directional wheels, combined wheels and legs and other omni-directional wheels, whether fixed or articulated (i.e. a tyred-walker, where the feet on a legged robot are replaced by drivable wheels).

1.3 Locomotor Choice

The choice of locomotor depends primarily on the type of environment that one will be operating in. A fairly generic decision-tree approach one might follow is presented below:

- **Air and Sea**

  If the robotic system is to be deployed in the air, there are very few choices, namely exclusively reaction-based systems such as jets, propellers and aerodynamic wings (gliders or self-propelled). The name of the game here is to generate airflow, reaction forces, whether it is using rotors as in a helicopter, or wings with jets to glide and fly.

  In the case of water-based systems, one might float and use propeller- or water-jet based propulsion systems with steering -angle control of lift-surfaces (rudder) or control of the propulsion-system-orientation (overboard-motor or jet-nozzle) itself. Once underwater, the choices are still akin to floating systems, in that ducted propellers, dubbed thrusters, or even jets (less used due to lower efficiencies) are used to propel the vehicle. Flotation provides for neutral buoyancy in many cases, while control-surfaces can be used to steer the system in all directions (such as in a torpedo or submarine). Ground-dwelling robots crawling along the ocean-floor might be built using legs, with the advantage that gravity-loads can be modified by way of flotation systems, giving designers more freedom.

- **Land**

  The choice of locomotor on land is more complex due to the wide spectrum of environments one can encounter. Available choices typically include wheel(s), tracks, legs and hybrids. The choice of locomotor thus depends completely on the type of environment and other drivers. Once might consider each of these locomotors using some of the guidelines discussed below.

  Wheels are most useful in near-flat or modest terrain, where obstacles are few, not taller than 40% of the wheel-height (to get over them), and smaller than the undercarriage height of the vehicle. In order to generate sufficient flotation and traction, designers might choose to add more than 3 or 4 wheels to the systems, and then control the size of the wheel based on the necessary support requirements (reduce ground-pressure). Steering mechanisms can be

1. the track can be thought of as a very large wheel due to the size of its contact area

avoided if the wheels are sideways-coupled and driven differentially to create forward/reverse motion with differential speeds resulting in skidding and thus steering (akin to a tank). Wheel compliance and active/passive suspensions take care of smoothing out the ride at higher speeds. Wheeled vehicles are capable of much higher speeds than wheeled or tracked systems, and are thus used in more benign environments such as indoors, roads but also somewhat-smooth outdoor areas, etc.

Tracked vehicles can be thought of vehicles with very large-diameter wheels, with the contact patch of a depressed wheel equivalent to that of the track. Unless the track is articulated, most tracked vehicles are not able to get over obstacles higher than 40% to 50% of their largest/highest sprocket diameter - shaping and articulation of the tread-drives can increase this height limitation though. Tracks are mostly used in outdoor rough terrain situations where an optimum of flotation, traction, speed and obstacle handling is sought.

Legs are typically useful for environments where the obstacle-size is equal to or greater than half the maximum underbody clearance height of the machine or the largest dimension of the locomotor-height. Hence a boulder-field with (i) large-enough boulders which a reasonably-sized wheeled vehicle could not climb over, with (ii) close enough inter-boulder spacing that would foil a vehicle of a reasonable size trying to get around them, or (iii) steep and loose-enough slopes where a tracked or wheeled vehicle would slip hopelessly, should most probably be tackled by a legged system. If power-consumption and speed constraints inherent in legged vehicles are not the main driver, and the obstacle size and spatial distribution demand a different type of locomotor, legs should be considered as a viable option. Another advantage of legs is that due to their infinite adjustability, they allow for stable platform motions during locomotion - i.e. the main body of the vehicle can maintain a stable posture despite the roughness of the terrain at any system-speed; this is not the case for other locomotors, which thus greatly impacts sensory and navigation accuracy. Legs are thus typically used in extreme terrain such as those encountered in logging, space exploration or seabed work (mine-detection, pylon-inspection, etc.).

Hybrid locomotion systems can vary greatly and are typically extensions on the above to get around some of the drawbacks of each. For instance an articulated tracked vehicle can emulate a large-height track and thus climb onto obstacles almost as high as the frontally-articulated track. A legged robot with wheels at the end of each leg rather than a foot-pad can walk over large obstacles yet also achieve higher traverse-speeds over smoother terrain. Robots or remote platforms operating in more constrained environemnts, such as pipes or vertical surfaces (windows, steel ship-/tank-sides), might use inch-worm rolling or clamping locomotors, or possibly even (electro-)magnetic or vacuum-cup feet to hold themselves against a vertical surface to avoid slippage due to gravity-loads.

1.4 Sensory Systems

A mobile or teleoperated robot system is usually a sensor-studded platform, with different sensors performing different functions. A good way to think about sensory systems in this context, is in terms of a hierarchical structure depicted below in Figure 3. The types of sensors are arranged in terms of increasing importance (downwards) for use in autonomous systems, as well as their data-use in increasingly complex tasks necessary for autonomy. To gain a better understanding of these individual categories, a simplistic overview of each is provided below.

HEALTH AND SAFETY MONITORING

SAFEGUARDING

POSITION ESTIMATION & NAVIGATION

MODELLING AND MAPPING

OTHER SENSORORY MODES

Figure 3: Hierarchical Sensory Systems Structure

- **HEALTH AND SAFETY MONITORING**

  Sensory systems are typically included aboard any remote system to allow for self-monitoring of essential parameters to ensure the proper operation of the system. The monitoring is typically performed by the on-board computer system at low and high bandwidths, some of it in analog form (circuit-logic without any software control) and some in digital form (computer software monitored). Such variables might include pressure, temperature, flow-rates and pressures, electrical motor-currents and power-supply voltages. The monitoring bandwidth depends solely on the criticality and characteristic response-time associated with potential failure modes in case any of these variables should stray from their operating range.

- **SAFEGUARDING**

  Safeguarding of the mobile robot system is implemented so that the remotely operational system does not harm its environment and/or itself to a point where continued operation would become too risky or impossible. As such, there are many styles of non-contact (more warning time and typically more costly) and contact-sensors (last line of defense and typically cheaper) already in use by the community. Such non-contact sensors could include acoustics-based sonar sensors, or optical systems such as LED-based transmission-/reflection-based proximity sensors. Contact-sensors would encompass such systems as simple trigger-switches, pressure-mats and force/torque monitoring devices (typically on manipulators), which can be used to monitor excessive force/torque thresholds, or even for active control tasks where the control of the force/torque exerted on the environment is an issue.

One interesting feature more and more common in real operational systems, is the notion of a ‘heartbeat’. Such a system is centered around a small microprocessor-system that checks the operation of the computing systems, operation of the communications networks and other key parameters, and issues a ‘ping’ to an on- and off-board monitoring system that decides on whether to shut down or keep the system operational, as long as it receives the ‘ping’ at the requested intervals - an interesting approach implemented solely in hardware to monitor the complex interlinked systems aboard a mobile robot.

- **POSITION ESTIMATION & NAVIGATION**

Most mobile robots need to know where they are located in the world, whether in a relative or absolute sense, and how to best proceed to the next waypoint or endgoal in an autonomous fashion. Most sensors used in that vein are either of a relative or absolute kind, in that their measurements are based on a previous position or data point (relative) or based on an absolute reference point (magnetic north, earth’s rotation and latitude and longitude). A large area of activity has revolved around improving positioning capabilities by integrating relative and absolute sensors in a sensory-fusion process, typically accomplished with Kalman filtering techniques, in the attempt to yield a better complete estimate of the state of the platform (XYZ position, YAW/PITCH/ROLL orientation and the associated velocities).

Relative sensors in terrestrial use could include accelerometers and inclinometers which can measure planar and vertical rates of velocity-change and inclination w.r.t. gravity vectors, and tachometers and encoders (optical or resistive) to measure rotational speed and angular positions). Above- and underwater positioning systems would be accomplished using radio-beacon triangulation (LORAN-C) or underwater sonar-ranging and -triangulation to position a vehicle accurately within an ocean-bed deployed acoustic net. Another method would use a platform-mounted camera coupled with vision software to extract key features (lines on the road, corridors, doors, etc.) to use that for relative positioning and heading control. Laser-based navigation systems relying on time-of-flight measurements can actually provide a locally accurate position estimate and data of value for absolute positioning and modeling.

Absolute sensors such as laser-/mechanical gyros and compasses are fairly standard, and with the advent of GPS and the more accurate differential GPS, absolute position, heading and rates are available to robot designers. Laser-based navigation systems such as retro-reflective laser-scanner systems used for AGVs can generate an absolute position estimate after the barcode targets have been surveyed - the same is true for an underwater acoustic positioning net, the net-transponders of which can be located accurately w.r.t. the surface-ship deploying an ROV, and then the ship positioned via GPS, allowing the actual ROV position to be calculated in terms of latitude and longitude.

Integration of sensors typically is accomplished via odometry (counting wheel rotations and accounting for heading changes), coupled with inertial navigation systems (combination of accelerometers, compasses, gyros and inclinometers), typically in the form of some non-trivial (possibly) Kalman Filtering method, depending on the desired accuracy of the sensory-fusion state-estimate.

- **MODELLING & MAPPING**

The modeling and mapping of the world surrounding an autonomous robot is of great utility to develop an awareness of the surrounding world with sufficient accuracy and resolution to allow higher-speed and safer autonomous traverse through/over the terrain in a post- or real-time situation. The notion here is to collect sufficient and accurate data on the location of all features in the scene, assign to them an absolute size/shape/location w.r.t. the vehicle and to use that information to build a three-dimensional map by which to navigate and image the surrounding world for post-mission tasks.

Typically, the sensors used for such tasks are (in increasing order of resolution, decreasing computational load and increased implementation cost) acoustic sonar-rings, stereo-cameras and (at least) two-dimensional laser-scanners. Acoustic sensors are cheap and simple to integrate, but developing a real-time, accurate, high-density and more than cross-sectional map of the world continues to be a research challenge. Camera-based three-dimensional mapping systems (bi- and tri-nocular stereo) continues to be a field of research and implementation examples. Many systems are available or in research-use today, with differing levels of accuracy and bandwidth. Their main use is for obstacle detection and avoidance. Even though the spatial resolution of a stereo-pair is better than for acoustic sensors, the use of stereo imagery for digital map-building is still limited. The most costly and accurate solution to three-dimensional modeling and mapping continues to be the laser-scanner system. Such a system is able to measure time-of-flight of laser-beams illuminating the environment through a 2- to 3-dimensional scanning mechanism, allowing a computer to build up accurate and high-resolution imagery of the surrounding environment. The challenge has, and continues to be, to build accurate three-dimensional models of computationally-tractable elements so that in real-time such a three-dimensional environmental model can be used for navigation, and sometimes even for post-processing applications (as-built mapping of facilities, reconnaissance, etc.).

- **OTHER**

Other sensory systems in use today, most of them in the area of manipulation though, are centered around devices able to measure presence/absence of contact and small contact forces and torques (such as IR sensory skins and resistive piezo-electric skins attached to robot arms). In addition, researchers have embarked on providing sensory perception beyond the visual (video), auditory (sound), and motion (vibration) cues to now include smell!

1.5 Applications Evolution

One can argue that mobile robots can be found in an ever-increasing number of application arenas, whether on land, at/under sea and even in the air. Certain areas pioneered the introduction of mobile systems, mainly driven by the commercial impetus and application viability. A somewhat representative, yet far from exhaustive, application family-tree for mobile robots is depicted in Figure 4.

MOBILE ROBOTS

AIR	SEA	LAND
UAVs	ROVs	Military
Military	Exploration	Hazardous/Nuclear
	Oil-Rig Service	Medical
		Planetary Exploration
		Construction
		Agriculture
		Mining
		Service
		Manufacturing/Warehousing
		Remote Inspection
		Environmental Remediation
		Entertainment
		Mass Transportation

Figure 4: Application Family Tree for Mobile Robots

In the (i) air, UAVs (Unmanned Air-vehicles) are mostly in use by the military in reconnaissance missions, while at (ii) sea and underwater, ROVs (Remotely Operated Vehicles) are in use for underwater exploration and search and rescue as well as offshore oil-rig servicing and maintenance. By far the largest applications arena is on (iii) land-based systems. The military is developing remote scout vehicles to do battleline reconnaissance, and the nuclear industry uses inspection robot systems for its power plants. The medical industry is developing surgery robots and assistive displays, and planetary exploration is proceeding with remote rovers. The construction, mining- and agricultural industries are automating their equipment to allow for automated field operations, such as excavation and harvesting and mineral haulage. The service sector has several automated systems for cleaning and mail/hospital delivery, and the manufacturing/warehousing industries use AGVs (Automated Guided Vehicles) to transfer materials/products on site. Several businesses have remote inspection robots for tanks and gas/sewer pipelines, environmental cleanup is counting on remote robotic systems to map and dismantle contaminated sites. The entertainment industry is using automatons and automated figures in theme-parks and movie sets, and mass transportation industries are in the alpha/beta testing phases to automate transportation beyond the people-movers to actual buses and private vehicles. The above list will continue to grow rapidly and reflects just a subset of possible arenas of mobile robot applications.

1.6 Theoretical Aspects and Research Topics

The areas that seem to always generate a lot of interest in the field of mobile robotics are those of locomotion and chassis/structural configuration. In general terms, the type of locomotor that is needed for a certain application depends largely on the type of terrain that the mobile robot will be expected to be operating in. 'Terrainability' has emerged as a term coined in the research community, with various definitions, which generically describe the ability of the robot to handle various terrains in terms of their ground support, obstacle sizes and spacing, passive/dynamic stability, etc. The overall configuration of the entire system can be developed to suit particular needs of the application, such as reconfigurability for ease of transport or access, suspension for high-speed operation, or even articulated frameworks and suspensions to increase the machine's terrainability.

The area of locomotion is probably the main area in mechanical mobile robot design most heavily studied in theoretical and experimental terms. Big issues in this area are ground support (contact pressure), traction and obstacle handling capabilities. More typical issues in locomotor design are also focussed on the details of actuator (motor, gearbox) design, suspension/steering methods and the ground-contactor design (i.e. feet on legged machines, magnetic or vacuum tracks/feet and even wheel/track tread/grouser systems).

The issue of robot system configuration is an area where the designer's systems integration experience, innovativeness and inventiveness plays a big role. Simple guidelines such as having a framework of three or four wheels for a statically stable wheeled mobile system, or the choice of a single, dual- or four- or six-legged walking system can be implemented in different configurations to suit the task. Designers usually use some key criteria such as static stability, power-consumption, etc. to make these choices during the design process. Other criteria which affect the system configuration could be due to (i) desired system rigidity (selection and configuration of structural members), (ii) ground clearance (size of locomotor and underhang of structural 'belly', (iii) overall weight (material selection and on/off-board power source), (iv) reconfigurability (collapsible locomotor or actuated frame structure), etc. It would be a very one-sided and excessively incomplete effort to try to numerically capture this part of the design process, since it largely depends on the application at hand, the particularity of the desired performance specifications and the inventiveness of the development team member(s). Suffice it to say that a large variety of capable and innovative robot systems have been developed with only wheels or legs, suited to different applications, and we expect this innovative trend to continue.

2.0 Theory

2.1 Terrainability - Sinkage and Traction

One of the most important criteria for outdoor off-road mobile robots is that of being able to locomote on and over its deployment terrain. The two more important criteria are those of sinkage and traction. Both depend highly on the soil properties such as granularity and moisture, as well as the weight and contact area of the locomotors for the robot and the surface-properties of the locomotors for proper traction. A typical set of figures used to explain sinkage via contact pressure and terrain characteristics is shown in Figure 5.

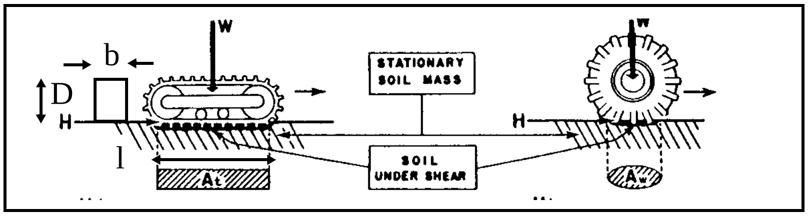


Figure 5: Traction diagram to evaluate locomotor terrainability

In order to properly size a track-system for instance, theories and data developed by Bekker, represent the best source of such information. In order to define such parameters as the track-width **b**, the track-height **D**, track-length **l**, grouser depth **h** and the robot weight **W**, use can be made of the well-known Bekker-parameters (internal friction angle ϕ, cohesion coefficient **c**, density ρ, deformation moduli $\mathbf{k_c}$ and $\mathbf{k_\phi}$, power ratio **n**, and derived parameters $\mathbf{N_c}$, $\mathbf{N_q}$ and $\mathbf{N_\gamma}$) and their use in several key equations derived by Bekker and shown below:

Sinkage-Depth ‘z’ vs. vehicle weight and soil parameters:

$$z = \left[\frac{\frac{W}{A}}{\frac{k_c}{b} + k_\phi}\right]^{\frac{1}{n}}$$

Drawbar-Pull - DP=H-$\mathbf{R_c}$ [Soil Traction (shear + friction)] - {Soil compaction resistance}

$$DP = H - R_c = [Ac + H' + W\tan\phi] - \left\{2\left[(n+1)(k_c + bk_\phi)^{\frac{1}{n}}\right]^{-1} \left[\frac{W}{l}\right]^{\frac{n+1}{n}}\right\}$$

One of the important rules-of-thumb is to consider that the track-sinkage should be less than 40% of the track-height, or the tracks will not be able to move through the medium. This requires as large a contact area as possible. Track-width should also be maximized to reduce sinkage in cohesive materials (loam and clay). In order to increase traction while reducing compaction and bulldozing resistance, the track-length should be optimized to allow for good traction (in addition to sizing and shaping the grousers) and reduced sinkage, without affecting the turning ability of the robot (expressed as the ratio of length to width, ideally between 1.0 and 1.8).

2.2 Terrainability - Obstacle-Handling: Wheeled Step-Climbing

The step-climbing problem for wheeled vehicles has been, and remains, one of the most illustrative examples of locomotor design and optimization. The typical 'ideal' geometry and free-body diagrams used to illustrate the theory behind wheel-size selection and actuator power specification can be seen in Figure 6.

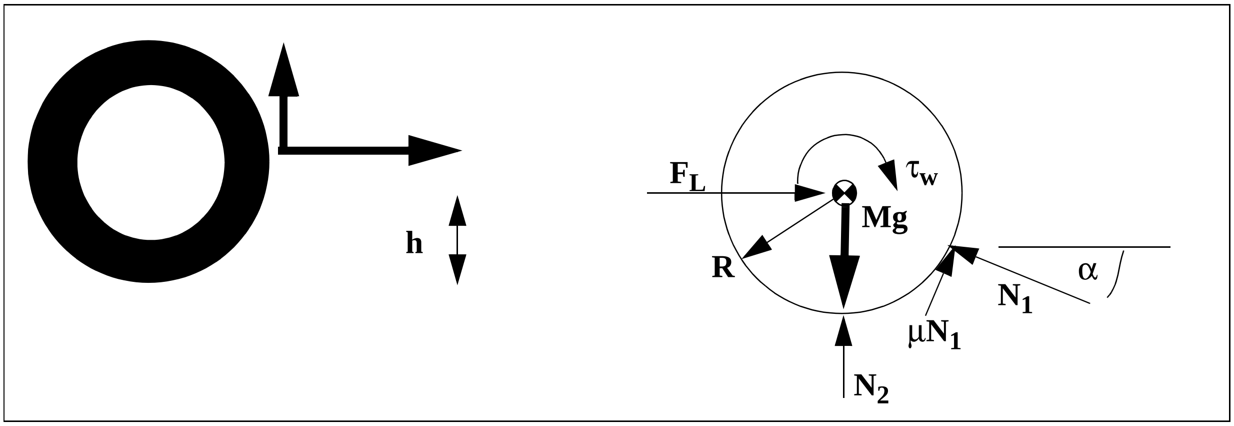


Figure 6: Idealized Step-climbing wheeled geometry and forces

If one wants to know how much torque (τ_w) would be required for a front-wheel driven (F_L=0) wheeled robot to make it over a certain sized step (h) using a certain-sized wheel (R), given a certain distributed wheel-load (Mg), one can show that the equation can be reduced to (note N_2=0 for lift-off and that no slippage on the step-edge occurs):

$$\tau_w \geq MgR\cos\alpha = MgR\cos\left[\operatorname{atan}\left\{\frac{R-h}{\sqrt{R^2-(R-h)^2}}\right\}\right]$$

Note that the required torque becomes smaller, should the mobile robot be all-wheel drive, since the rear-wheels provide additional push (F_L> 0), where the magnitude of said push depends on the net traction of the rear wheels (dependent on soil properties and tyre-geometry). Note further that as h -> R, the necessary motor torque rapidly approaches infinity, which implies that smooth tyres can not overcome a step-height equal to their wheel-radius, even if rear-wheel drive assist is present.

In order to reduce the reduced terrain capability of wheeled vehicles, tyres (and even caterpillar treads for that matter) can be designed with grousers to allow the climbing of obstacles where R=h. The fact that tyres are not always perfectly rigid cylinders, but rather compliant geometries, helps in step-climbing as depicted in Figure 7 on page 13. Notice that a grouser provides an effective leverage point, allowing the wheel to lift itself onto the step, assuming enough torque is available - note that a pure rear-wheel drive vehicle could not overstep an obstacle where h=R! In the case of the compliant tyre contacting the step, one can see that $R^* \leq R$, reducing the required torque τ_w, while also providing an effective grouse-like overhang that would tend to allow climbing obstacles where h can even be slightly larger than R, assuming no slippage occurs!

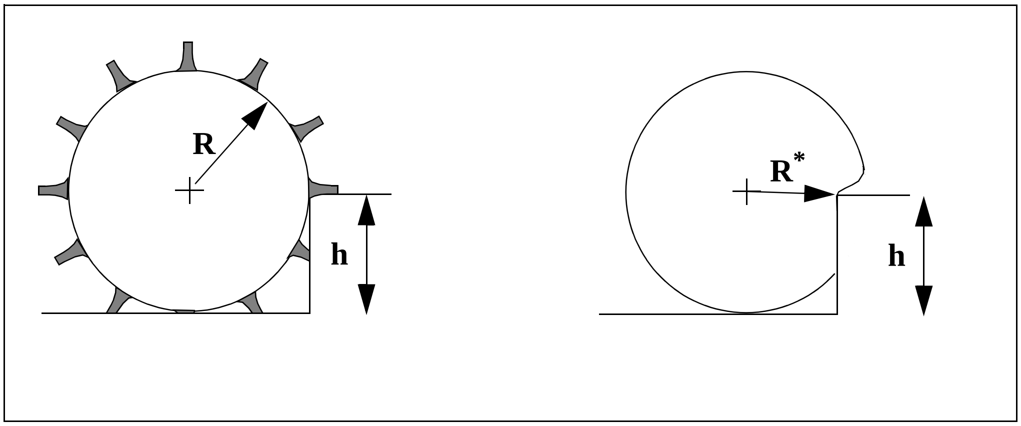


Figure 7: Impact of wheel-grousers and -compliance on step-climbing

2.3 Locomotor Actuation - Wheeled Actuator Sizing

Another recurring requirement revolves around the sizing of the drive system to allow a wheeled vehicle to negotiate inclined slopes. Typically in the case of electrical wheel-driven system, a generic front- and side-view of a wheel and its actuator system can be diagrammatically simplified as shown in Figure 8.

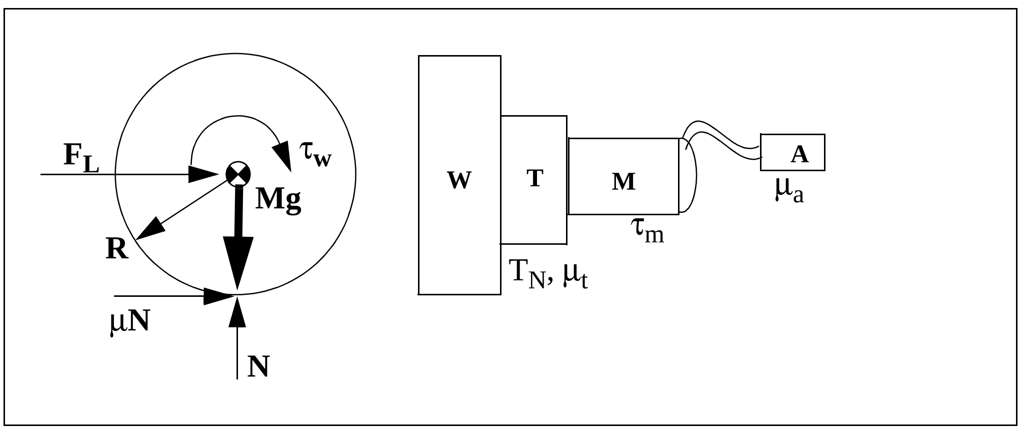


Figure 8: Idealized rendition of a wheel and its drivetrain

Depicted are a wheel (W) of radius R and mass M, coupled to a transmission (T) with a transmission ratio T_N and efficiency μ_t, a motor (M) outputting torque τ_m driven by an amplifier (A) with efficiency μ_a. The net forward propulsive force F_L required to keep the vehicle at a certain speed (remember that efficiencies refer to a measure of dynamic frictional effects and not static conditions) on certain terrain can be derived from the equation:

$$F_L = \frac{\tau_w}{R} = \frac{\tau_m T_N}{R}\mu_t\mu_a$$

If one defines the terrain to be a slope of angle θ, and the vehicle to have a mass M, as shown in Figure 9, the required motor-torque (τ_m) for a four-wheel driven mobile robot vehicle can be calculated as:

$$4 \times F_L \geq Mg\sin\theta \leq 4 \times \frac{\tau_m T_N}{R}\mu_t\mu_a \quad \text{or in re-arranged form:} \quad \tau_m \geq \frac{MgR}{4T_N} \times \frac{\sin\theta}{\mu_t\mu_a}$$

Notice that the assumption here again is that none of the wheels slip, implying that the frictional forces at each wheel (μN) which differ due to the uneven weight distribution, are larger than the applied force F_L (i.e $\mu N \geq F_L$).

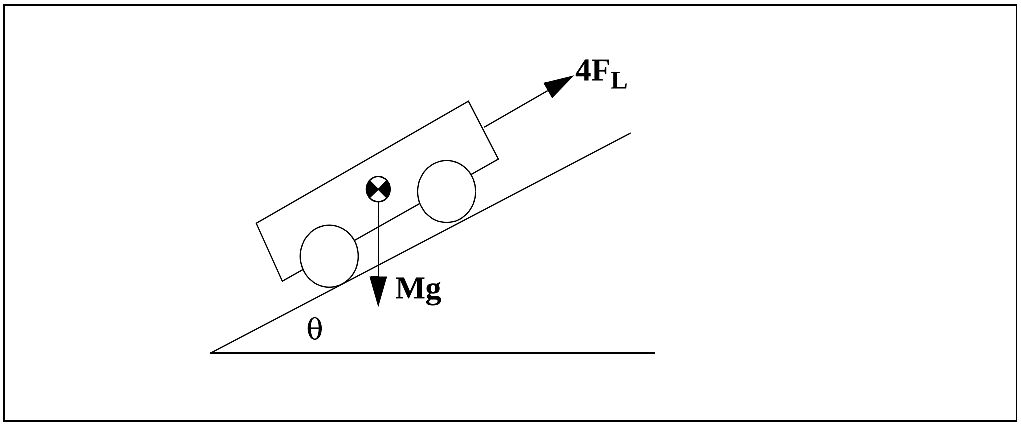
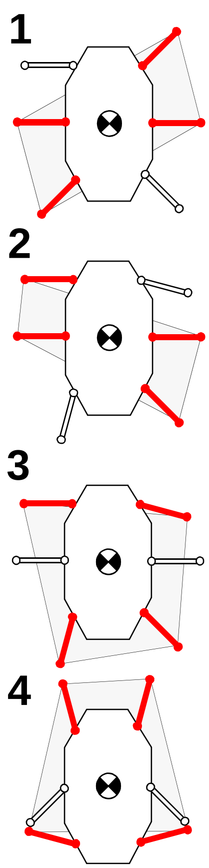
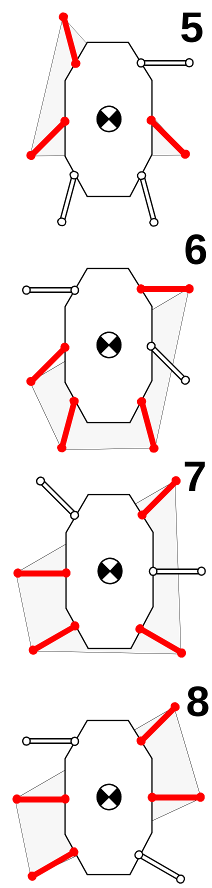


Figure 9: Inclined slope-climbing vehicle condition

2.4 Static Stability - Legged Configurations and Gait Selection





When legged robots are being configured, one important decision is whether to design a dynamically- or statically stable system. A good example of a dynamically stable legged robot would be that of a monoped, and possibly even a biped or quadruped, even though the latter two are more quasi-statically stable when at rest (such as humans or animals when standing). In the case of a passively stable legged walker, most systems usually have six or eight legs. The topic of guaranteed stability can best be illustrated through the illustration of an eight-image-mosaic of a six-legged walker with a specific gait shown in the bordering images to the left and right. Notice that we have depicted weight-supporting legs (those in contact with the ground and sharing in the load supporting the walker) as shaded legs, while the recovering legs (those off the ground and moved forward for the next step) are shown in solid white - the support-polygon is shown as a shaded area underneath the walker.

As the walker traverses a certain distance of terrain, its legs go through a sequence of steps. During any phase of the gait, the center of gravity of the walker, denoted by the C.G.-symbol[1], <u>must</u> always lie within the shaded support polygon described by the polygon drawn through all ground-contacting feet of the walker - the polygon's vertices. As can be seen from the depiction, for this legged walker (six legs) its legged geometry is acceptable in terms of guaranteeing stability for flat-floor walking. The same method can be used for incline-walking, by simply using the projection-location of the center-of-gravity vector for the walker with the plane described by the feet of all ground-contacting legs.

2.5 Locomotion Power - Legged Propulsion Power

A legged walker typically needs to clear certain-size obstacles as it crosses rugged terrain, requiring the legs to jointly lift the body of the vehicle to specific heights. In general, one can say that the total energy consumed for the execution of such motions is dependent on the mass of the vehicle (M), the characteristic height to which it needs to be lifted (H_c), and the frequency with which these motions occur (N_t) - power consumption can be computed by determining the characteristic raise-time (Δt) for the system. The graphic expressing this power consumption is depicted in Figure 10,

1. - Location of center of gravity

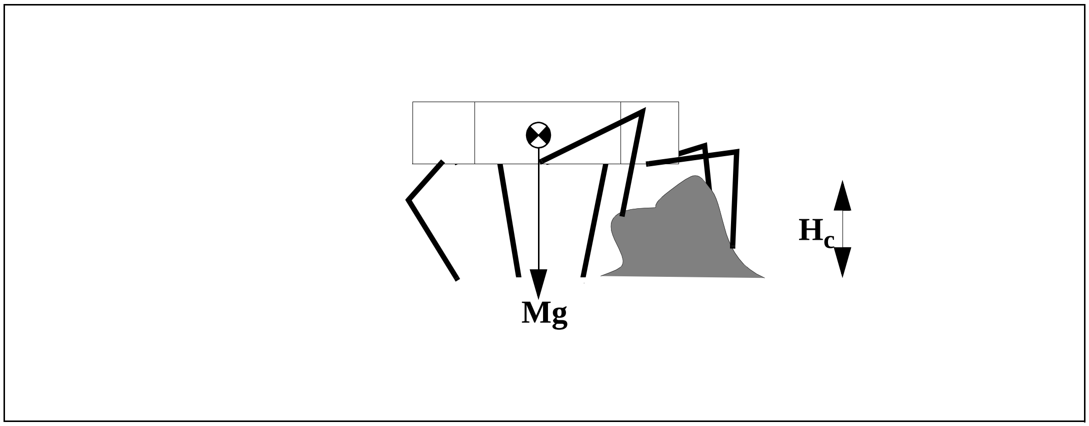


Figure 10: Legged power-consumption for rugged terrain traverse

where the robot crosses an obstacle of height H_c. Assuming that we want to keep the walker as close to the ground as possible, in order to maximize stability and reduce power consumption due to gravity-load cancellations in articulated legs, one can express the net power consumption due to raising and lowering the body P_b as:

$$P_b = 2\frac{MgH_c}{N_t \Delta t}$$

Note that power is also consumed when the body propels itself forward or in reverse, with load-bearing legs propelling the body and recovering legs moving their own weight - a walker is hence always consuming power, even going down-hill, since to date no simple method of energy-recovery exists for legged machines, unlike in wheeled vehicles (regenerative braking).

3.0 Learning by Case Studies

This section will illustrate the application of the more theoretical tools in a wide number of practical mechanical design areas in mobile and legged robotics. The examples have been grouped into areas including locomotion systems and overall system configurations.

3.1 Locomotor Systems

Drivetrain Design

A drivetrain was designed for a mobile robotic system intended to inject a toxic rewaterproofing chemical into each of the more than 15,000 heat-resistant tiles on the underside of NASA's space-shuttles while being serviced at Cape Canaveral. A picture of the actual robot system, the meccanum wheel used for the system and the cross-section of the drivetrain design are shown in Figure 11.

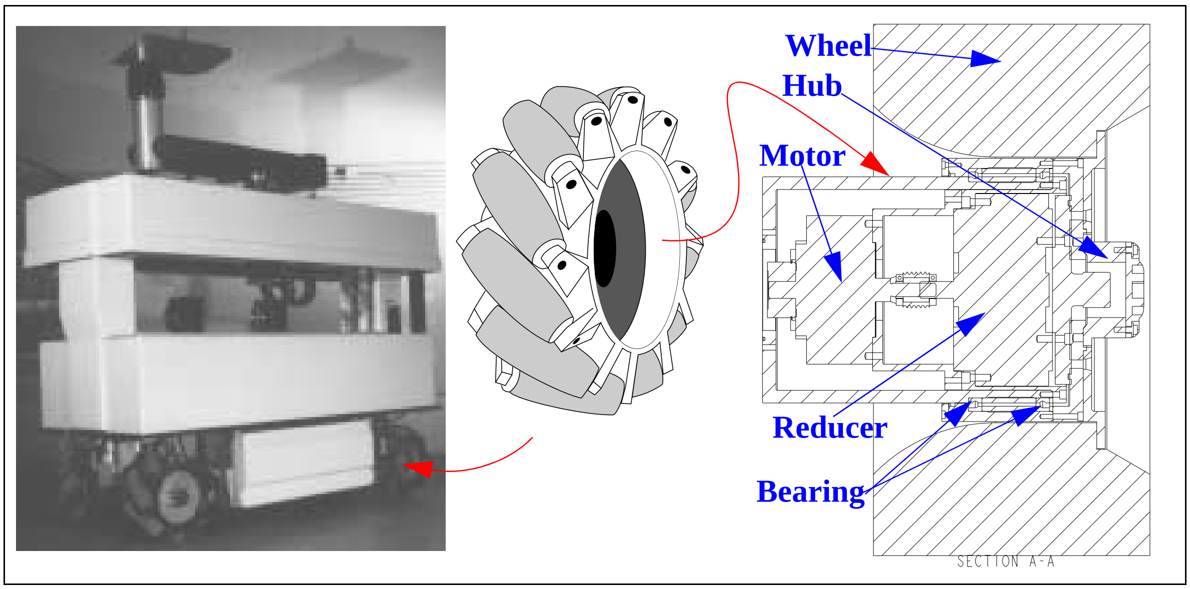


Figure 11: Tessellator Robot System, Meccanum-Wheel and Drivetrain X-section

Notice the wheeled mobile base, which carries a planar manipulator system with a vertical wrist and a sensing and tooling plate. The wheels carry on the inside a compact brushless DC motor, coupled to a cycloidal planetary reducer, controlled via motor-mounted resolver, and load-isolated using a pair of angular contact bearings. A novel feature is the coupling of a spline-hub from a TOYOTA 4-wheeler, to allow the decoupling of the non-backdriveable actuator from the wheel, allowing operators to move the robot around without electric power and without having to backdrive the transmission. The torque- and speed-curve performance was developed around 2 set-points. The one of driving over a 2-inch obstacle at very low speeds (stall conditions - see step-climbing equations), and maximum speed of the robot during locomotion (motor-torques at speed - see drivetrain efficiency calculations).

Impulse Leg Actuator

Rather than the typical continuous active power systems found in standard actuation systems, consisting of a motor (position/torque/velocity controlled), a transmission and output coupling, it is important to note that one can deliver much larger amounts of power over shorter time-periods using impulse actuator, such as the ones used in a single-legged soccer-ball kicking robot. The system dubbed *RoboLeg*, was developed by Bally Design and Automatika, Inc. for Adidas AG in order for them to rapidly and reliably test new soccer-shoe and -ball designs for better spin-control and hang-time.

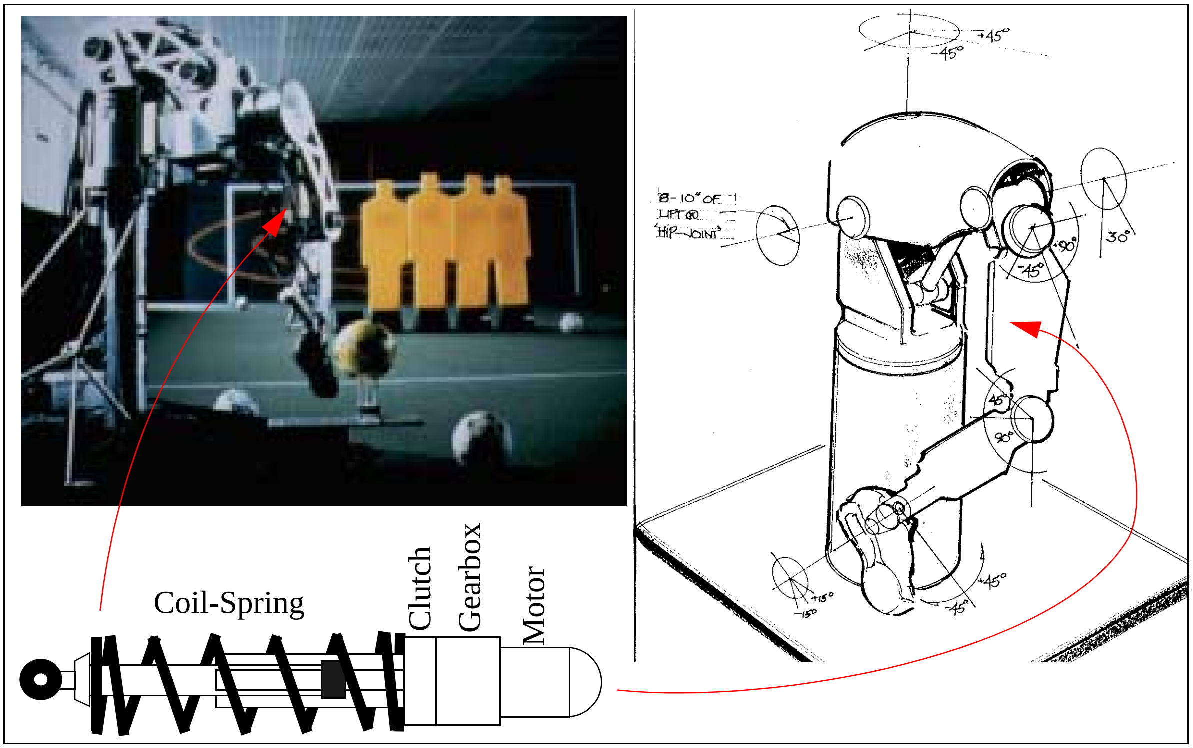


Figure 12: *RoboLeg* robotic soccer-ball kicking leg using impulse actuators to simulate human double-pendulum kick in the game of soccer.

As can be seen in Figure 12, the system uses an anthropomorphic leg geometry, where the hip- and knee-joints are powered using impact actuators. The entire kick is programmable and is over in less than 1/10 of a second. The impact actuator consists of a high-speed heavily geared motor-transmission system that preloads an energy storage device such as a coil-spring (linear actuator - shown above) or spring washers (rotary actuator). A simple clutch on the output of the transmission-box allows one to connect the actuator to the motor (loading phase) or free-wheel the system so that the energy stored in the spring can be released while minimizing friction and without backdriving the actuator.

Legged Clamper Design

Another interesting mechanical design is that of a clamper-inchworm system that locomotes along a cylindrical pipe-section, and is used to propel a tooling head along the pipe, that uses mechanical and water-cutters to abate asbestos insulation from the pipe. The overall system view is shown in Figure 13, as well as the two positions of the clamping mechanism used to clamp onto the pipe. The system architecture is one of a simple push-pull linkage mechanism driven by pinion/sector gear arrangement (crank-slider linkage arrangement) and an idler and follower linkage that eventually clamps onto the pipe using sharpened wheels (for self-alignment). Using the principal of mechanical advantage, the clamping forces can be very high for a certain range of motion of the linkage. By resizing the linkage lengths, the system can be tailored to clamp onto pipes of different diameters.

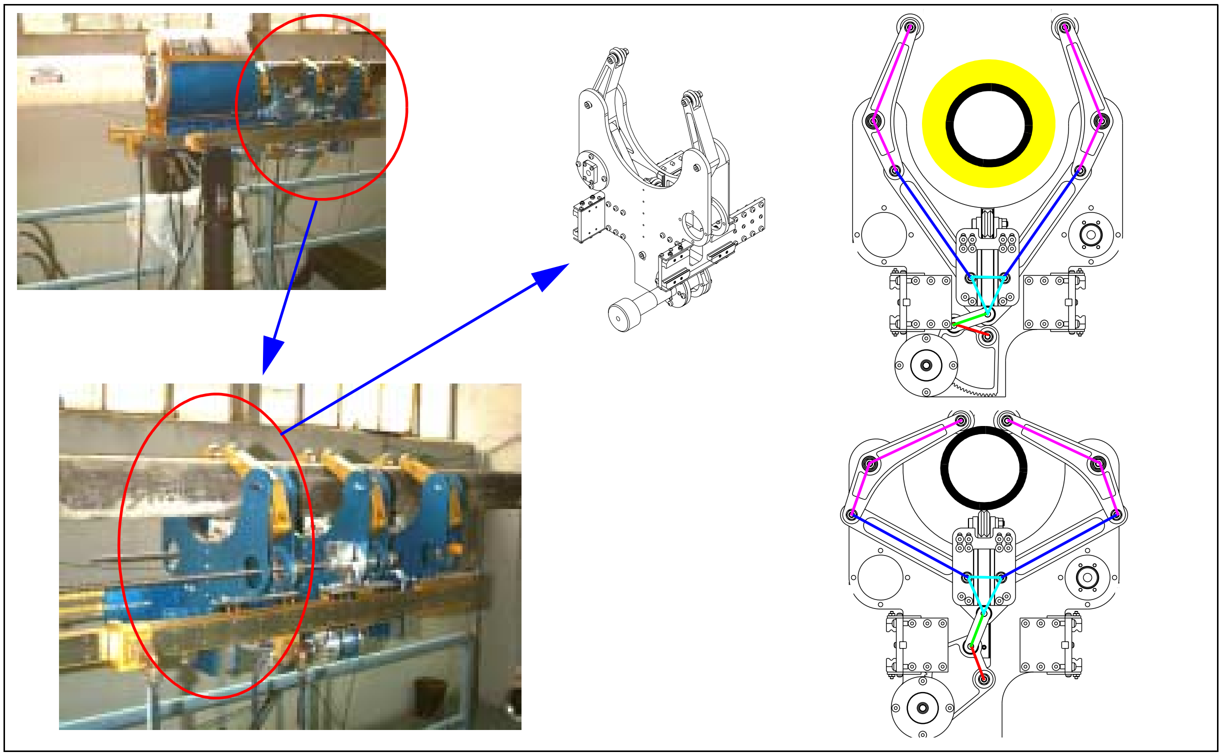
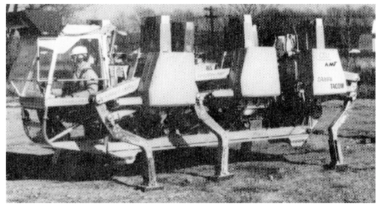


Figure 13: *BOA's* inch-worm locomotor & detailed view of open/close clamper positions

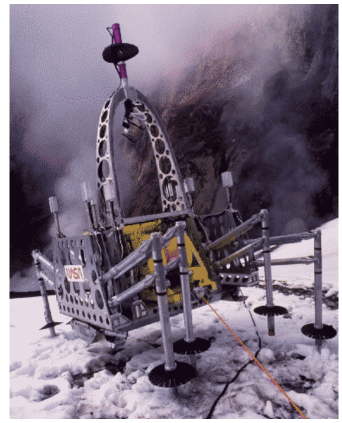
Legged System Design

Several mechanical designs for legs and their attachment frames exist at this point in time. Maybe some of the more famous ones are those developed for a few more well known robot systems such as the OSU-*Walker*, the *Ambler*, *PLUSTECH's* legged logger and the NASA *Dante II* robot, all depicted in Figure 14. Notice that in the case of *Ambler*, the legged configuration is that of an orthogonal leg, the ASV walker has an articulated pantograph mechanism, Dante II uses a pantograph leg in a sideways arrangement and PLUSTECH uses a rotary-jointed leg configuration.

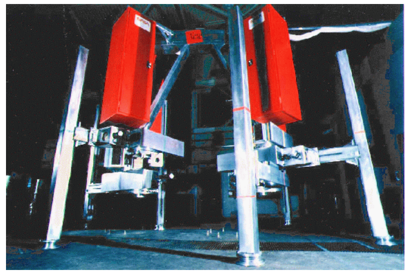
ASV Walker



PLUSTECH Logger



Dante II

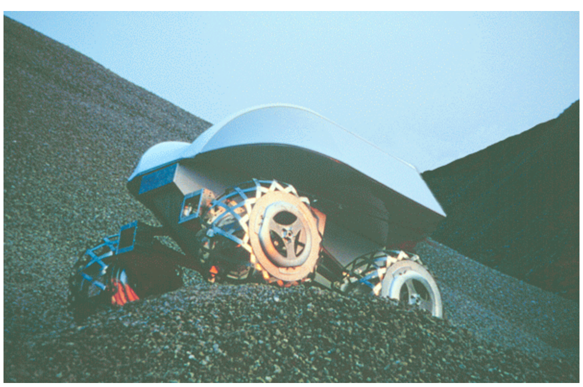


AMBLER

Figure 14: Articulated leg designs: *ASV, PLUSTECH, Ambler* and *Dante II*

Steering System

An interesting system, dubbed *Nomad*, designed to perform 200+km autonomous desert traverses on earth in preparation for planetary exploration, uses an interesting linkage to allow for the compact storage of the drive-wheels and -train, as well as the combined steering of the two wheels on each side in order to achieve smoother turning radii while minimizing slippage typical for skid-steer driven wheeled vehicles. The *Nomad* vehicle is depicted in Figure 15.



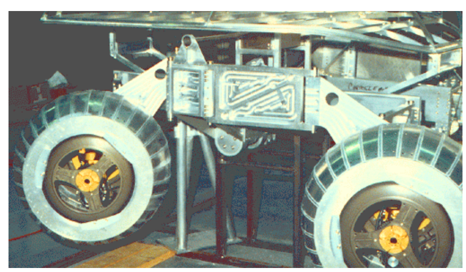


Figure 15: The articulated steering and stowage feature of the *Nomad* autonomous rover

3.2 System Configurations

Collapsible Frame Structure

One good example of a mobile robot system that uses almost its entire structural system in an active fashion to reconfigure itself, can be found in *Houdini* (see Figure 16), a robot developed for the Department of Energy. The robot was developed as an internal tank cleanup system that would remotely access hazardous (or petro-chemical) waste-storage tanks through a 24-inch diameter opening in the collapsed position, and then open up to a full 8-foot by 6-foot footprint and carry a manipulator arm with exchangeable end-effector tooling and articulated plow.

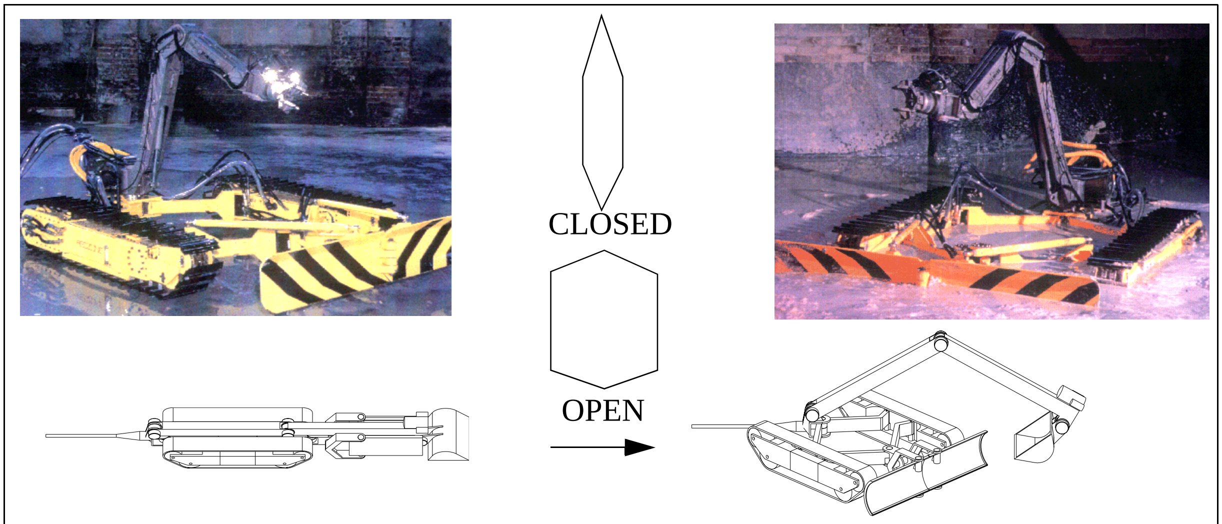
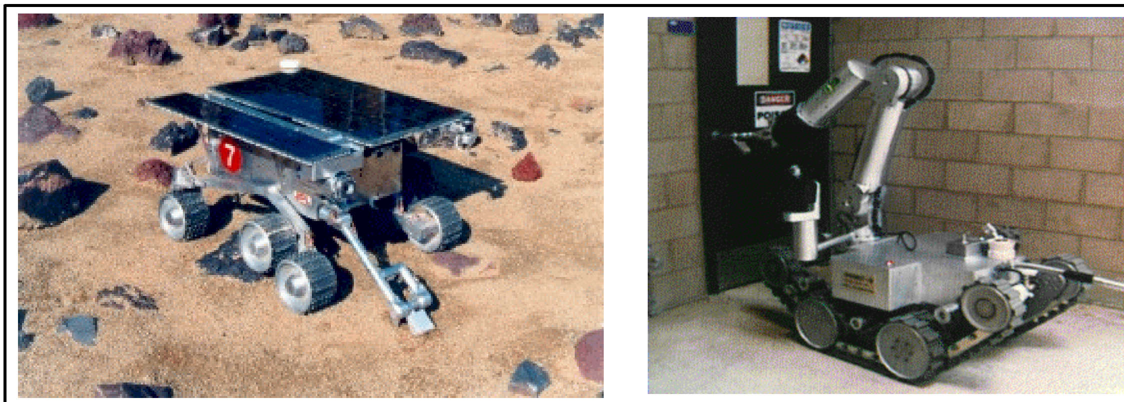


Figure 16: *Houdini's* reconfigurable structural frame design for access into tight spaces

Note that the 'benzene-ring' shaped frame members actuate the two tread-drives sideways and interlock at their end of travel, with the plow opened through passively-coupled linkages onto the frame-members.

Articulated Frame-, Suspension- and Obstacle-Handling System

Some interesting research and commercial examples for articulated wheeled and tracked designs are currently in use as research-, exploratory and remote reconnaissance systems. Two noteworthy systems are NASA's latest *Rocky 7* wheeled robot, whose planetary incarnation (*Sojourner)* has explored the surface of Mars in 1997 for over 80 days as part of NASA's Pathfinder mission, as well as the *Andros*-family of robots from REMOTEC, Inc., which are used in hazardous waste cleanup and in law enforcement - both shown in Figure 17.



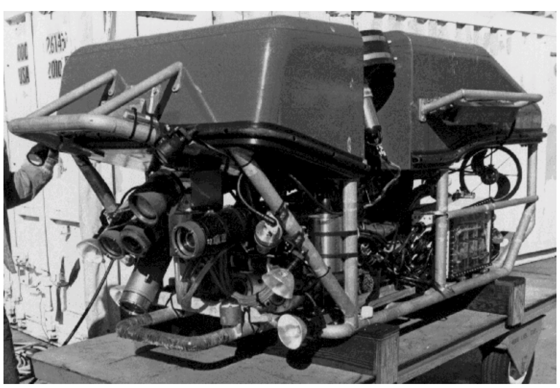
Rocky 7 Andros Mark V

Figure 17: Interesting articulated wheeled and tread-driven mobile robot systems

Notice that in the case of *Rocky*, a passive rocker-bogey linkage arrangement allows for the handling of larger obstacles than the wheel-size would allow, thereby reducing the required wheel-size and suspension system. The *Andros Mark V* robot system uses a set of articulated rear- and front-driven treads to allow it to climb over obstacles and up stairs more readily than a tracked vehicle of similar size.

Underwater Robot Frame System

Underwater robots are typically built quite differently from land-based systems, since they take advantage of buoyancy (corollary to zero-gravity space-systems). Hence they only need minimal framework to retain a desirable configuration, and provide for tie-downs for equipment, and thus need to only resist thruster- and hydrodynamic forces, rather than also gravitational forces. A typical ROV used in the exploration of the TITANIC and the discovery of underwater volcanoes and the recovery of roman amphoras from mediterranean roman shipwrecks, would be the *Jason Jr.* and *Jason* ROVs built at the Woods Hole Oceanographic Institution. Notice that these vehicles vary in size by up to a factor of 5, yet in each case, the framework consists of simple tubular aluminum (speed-rail) or flat-stock painted steel, that is used to tie-down the pressure-housings that contain all power systems, electronics and computing. The remainder of the framework is tailored to fasten to the flotation system, which for high-pressures is usually syntactic foam (miniature glass-spheres in an epoxy resin matrix). The overall views for both ROVs and the frame-view of *Jason Jr.* are shown in Figure 18.



JASON

JASON JR.

Figure 18: *Jason Jr.* & *Jason's* ROVs with typical ROV frame structure

MonoCoque Frame Design

Another example of a different type of frame design, can almost be termed a frameless design in that the actual robot structural elements are functional components of the robot and do not by themselves get attached to another framing system. A good example of this approach is the *Neptune* oil-storage tank inspection robot system, built for the US Army Corps of Engineers and Raytheon Engineers, Inc., depicted in

Figure 19. The robot was designed to be used in explosive environments, specifically light-crude storage tanks, where a remote internal visual and ultrasonic inspection of the bottom-plates of the tank without the need for draining and cleaning the tank and providing access to humans would be desirable.

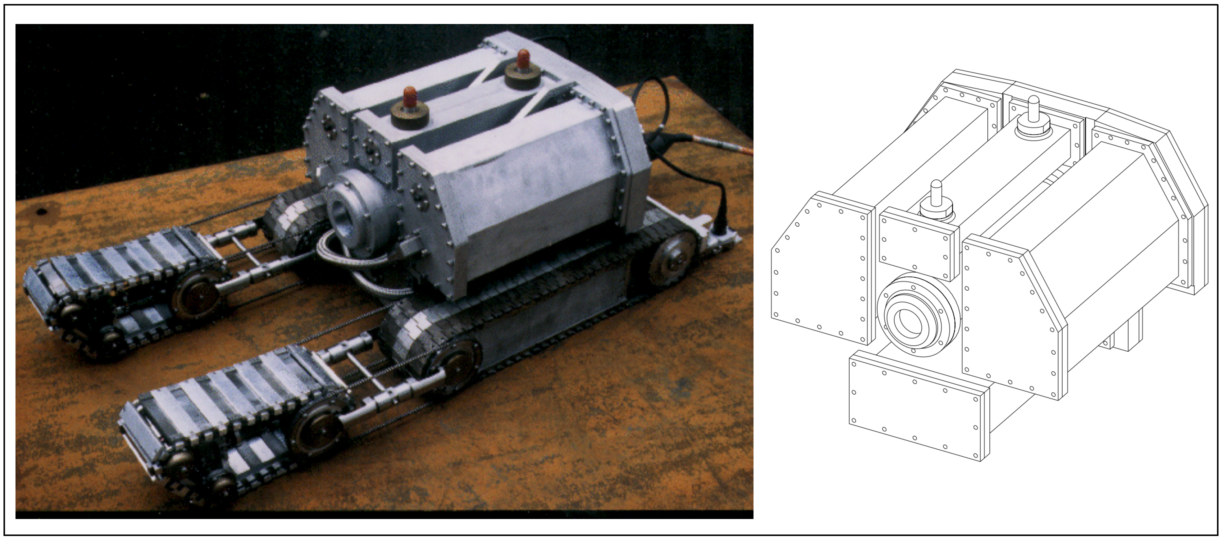


Figure 19: *Neptune* aboveground oil storage tank inspection robot

Notice that the system was again designed to fit through a 24-inch diameter opening, and is made solely of internally-pressurized equipment enclosures housing electronics and power systems, which are tied together in the rear by a hollow back-plate for cable-routing; not a single frame-member is used to hold any of the enclosures nor the tread locomotors.

3.3 Configuration Analysis

It is always tempting in case studies to provide purely informational reviews of robot designs that people have generated over the years - to be complete such a section would represent a directory in itself, since there are a large number of differing systems out in the world and in operation. In almost all cases, it is hard for any observer to determine why the configuration of a specific robot was chosen, what others were considered and what rationale was used to decide upon a specific configuration, locomotor, power-, computing and sensory system. Pontificating after the fact and analyzing designs based on one’s personal perspective is thus not necessarily a very objective nor fair undertaking. This dilemma of trying to provide the reader with a generic overview and guidelines, while working without the benefit of in-detail insight into each of the robots systems without which a fair and objective evaluation is impossible, thus leads us to realize a main point about mobile robot configuration: *Personal experience and backgrounds of a multidisciplinary team strongly influence a robot configuration, including the availability and maturity of existing technologies as well as the constraints of the application and the environment.* Useful design guidelines, mixed with a rigorous approach to evaluating alternative locomotion, actuation, power, computing and sensory systems are not treated or summarized in a single place, but rather sparsely distributed across multiple disciplines and centered around certain key figures and programs - it would seem to be high time to generate such a documentary volume to guide the way of future roboticists in this area - a far from trivial task!

4.0 Emerging Trends and Open Challenges in Robot Design

In the are of overall mobile system design, and mechanical design in particular, there are some areas where work continues and is still needed to further advance this field. The areas that are continually tackled by researchers and engineers lie in the overall areas of (i) system configuration, (ii) overall power and computing/communications autonomy, (iii) wheeled/tracked locomotion and (iv) legged locomotion.

4.1 System Configuration

There is no stead-fast set of rules when it comes to system configuration design. The trend in industry and in research is leaning towards the development of task-specific machines rather than generic systems that are usable in a wide array of environments. The analogy to be made is that, like industrial robot arms which are targeted at either highly-dexterous assembly tasks, high-precision trajectory following for spray-painting or point-to-point heavy-load transfer, mobile and legged robots have to be designed for a specific task-set. As such, a pipe-crawling robot can be used for sewer-line inspection, but not necessarily for large tank inspections. Due to the fact that mobile and legged systems work in a more unstructured world (except for AGVs in factory/warehousing operations), and in a much more expansive world without controllable conditions, they are usually designed for a well-formulated task to reduce complexity, cost and increase reliability and overall performance. The notion of a generic mobile robot akin to an android or pegasus-like device, might remain stuck on the drawing boards of science-fiction writers and cartoonist for a while to come, unless better software, higher-density compact power-supplies and compact actuators and sensors become a technical reality.

4.2 Autonomy - Power and Computing/Communications

Mobile and legged robot systems, whether autonomous or teleoperated, all continue to grapple with the fact that there are limits to the levels of available power, computing and communications. Any mobile system is usually a compromise in terms of these major drivers, since due to the range or working environment, the system might have to carry an umbilical power-cable. On the other hand, due to size and processing constraints, the necessary computing power might not be able to reside on-board, but rather off-board and rely upon a high-bandwidth data link to receive data and return commands. This constraint is the one most rapidly being eroded, since computing power is still on a geometric growth-rate, while power- and space-requirements are continually decreasing (only linearly though). Once on-board computing is implemented, the communications link requirements for real-time/telepresence experiences can become rather daunting. Given satellite communications and RF spread-spectrum technologies as well as fiber-optic telecommunications, we have begun tackling this bottleneck, with new applications continually demanding faster, cleaner and better links, thereby pushing technology developments. Communications bottlenecks will in the foreseeable future continue to drive designers into compromises in terms of overall system design.

4.3 Wheeled/Tracked Locomotion

There will continue to be a need for standard wheeled and tracked mobile robot systems in existing applications, where existing equipment or related configurations will require automation through retrofit. As developments have shown in the past 5 to 10 years, incremental innovations in terms of omni-directional wheels and articulated track-systems will enable designers to develop systems for particular applications, which will blaze the trail for the use of such locomotors in applications with similar environments/terrain. The use of articulated frame- and suspension systems to increase the terrainability of wheeled systems as well as the design of traction features for increased locomotion capability will see continued work in the research and commercial world. Tracked systems will become more capable through the use of articulated and steerable chain designs, enabling smaller and simpler system designs to carry out novel tasks. The limit in this field will only be the innovative spirit and inventive capabilities of designers and inventors in this world!

4.4 Legged Locomotion

The field of legged locomotion will continue to be a primary target of curiosity and one-off system developments. Most major multi-legged system developments have been in the area of research and exploration. Notable systems have been developed for research and potential planetary exploration use, but none have really been a commercial success. To date, the only legged system that has to my knowledge seen any real-world use are drag-line open-pit mine-excavator systems, and possibly rough-terrain logging systems in Finland (even then the commercial success of the latter is questionable at this time). In order for such systems to become a success, the control and computing complexity of such systems has to be reduced through better software and more capable sensing and computing, and the ultimate operational achilles-heel of any system, parts count and complexity (resulting in increased failure modes and reduced reliability) needs to be reduced to allow operational availability (MTBF - mean time between failures) comparable to wheeled and tracked systems.

One continued area of research limited to university-level and internal company research efforts (mostly in Japan), is that of biped locomotion. The manifestation is one of development of anthropomorphic systems with locomotion capabilities akin to humans and state-of-the-art sensing and computing systems. The immediate goals of studying overall system capability and long-term potential are obvious, yet the advent of a commercial bipedal system with a clearly defined task in a commercial setting has still escaped developers. Research will and should continue in this area, but overall system capabilities as expressed in terms of power-, sensory-, computing- and communications-autonomy have to see improvements of one- to two-orders of magnitude before bipeds can become viable automatons. It might only be a matter of time before dramatic new technology developments help bring that vision closer to reality in the next decade or two.

4.5 System Integration

Even though it would not be termed a ‘research-’ nor ‘scientific-pursuit’ area, the art of retrofitting and integrating components to achieve a working and modular and maintainable system is still a completely experiential artform[1]. In the aerospace industry, the closest analog job description they have is that of the packaging engineer. In the case of robotic systems, all engineering disciplines should be trained in the pitfalls and dos-and-don’ts of systems integration. It is the authors opinion that an edited book-release on this subject is long overdue, seeing as their is no real authoritative publication on mobile robot design and integration.

4.6 System Retrofitting

The definition of mobile robots is also expanding into the more traditional field of construction, agriculture and mining. In these areas, researchers and industrial outfits are working towards retrofitting their existing equipment with autonomy-modules (sensing, computing, actuation, etc.) to allow their typical manually-operated equipment to not only operate remotely, but to also operate autonomously and under minimal supervision by an operator. This area will continue growing to the point where such integrated autonomous or intelligent platforms built today by such household names such as JOHN DEERE, CATERPILLAR, JOY MINING Co., TORO and HOOVER will eventually offer systems of substantial automation and autonomy which will challenge all fields including electronics, computing and mechanical design to develop a fully integrated, working, robust and long-lived maintainable product. Again, even though not a pure science, this field of applied research and engineering will continue to expand and possibly dominate the field of robotics in the near-term.

1. I use this term on purpose, because there are no rigid steadfast rules for this process and it depends on the individual(s) in charge of that process.

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