For Vicky, Conor, and Alex

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Introduction

This book is meant to be interesting, helpful, and educational to hobbyists, students, educators, and midlevel engineers studying or designing mobile robots that do real work. It is primarily focused on mechanisms and devices that relate to vehicles that move around by themselves and actually do things autonomously, i.e. a robot. Making a vehicle that can autonomously drive around, both indoors and out, seems, at first, like a simple thing. Build a chassis, add drive wheels, steering wheels, a power source (usually batteries), some control code that includes some navigation and obstacle avoidance routines or some other way to control it, throw some bump sensors on it, and presto! a robot.

Unfortunately, soon after these first attempts, the designer will find the robot getting stuck on what seem to be innocuous objects or bumps, held captive under a chair or fallen tree trunk, incapable of doing anything useful, or with a manipulator that crushes every beer can it tries to pick up. Knowledge of the mechanics of sensors, manipulators, and the concept of mobility will help reduce these problems. This book provides that knowledge with the aid of hundreds of sketches showing drive layouts and manipulator geometries and their work envelope. It discusses what mobility really is and how to increase it without increasing the size of the robot, and how the shape of the robot can have a dramatic effect on its performance. Interspersed throughout the book are unusual mechanisms and devices, included to entice the reader to think outside the box. It is my sincere hope that this book will decrease the time it takes to produce a working robot, reduce the struggles and effort required to achieve that goal, and, therefore, increase the likelihood that your project will be a success.

Building, designing, and working with practical mobile robots requires knowledge in three major engineering fields: mechanical, electrical, and software. Many books have been written on robots, some focusing on the complete robot system, others giving a cookbook approach allowing a novice to take segments of chapters and put together a unique robot. While there are books describing the electric circuits used in robots, and books that teach the software and control code for robots, there are few that are focused entirely on the mechanisms and mechanical devices used in mobile robots.

This book intends to fill the gap in the literature of mobile robots by containing, in a single reference, complete graphically presented information on the mechanics of a mobile robot. It is written in laymen's language and filled with sketches so novices and those not trained in mechanical engineering can acquire some understanding of this interesting field. It also includes clever schemes and mechanisms that mid-level mechanical engineers should find new and useful. Since mobile robots are being called on to perform more and more complex and practical tasks, and many are now carrying one or even two manipulators, this book has a section on manipulators and grippers for mobile robots. It shows why a manipulator used on a robot is different in several ways from a manipulator used in industry.

Autonomous robots place special demands on their mobility system because of the unstructured and highly varied environment the robot might drive through, and the fact that even the best sensors are poor in comparison to a human's ability to see, feel, and balance. This means the mobility system of a robot that relies on those sensors will have much less information about the environment and will encounter obstacles that it must deal with on its own. In many cases, the microprocessor controlling the robot will only be telling the mobility system "go over there" without regard to what lays directly in that path. This forces the mobility system to be able to handle anything that comes along.

In contrast, a human driver has very acute sensors: eyes for seeing things and ranging distances, force sensors to sense acceleration, and balance to sense levelness. A human expects certain things of an automobile's (car, truck, jeep, HumVee, etc.) mobility system (wheels, suspension, and steering) and uses those many and powerful sensors to guide that mobility system's efforts to traverse difficult terrain. The robot's mobility system must be passively very capable, the car's mobility system must feel right to a human.

For these reasons, mobility systems on mobile robots can be both simpler and more complex than those found in automobiles. For example, the Ackerman steering system in automobiles is not actually suited for high mobility. It feels right to a human, and it is well suited to higher speed travel, but a robot doesn't care about feeling right, not yet, at least! The best mobility system for a robot to have is one that effectively accomplishes the required task, without regard to how well a human could use it.

Because the photopolymer used in the SL process tends to curl or sag as it cures, models with overhangs or unsupported horizontal sections must be reinforced with supporting structures: walls, gussets, or columns. Without support, parts of the model can sag or break off before the polymer has fully set. Provision for forming these supports is included in the digitized fabrication data. Each scan of the laser forms support layers where necessary while forming the layers of the model.

When model fabrication is complete, it is raised from the polymer vat and resin is allowed to drain off; any excess can be removed manually from the model's surfaces. The SL process leaves the model only partially polymerized, with only about half of its fully cured strength. The model is then finally cured by exposing it to intense UV light in the enclosed chamber of post-curing apparatus (PCA). The UV completes the hardening or curing of the liquid polymer by linking its molecules in chainlike formations. As a final step, any supports that were required are removed, and the model's surfaces are sanded or polished. Polymers such as urethane acrylate resins can be milled, drilled, bored, and tapped, and their outer surfaces can be polished, painted, or coated with sprayed-on metal.

The liquid SL photopolymers are similar to the photosensitive UV-curable polymers used to form masks on semiconductor wafers for etching and plating features on integrated circuits. Resins can be formulated to solidify under either UV or visible light.

The SL process was the first to gain commercial acceptance, and it still accounts for the largest base of installed RP systems. 3D Systems of Valencia, California, is a company that manufactures stereolithography equipment for its proprietary SLA process. It offers the *ThermoJet Solid Object Printer*. The SLA process can build a model within a volume measuring $10 \times 7.5 \times 8$ in. ($25 \times 19 \times 20$ cm). It also offers the SLA 7000 system, which can form objects within a volume of $20 \times 20 \times 23.62$ in. ($51 \times 51 \times 60$ cm). Aaroflex, Inc. of Fairfax, Virginia, manufactures the Aacura 22 solid-state SL system and operates AIM, an RP manufacturing service.

Solid Ground Curing (SGC)

Solid ground curing (SGC) (or the "solider process") is a multistep in-line process that is diagrammed in Figure 2. It begins when a photomask for the first layer of the 3D model is generated by the equipment shown at the far left. An electron gun writes a charge pattern of the photomask on a clear glass plate, and opaque toner is transferred electrostatically to the plate to form the photolithographic pattern in a xerographic process.

Acknowledgments

This book would not even have been considered and would never have been completed without the encouragement and support of my loving wife, Victoria. Thank you so much.

In addition to the support of my wife, I would like to thank Joe Jones for his input, criticism, and support. Thank you for putting up with my many questions. Thanks also goes to Lee Sword, Chi Won, Tim Ohm, and Scott Miller for input on many of the ideas and layouts. The process of writing this book was made much easier by iRobot allowing me to use their office machines. And, lastly, thanks to my extended family, especially my Dad and Jenny for their encouragement and patience.

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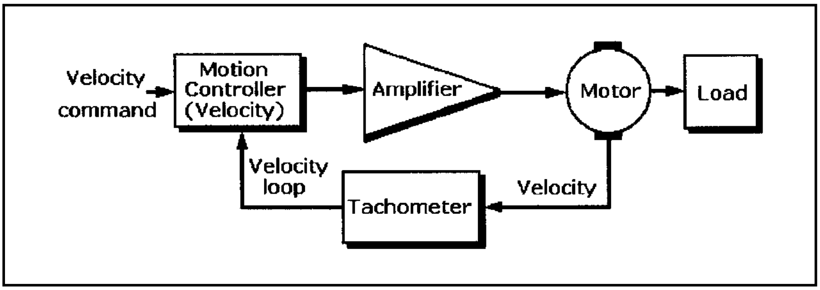

Figure 1-4 Block diagram of a velocity-control system.

to the motion controller so that it can compute a corrective signal for the amplifier to keep motor speed within those preset limits despite load changes.

A *position-control loop,* as shown in block diagram Figure 1-5, typically contains either an encoder or resolver capable of direct or indirect measurements of load position. These sensors generate error signals that are sent to the motion controller, which produces a corrective signal for amplifier. The output of the amplifier causes the motor to speed up or slow down to correct the position of the load. Most position control closed-loop systems also include a velocity-control loop.

The *ballscrew slide mechanism*, shown in Figure 1-6, is an example of a mechanical system that carries a load whose position must be controlled in a closed-loop servosystem because it is not equipped with position sensors. Three examples of feedback sensors mounted on the ballscrew mechanism that can provide position feedback are shown in Figure 1-7: (a) is a rotary optical encoder mounted on the motor housing with its shaft coupled to the motor shaft; (b) is an optical linear encoder with its gradu-

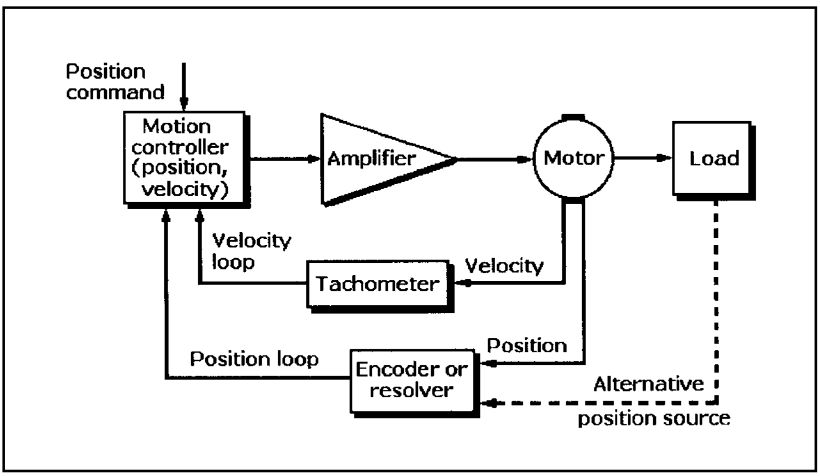

Figure 1-5 Block diagram of a position-control system.

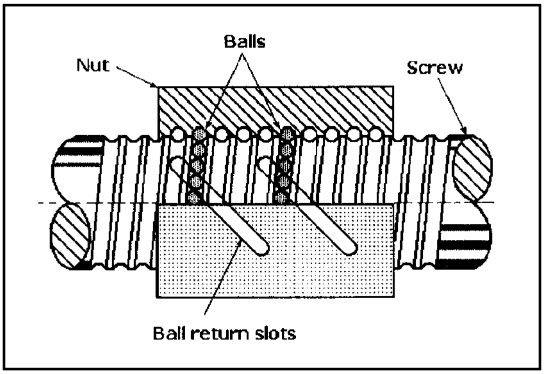

Figure 1-11 Ballscrew drive: Ballscrews use recirculating balls to reduce friction and gain higher efficiency than conventional leadscrews.

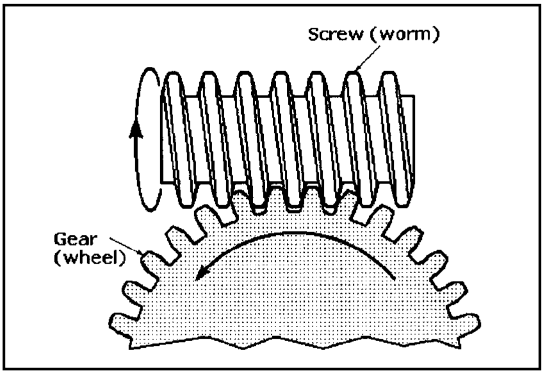

Figure 1-12 Worm-drive systems can provide high speed and high torque.

Linear guides or stages constrain a translating load to a single degree of freedom. The linear stage supports the mass of the load to be actuated and assures smooth, straight-line motion while minimizing friction. A common example of a linear stage is a ballscrew-driven single-axis stage, illustrated in Figure 1-13. The motor turns the ballscrew, and its rotary motion is translated into the linear motion that moves the carriage and load by the stage's bolt nut. The bearing ways act as linear guides. As shown in Figure 1-7, these stages can be equipped with sensors such as a rotary or linear encoder or a laser interferometer for feedback.

A ballscrew-driven single-axis stage with a rotary encoder coupled to the motor shaft provides an indirect measurement. This method ignores

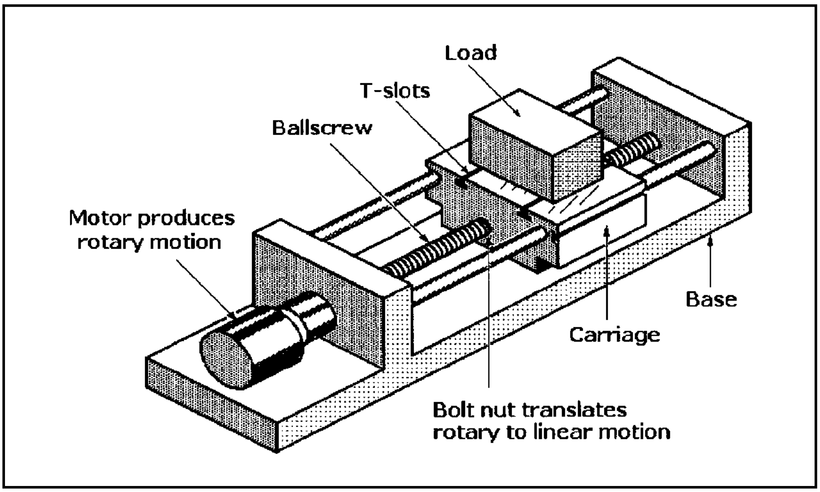

Figure 1-13 Ballscrew-driven single-axis slide mechanism translates rotary motion into linear motion.

mutation. The stator is formed as an ironless sleeve of copper coils bonded together in polymer resin and fiberglass to form a rigid structure similar to cup-type rotors. However, it is fastened inside the steel laminations within the motor housing.

This method of construction permits a range of values for starting current and specific speed (rpm/V) depending on wire gauge and the number of turns. Various terminal resistances can be obtained, permitting the user to select the optimum motor for a specific application. The Hall-effect sensors and a small magnet disk that is magnetized widthwise are mounted on a disk-shaped partition within the motor housing.

Position Sensing in Brushless Motors

Both magnetic sensors and resolvers can sense rotor position in brushless motors. The diagram in Figure 1-25 shows how three magnetic sensors can sense rotor position in a three-phase electronically commutated brushless DC motor. In this example the magnetic sensors are located inside the end-bell of the motor. This inexpensive version is adequate for simple controls.

In the alternate design shown in Figure 1-26, a resolver on the end cap of the motor is used to sense rotor position when greater positioning accuracy is required. The high-resolution signals from the resolver can

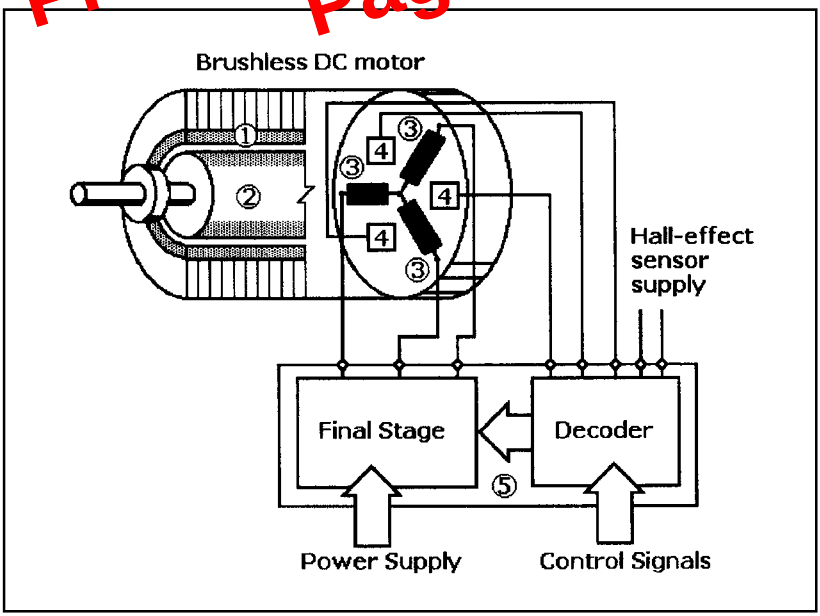

Figure 1-25 A magnetic sensor as a rotor position indicator: stationary brushless motor winding (1), permanent-magnet motor rotor (2), three-phase electronically commutated field (3), three magnetic sensors (4), and the electronic circuit board (5).

Absolute Encoders

An *absolute shaft-angle optical encoder* contains multiple light sources and photodetectors, and a code disk with up to 20 tracks of segmented patterns arranged as annular rings, as shown in Figure 1-37. The code disk provides a binary output that uniquely defines each shaft angle, thus providing an absolute measurement. This type of encoder is organized in essentially the same way as the incremental encoder shown in Figure 1-35, but the code disk rotates between linear arrays of LEDs and photodetectors arranged radially, and a LED opposes a photodetector for each track or annular ring.

The arc lengths of the opaque and transparent sectors decrease with respect to the radial distance from the shaft. These disks, also made of glass or plastic, produce either the natural binary or Gray code. Shaft position accuracy is proportional to the number of annular rings or tracks on the disk. When the code disk rotates, light passing through each track or annular ring generates a continuous stream of signals from the detector array. The electronics board converts that output into a binary word. The value of the output code word is read radially from the most significant bit (MSB) on the inner ring of the disk to the least significant bit (LSB) on the outer ring of the disk.

The principal reason for selecting an absolute encoder over an incremental encoder is that its code disk retains the last angular position of the encoder shaft whenever it stops moving, whether the system is shut down deliberately or as a result of power failure. This means that the last readout is preserved, an important feature for many applications.

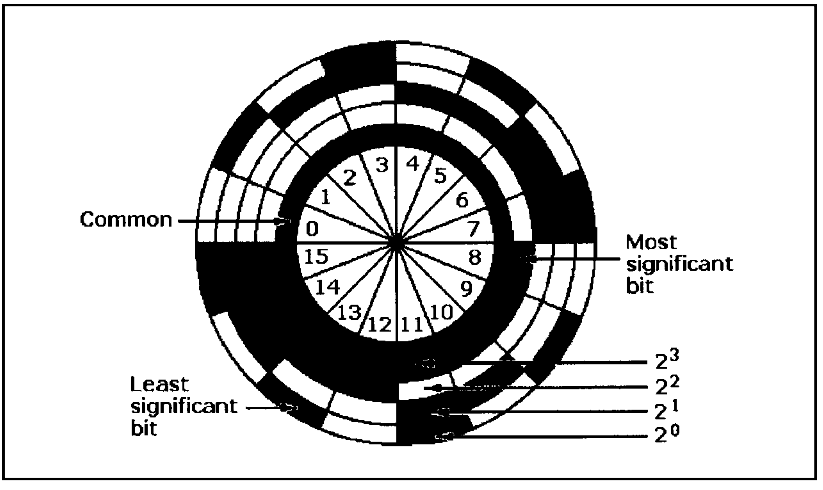

Figure 1-37 Binary-code disk for an absolute optical rotary encoder. Opaque sectors represent a binary value of 1, and the transparent sectors represent binary 0. This four-bit binary-code disk can count from 1 to 15.

quasi sine wave (depending on the type of magnetic sensing device) can be used to count revolutions per minute (rpm) or determine motor shaft accurately. The phase shift between channels A and B permits them to be compared by the motion controller to determine the direction of motor shaft rotation.

Resolvers

A resolver is essentially a rotary transformer that can provide position feedback in a servosystem as an alternative to an encoder. Resolvers resemble small AC motors, as shown in Figure 1-40, and generate an electrical signal for each revolution of their shaft. Resolvers that sense position in closed-loop motion control applications have one winding on the rotor and a pair of windings on the stator, oriented at 90º. The stator is made by winding copper wire in a stack of iron laminations fastened to the housing, and the rotor is made by winding copper wire in a stack of laminations mounted on the resolver's shaft.

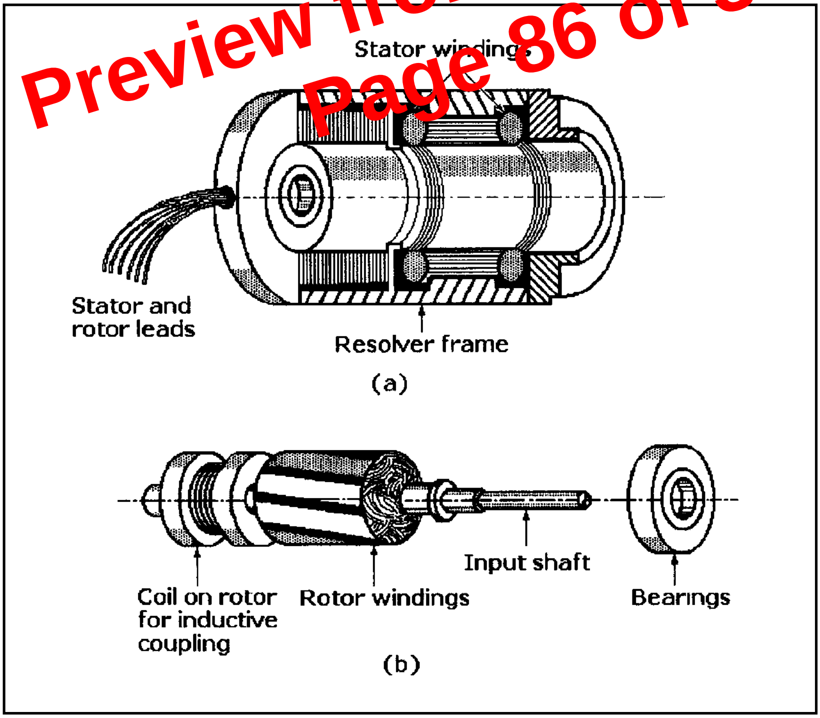

Figure 1-40 Exploded view of a brushless resolver frame (a), and rotor and bearings (b). The coil on the rotor couples speed data inductively to the frame for processing.

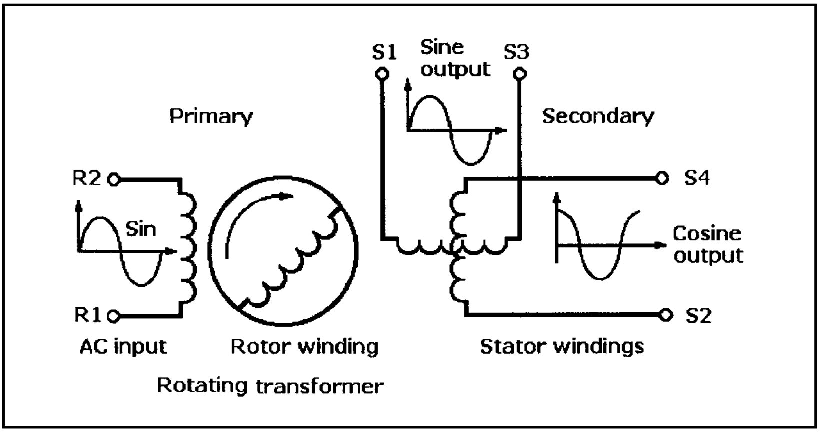

Figure 1-41 Schematic for a resolver shows how rotor position is transformed into sine and cosine outputs that measure rotor position.

Figure 1-41 is an electrical schematic for a brushless resolver showing the single rotor winding and the two stator windings 90° apart. In a servosystem, the resolver's rotor is mechanically coupled to the drive motor and load. When a rotor winding is excited by an AC reference signal, it produces an AC voltage output that varies in amplitude according to the sine and cosine of shaft position. If the phase shift between the applied signal to the rotor and the induced signal appearing on the stator coil is measured, that angle is an analog of rotor position. The absolute position of the load being driven can be determined by the ratio of the sine output amplitude to the cosine output amplitude as the resolver shaft turns through one revolution. (A single-speed resolver produces one sine and one cosine wave as the output for each revolution.)

Connections to the rotor of some resolvers can be made by brushes and slip rings, but resolvers for motion control applications are typically brushless. A rotating transformer on the rotor couples the signal to the rotor inductively. Because brushless resolvers have no slip rings or brushes, they are more rugged than encoders and have operating lives that are up to ten times those of brush-type resolvers. Bearing failure is the most likely cause of resolver failure. The absence of brushes in these resolvers makes them insensitive to vibration and contaminants. Typical brushless resolvers have diameters from 0.8 to 3.7 in. Rotor shafts are typically threaded and splined.

Most brushless resolvers can operate over a 2- to 40-volt range, and their winding are excited by an AC reference voltage at frequencies from 400 to 10,000 Hz. The magnitude of the voltage induced in any stator winding is proportional to the cosine of the angle, q, between the rotor coil axis and the stator coil axis. The voltage induced across any pair of stator terminals will be the vector sum of the voltages across the two connected coils. Accuracies of ±1 arc-minute can be achieved.

In feedback loop applications, the stator's sinusoidal output signals are transmitted to a resolver-to-digital converter (RDC), a specialized analog-to-digital converter (ADC) that converts the signals to a digital representation of the actual angle required as an input to the motion controller.

Tachometers

A tachometer is a DC generator that can provide velocity feedback for a servosystem. The tachometer's output voltage is directly proportional to the rotational speed of the armature shaft that drives it. In a typical servosystem application, it is mechanically coupled to the DC motor and feeds its output voltage back to the controller and amplifier to control drive motor and load speed. A cross-sectional drawing of a tachometer built into the same housing as the DC motor and a resolver is shown in Figure 1-42. Encoders or resolvers are part of separate loops that provide position feedback.

As the tachometer's armature coils rotate through the stator's magnetic field, lines of force are cut so that an electromotive force is induced in each of its coils. This emf is directly proportional to the rate at which

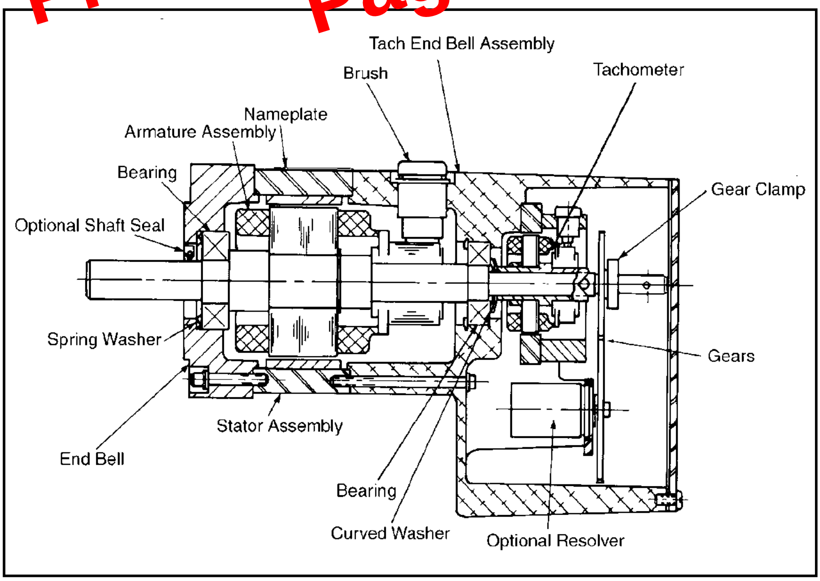

Figure 1-42 Section view of a resolver and tachometer in the same frame as the servomotor.

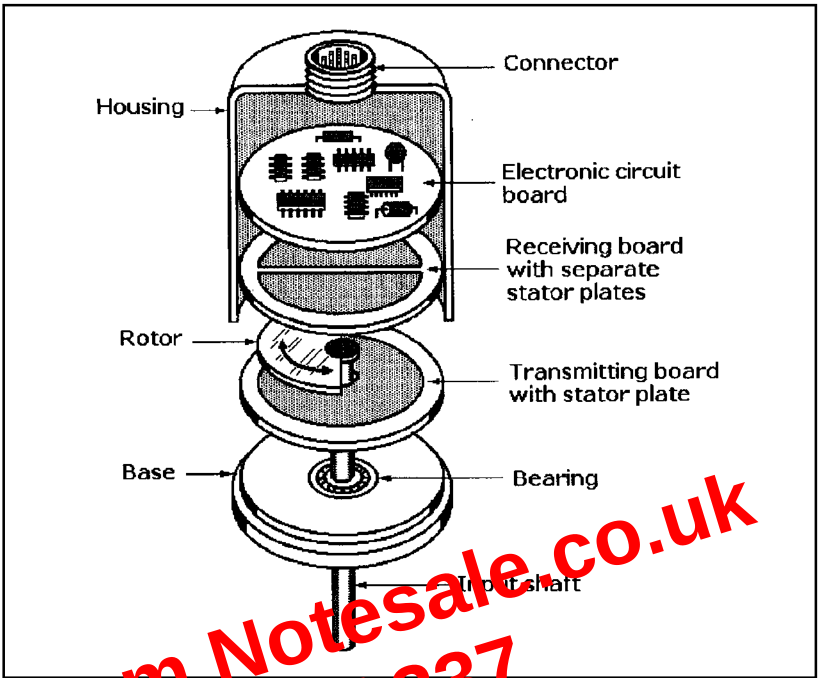

Figure 1-47 Exploded view of an angular displacement transducer (ADT) based on a differential variable capacitor.

The base is the mounting platform for the transducer assembly. It contains the axial ball bearing that supports the shaft to which the rotor is fastened. The base also supports the transmitting board, which contains a metal surface that forms the lower plate of the differential capacitor. The semicircular metal rotor mounted on the shaft is the variable plate or rotor of the capacitor. Positioned above the rotor is the receiving board containing two separate semicircular metal sectors on its lower surface. The board acts as the receiver for the AC signal that has been modulated by the capacitance difference between the plates caused by rotor rotation.

An electronics circuit board mounted on top of the assembly contains the oscillator, demodulator, and filtering circuitry. The ADT is powered by DC, and its output is a DC signal that is proportional to angular displacement. The cup-shaped housing encloses the entire assembly, and the base forms a secure cap.

DC voltage is applied to the input terminals of the ADT to power the oscillator, which generates a 400- to 500-kHz voltage that is applied across the transmitting and receiving stator plates. The receiving plates are at virtual ground, and the rotor is at true ground. The capacitance value between the transmitting and receiving plates remains constant,

Technical Considerations

Important factors to consider when selecting solenoids are their rated torque/force, duty cycles, estimated working lives, performance curves, ambient temperature range, and temperature rise. The solenoid must have a magnetic return path capable of transmitting the maximum amount of magnetic flux density with minimum energy input. Magnetic flux lines are transmitted to the plunger or armature through the bobbin and air gap back through the iron or steel shell. A ferrous metal path is more efficient than air, but the air gap is needed to permit plunger or armature movement. The force or torque of a solenoid is inversely proportional to the square of the distance between pole faces. By optimizing the ferrous path area, the shape of the plunger or armature, and the magnetic circuit material, the output torque/force can be increased.

The torque/force characteristic is an important solenoid specification. In most applications the force can be a minimum at the start of the plunger or armature stroke but must increase at a rapid rate to reach the maximum value before the plunger or armature reaches the backstop.

The magnetizing force of the solenoid is proportional to the number of copper wire turns in its coil, the magnitude of the current, and the permeance of the magnetic circuit. The pull force required by the load must not be greater than the force developed by the solenoid during any portion of its required stroke, or the plunger or armature will not pull in completely. As a result, the load will not be moved the required distance.

Heat buildup in a solenoid is a function of power and the length of time the power is applied. The permissible temperature rise limits the magnitude of the input power. If constant voltage is applied, heat buildup can degrade the efficiency of the coil by effectively reducing its number of ampere turns. This, in turn, reduces flux density and torque/force output. If the temperature of the coil is permitted to rise above the temperature rating of its insulation, performance will suffer and the solenoid could fail prematurely. Ambient temperature in excess of the specified limits will limit the solenoid cooling expected by convection and conduction.

Heat can be dissipated by cooling the solenoid with forced air from a fan or blower, mounting the solenoid on a heat sink, or circulating a liquid coolant through a heat sink. Alternatively, a larger solenoid than the one actually needed could be used.

The heating of the solenoid is affected by the duty cycle, which is specified from 10 to 100%, and is directly proportional to solenoid *on* time. The highest starting and ending torque are obtained with the lowest duty cycle and *on* time. Duty cycle is defined as the ratio of *on* time to the sum of *on* time and *off* time. For example, if a solenoid is energized for 30 s and then turned off for 90 s, its duty cycle is $^{30}/_{120} = ^{1}/_{4}$, or 25%.

The amount of work performed by a solenoid is directly related to its size. A large solenoid can develop more force at a given stroke than a small one with the same coil current because it has more turns of wire in its coil.

Open-Frame Solenoids

Open-frame solenoids are the simplest and least expensive models. They have open steel frames, exposed coils, and movable plungers centered in their coils. Their simple design permits them to be made inexpensively in high-volume production runs so that they can be sold at low cost. The two forms of open-frame solenoid are the *C-frame solenoid* and the *box-frame solenoid*. They are usually specified for applications where very long life and precise positioning are not critical requirements.

C-Frame Solenoids

C-frame solenoids are low-cost commercial solenoids intended for light-duty applications. The frames are typically laminated steel formed in the shape of the letter C to complete the magnetic circuit through the core, but they leave the coil windings without a complete protective cover. The plungers are typically made as laminated steel bars. However, the coils are usually potted to resist airborne and liquid contaminants. These solenoids can be found in appliances, printers, coin dispensers, security door locks, cameras, and vending machines. They can be powered with either AC or DC current. Nevertheless, C-frame solenoids can have operational lives of millions of cycles, and some standard catalog models are capable of strokes up to 0.5 in. (13 mm).

Box-Frame Solenoids

Box-frame solenoids have steel frames that enclose their coils on two sides, improving their mechanical strength. The coils are wound on phenolic bobbins, and the plungers are typically made from solid bar stock. The frames of some box-type solenoids are made from stacks of thin insulated sheets of steel to control eddy currents as well as keep stray circulating currents confined in solenoids powered by AC. Box-frame soleelectronics, which is, in turn, controlled by the software, which takes inputs from the sensors to make its decisions. The relationship between the sensors and actuators is much more complicated than just one sensor connected through software to one actuator. The sensors work sometimes individually and sometimes as a group. The control software must look at the inputs from the all sensors, make intelligent decisions based on that information, and then send commands to one, or many of the actuators. Bugs will be found at any point in this large number of combinations of sensors and actuators.

Mechanical bugs, electronic bugs, software bugs, and bugs caused by interactions between those engineering disciplines will appear and solutions must be found for them. Every actuator adds a whole group of relationships, and therefore the potential for a whole group of bugs.

Reliability

For much the same reasons, reliability is also affected by actuator count. There are simply more things that can go wrong, and they will. Every moving part has a limited lifetime, and every piece of the robot has a chance of being made incorrectly, assembled incorrectly, becoming loose from vibration, being damaged by something in the environment, etc. A rule of thumb is that every part added potentially decreases reliability.

Cost

Cost should also be figured in when working on the initial phases of design, though for some applications cost is less important. Each actuator adds its own cost, its associated electronics, the parts that the actuator moves or uses, and the cost of the added debug time. The designer or design team should seriously consider having a slightly less capable platform or manipulator and leave out one or two actuators, for a significant increase in reliability, greatly reduced debug time, and reduced cost.

Face gears have straight tooth surfaces, but their axes lie in planes perpendicular to shaft axes. They are designed to mate with instantaneous point contact. These gears are used in right-angle drives, but they have low load capacities.

Designing a properly sized gearbox is not a simple task and tables or manufacturer's recommendations are usually the best place to look for help. The amount of power a gearbox can transmit is affected by gear size, tooth size, rpm of the faster shaft, lubrication method, available cooling method (everything from nothing at all to forced air), gear materials, bearing types, etc. All these variables must be taken into account to come up with an effectively sized gearbox. Don't be daunted by this. In most cases the gearbox is not designed at all, but easily selected from a large assortment of off-the-shelf gearboxes made by one of many manufacturers. Let's now turn our attention to more complicated gearboxes that do more than just exchange speed for torque.

Worm Gears

Worm gear drives get their name from the unusual input gear which looks vaguely like a worm wrapped around a shaft. They are used primarily for high reduction ratios, from 5:1 to 100s:1. Their main disadvantage is inefficiency caused by the worm gear's sliding contact with the worm wheel. In larger reduction ratios, they can be self locking, meaning when the input power is turned off, the output cannot be rotated. The following section discusses an unusual double enveloping, internally-lubricated worm gear layout that is an attempt to increase efficiency and the life of the gearbox.

WORM GEAR WITH HYDROSTATIC ENGAGEMENT

Friction would be reduced greatly.

Lewis Research Center, Cleveland, Ohio

In a proposed worm-gear transmission, oil would be pumped at high pressure through the meshes between the teeth of the gear and the worm coil (Figure 2-16). The pressure in the oil would separate the meshing surfaces slightly, and the oil would reduce the friction between these sur-

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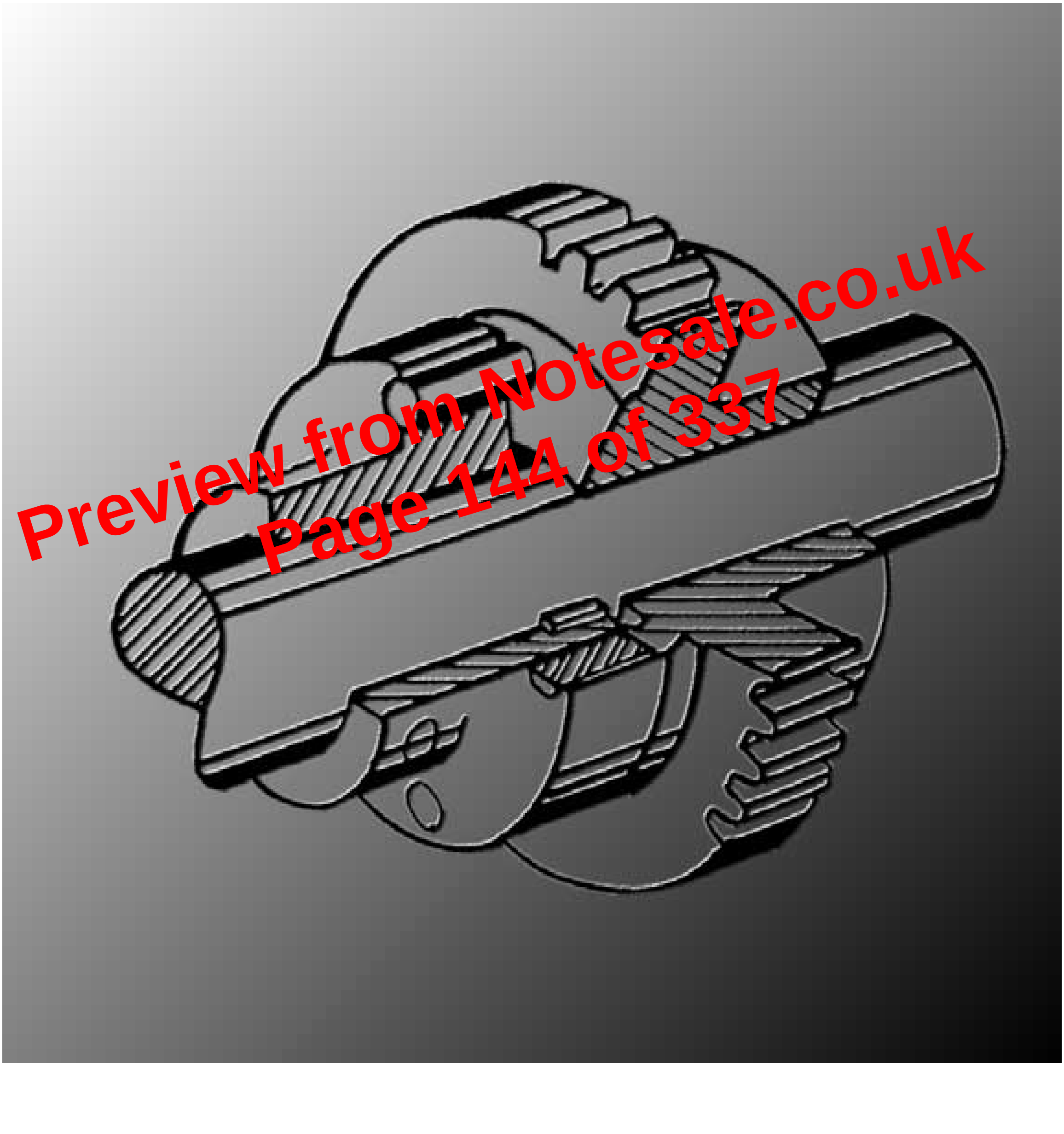
Chapter 3 Direct Power Transfer Devices



Given the definition of robot in the introduction to this book, the most vital mechanical part of a robot must be its mobility system, including the suspension and drivetrain, and/or legs and feet. The ability of the these systems to effectively traverse what ever terrain is required is paramount to the success of the robot, but to my knowledge, there has never been an apples to apples comparison of mobility systems.

First, just what is a mobility system? A mobility system is all parts of a vehicle, a land-based robot for the purposes of this book, that aid in locomoting from one place to another. This means all motors, gearboxes, suspension pieces, transmissions, wheels, tires, tracks, springs, legs, foot pads, linkages, mechanisms for moving the center of gravity, mechanisms for changing the shape or geometry of the vehicle, mechanisms for changing the shape or geometry of the drivetrain, mechanisms and linkages for steering, etc., are part of mobility systems.

The systems and mechanisms described in this book are divided into four general categories: wheeled, tracked, walkers, and special cases. Each gets its own chapter and following the chapter on special cases is a separate chapter devoted to comparing the effectiveness of many of the systems.

There are some that are described in the text that are not discussed in Chapter Nine. These are mostly very interesting designs that are worth describing, but their mobility or some other trait precludes comparing them to the other designs. Most of the systems discussed in Chapter Eight fall into this category because they are designed to move through very specific environments and are not general enough to be comparable. Some wheeled designs are discussed simply because they are very simple even though their mobility is limited. This chapter deals with wheeled systems, everything from one-wheeled vehicles to eight-wheeled vehicles. It is divided into four sections: vehicles with one to three wheels and four-wheeled diamond layouts, four- and five-wheeled layouts, six-wheeled layouts, and eight-wheeled layouts.

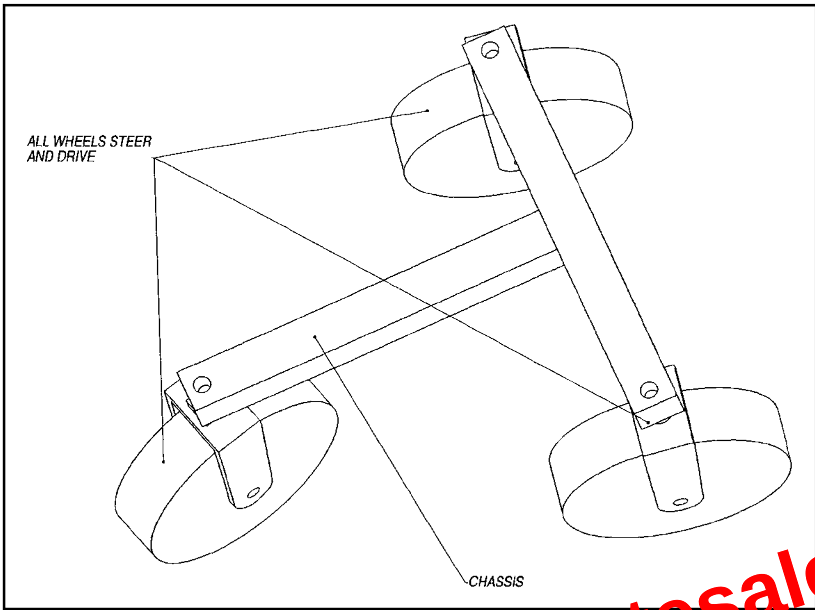


Figure 4-8 Reversed tricycle, all drive, all steer

The most complicated and highest mobility three-wheeled layout is one where all wheels are powered and steered. This layout is extremely versatile, providing motion in any direction without the need to be moving it can turn in place. This ability is called holonomic motion and is very useful for mobile robots because it can significantly improve mobility in cluttered terrain. Of the vehicles discussed so far, all, except the front steer reversed tricycle, can be made holonomic if the third wheel lies on the circumference of the circle whose center is midway between the two opposing wheels, and the steering or passive wheel can swing through 180 degrees. To be truly holonomic, even in situations where the vehicle is enclosed on three sides, like in a dead-end hallway, the vehicle itself must be round. This enables it to turn at any time to find a path out of its trap. See Figure 4-8.

Before we investigate four-wheeled vehicles, there is a mechanism that must be, at least basically, understood—the differential. The differential (Figure 4-9) gets its name from the fact that it differentiates the rotational velocity of two wheels driven from one drive shaft. The most basic differential uses a set of gears mounted inside a larger gear, but on an axis that lies along a radius of the larger gear. These gears rotate with the large gear, and are coupled to the axles through crown gears on the ends of the axles. When both wheels are rolling on relatively high fric-

FOUR-WHEELED LAYOUTS

The most basic four-wheeled vehicle actually doesn't even use a differential. It has two wheels on each side that are coupled together and is steered just like differential steered tricycles. Since the wheels are in line on each side and do not turn when a corner is commanded, they slide as the vehicle turns. This sliding action gives this steering method its name—Skid Steer. Notice that this layout does not use differentials, even though it is also called differential steering.

Skid steered vehicles are a robust, simple design with good mobility, in spite of the inefficiency of the sliding wheels. Because the wheels don't turn, it is easy to attach them to the chassis, and they don't take up the space required to turn. There are many industrial off-road skid steered vehicles in use, popularly called Bobcats. Figure 4-10 shows that a skid steered vehicle is indeed very simple.

The problem with skid steered, non-suspended drivetrains is that as the vehicle goes over bumps, one wheel necessarily comes off the ground. This problem doesn't exist in two or three wheeled vehicles, but is a major thing to deal with on vehicles with more than three wheels. Though not a requirement for good mobility, it is better to use some mechanism that keeps all the wheels on the ground. There are many ways to accomplish this, starting with a design that splits the chassis in two.

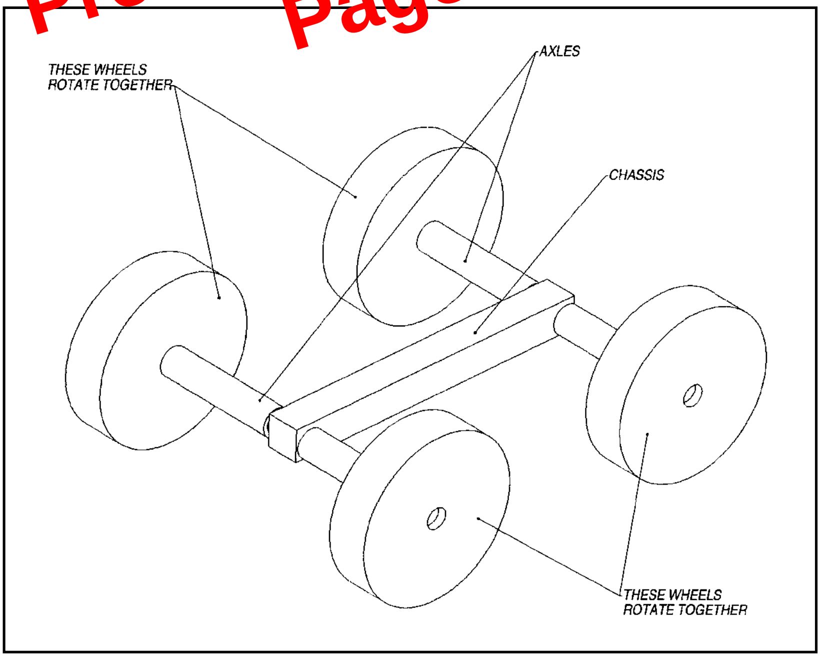


Figure 4-10 All four fixed, skid steered

own motor. This design cannot turn in place, but careful layout can produce a vehicle that can turn in little more than twice its width.

Greater mobility is achieved if the center joint also allows a rolling motion between the two sections. This degree of freedom keeps all four wheels on the ground while traversing uneven terrain or obstacles. It also improves traction while turning on bumps. Highest mobility for this layout would come from powering both the pivot and roll joints with their own motors and each wheel individually powered for a total of six motors. Alternatively, the wheels could be powered through limited slip differentials and the roll axis left passive for less mobility, but only three motors. Figures 4-18 and 4-19 show these two closely related layouts.

An unusual and unintuitive layout is the five-wheeled drivetrain. This is basically the tricycle layout, but with an extra pair of wheels in the back to increase traction and ground contact area. The front wheel is not normally powered and is only for steering. Figure 4-20 shows this is a fairly simple layout relative to its mobility, especially if the side wheel pairs are driven together through a simple chain or belt drive. Although the front wheels must be pushed over obstacles, there is ample traction from all that rubber on the four rear wheels.

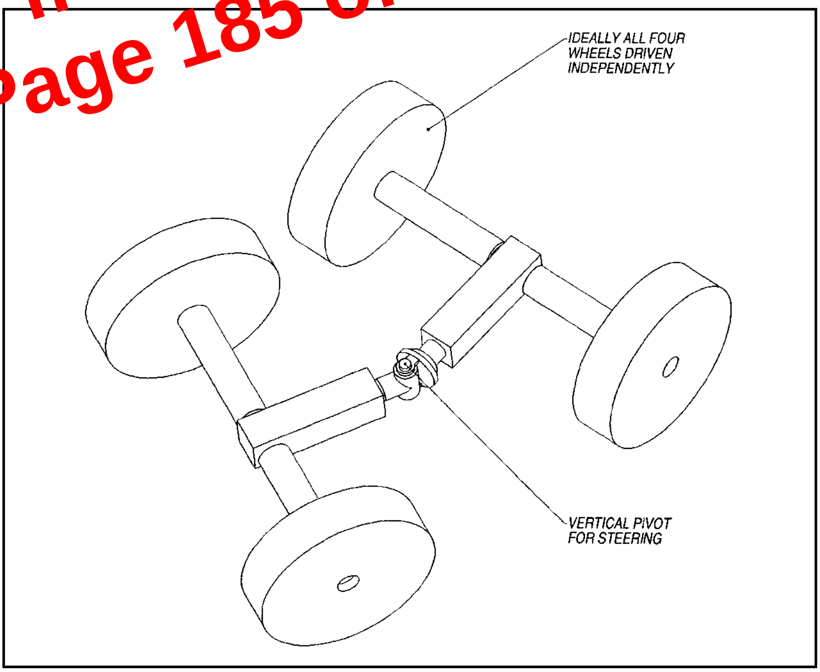


Figure 4-18 Two-sections connected through vertical axis joint

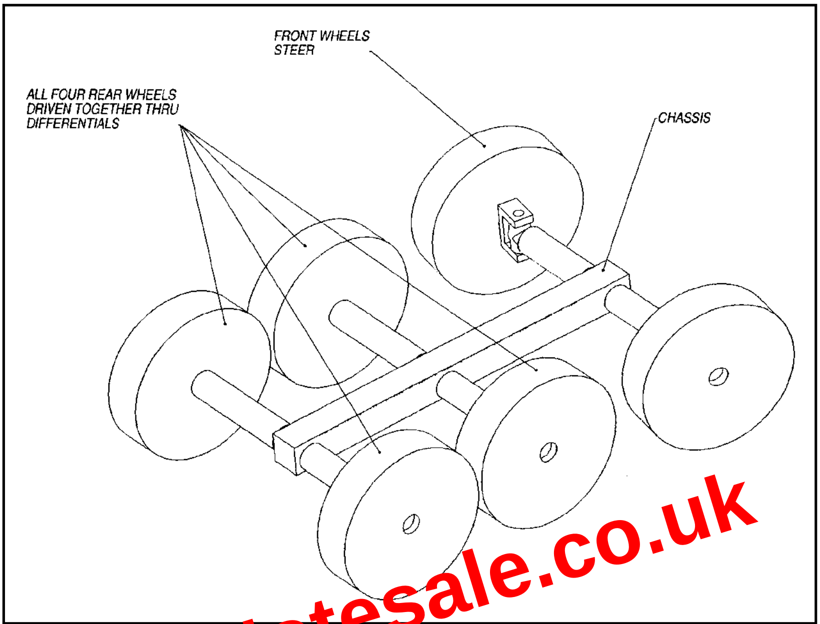


Figure 4-24 Six wheels, front pair steer

This has better steering efficiency, but, surprisingly, not much better mobility. Incorporating the Ackerman steering layout removes the ability of the robot to turn in place. This can be a real handicap in tight places. Figure 4-24 shows the basic layout. Remember that the relative sizes of wheels and the spacing between them can be varied to produce different mobility characteristics.

The epitome of complexity in a once commercially available six-wheeled vehicle, not recommended to be copied for autonomous robot use, is the Alvis Stalwart. This vehicle was designed with the goal of going anywhere in any conditions. It was a six-wheeled (all independently suspended on parallel links with torsion arms) vehicle whose front four wheels steered. Each bank of three wheels was driven together through bevel gears off half-shafts. It had offset wheel hub reduction gear boxes, a lockable central differential power transfer box with integral reversing gears, and twin water jet drives for amphibious propulsion. All six wheels could be locked together for ultimate straight-ahead traction. No sketch is included for obvious reasons, but a website with good information and pictures of this fantastically complicated machine is *www.4wdonline.com/Mil/alvis/stalwart.html*.

The main problem with these simple layouts is that when one wheel is up on a bump, the lack of suspension lifts the other wheels up, drastically reducing traction and mobility. The ideal suspension would keep the load

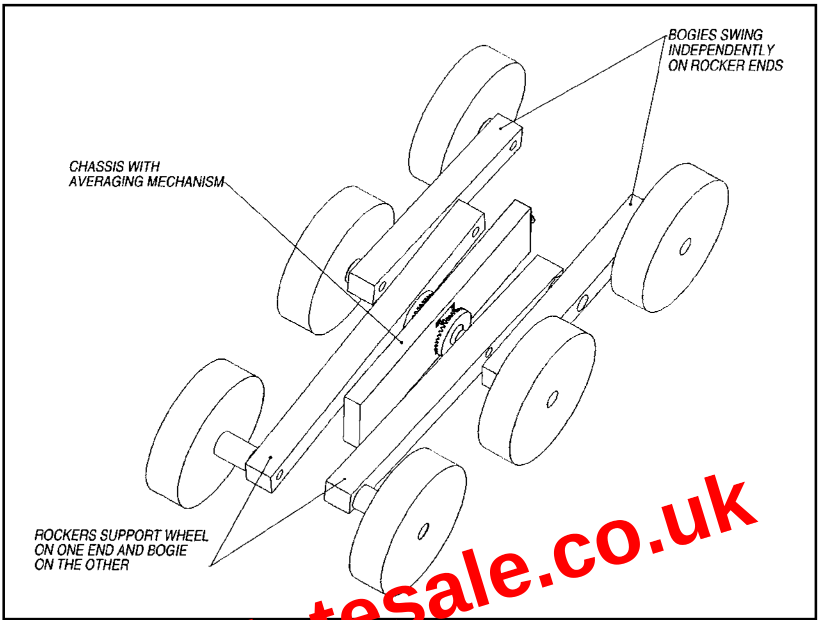


Figure 4-26 Rocker bogie

can negotiate obstacles that are twice the wheel height. This figure shows only the basic parts of the mobility layout. The part labeled "chassis" is the backbone or main support piece for the main body, which is not shown.

The very fact that each wheel is passively loaded by the rocker bogie suspension reduces its negotiable chasm width. Lockable pivots on the bogie can extend the negotiable chasm width by making the center wheels able to support the weight of the entire vehicle. This adds yet another actuator to this already complicated layout. This actuator can be a simple band or disc brake.

The rocker bogie suspension can be skid steered, but the side forces on the wheels produce moments in the rockers for which the rockers must be designed. Since the wheels are at the end of arms that move relative to each other, the most common layout puts a motor in each wheel. Steering is done by turning both the front and the rear wheels with their own steering motors. This means that this layout uses 10 motors to achieve its very high mobility. In this design, the large number of actuators reduces the number of moving parts and over all complexity.

The steering geometry allows turning in place with no skidding at all. This is the layout used on Sojourner, the robot that is now sitting on Mars after completing an entirely successful exploration mission on the Red Planet. Mobility experts claim this layout has the highest mobility possi-

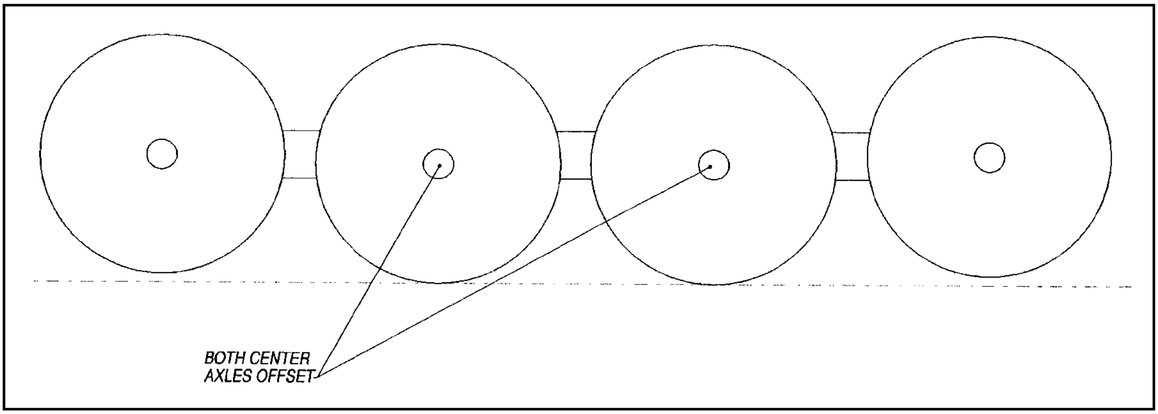


Figure 4-27 Eight wheels, all fixed, center axles offset

reduce the number of actuators, even with four corner steering, to eight. No known instances of this layout, shown in Figure 4-28, have been built for testing, though it seems like an effective layout.

With eight wheels, there is the possibility of dividing the vehicle into two sections, each with four wheels. The two parts are then either connected through a passive joint and individually skid steered, or the joint is articulated and steering is done by bending the vehicle in the middle. This is identical to the four tracked layouts discussed and shown in chapter five. This can be a very effective layout for obstacle negotiation and crevasse crossing, but cannot turn in place. Figure 4-29 shows an example of a two-part passive joint eight-wheeled layout. Figure 4-30 adds a roll joint to aid in keeping more wheels on the ground.

Another eight-wheeled layout, also applicable to a four-tracked vehicle, uses a transverse pivot, which allows the two halves to pitch up and down. It is skid steered, and is suited for bumpy terrain, but which has few obstacles it must go around. Imagine the vehicle in Figure 4-30, but with the pivot axis on its side. This layout is similar to the double rocker layout, with similar mobility and fewer moving parts.

The two halves of an eight-wheeled layout can also be coupled together with a ball joint. The ball joint allows pitch, roll, and yaw between the two parts which facilitates keeping all eight wheels on the ground most of the time. The ball joint is a simple joint and can be made robust. It has a limited range of motion around two of the axis, but the third axis can rotate three hundred sixty degrees. Aligning this axis vertically aligns it in the steering axis. This allows the vehicle to have a tighter steering radius, but it cannot turn in place. Figure 4-31 shows the four-wheeled sections connected through a vertical axis ball joint. The ball joint is difficult to use with a four-wheeled vehicle because the

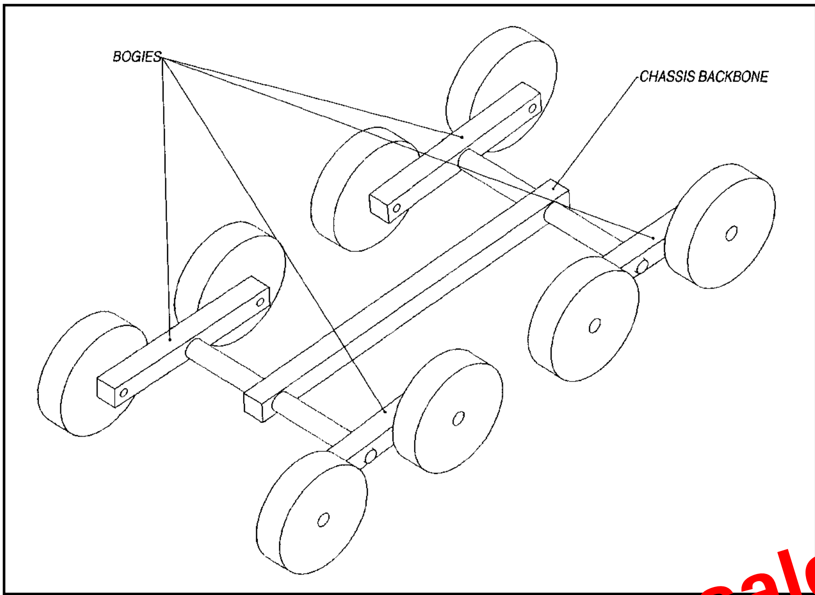


Figure 4-28 Eight wheels, double bogie

wheel torque would try to spin the section around the wheels. This problem can be reduced if the wheels are coupled together so their torques are always nearly identical.

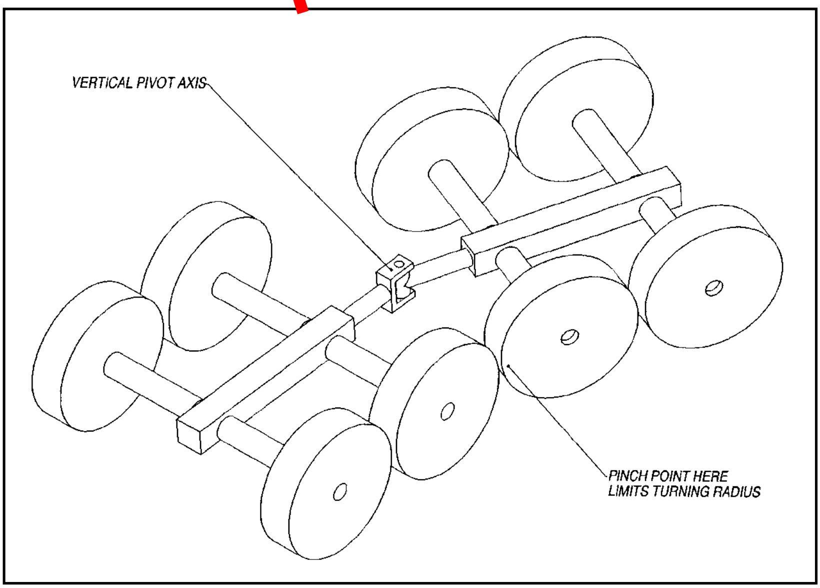


Figure 4-29 Two part, eight wheeled, vertical center pivot

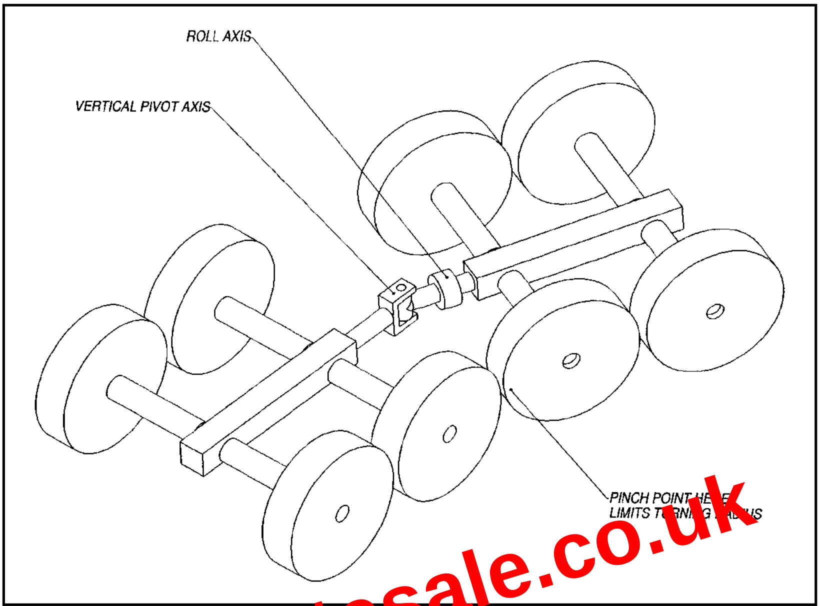


Figure 4-30 Two part, eight wheeled, vertical and roll joints

For a truly complicated wheeled drive mechanism, the Tri-star Land-Master from the movie *Damnation Alley* is probably the most impressive. This vehicle, of which only one was built, is a two-section, center pivot steered layout with a Tri-star wheel at each corner. The Tri-star wheels consist of three wheels, all driven together, arranged in a three-

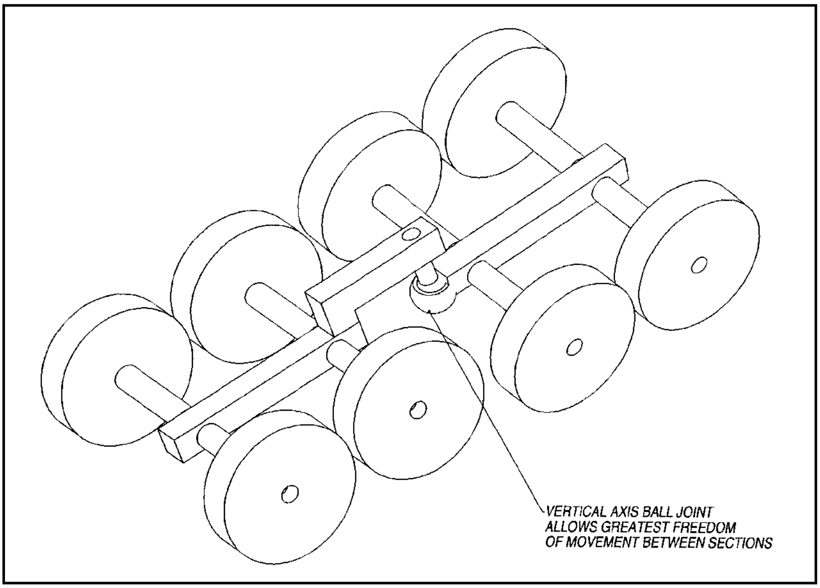


Figure 4-31 Two part, eight wheeled, vertical ball joint

pointed star on a shared hub that is also driven by the same shaft that drives the wheels. When a bump or ditch is encountered that the wheels alone cannot traverse, the whole three-wheeled system rotates around the center hub and the wheels essentially become very large cleats. The Tristar wheels are driven through differentials on the Land-Master, but powering each with its own motor would increase mobility even further.

The same trick that reduces steering power on skid steered wheeled vehicles can be applied to tracks, i.e., lowering the suspension a little at the middle of the track. This has the effect of raising the ends, reducing the power required to skid them around when turning. Since this reduces the main benefit of tracks, having more ground contact surface area, it is not incorporated into tracked vehicles very often.

VARIOUS TRACK CONSTRUCTION METHODS

Tracks are constructed in many different ways. Early tracks were nearly all steel because that was all that was available that was strong enough. Since the advent of Urethane and other very tough rubbers, tracks have moved away from steel. All-steel tracks are very heavy and on smaller vehicles, this can be a substantial problem. On larger vehicles or vehicles designed to carry high loads, steel linked tracks may be the best solution. There are at least six different general construction techniques for tracks.

- All steel hinged links
- Hinged steel links with removable urethane road pads
- Solid urethane
- Urethane with embedded steel tension members
- Urethane with embedded steel tension members and external steel shoes (sometimes called cleats)
- Urethane with embedded steel tension members and embedded steel transverse drive rungs with integral guide teeth

All-steel hinged linked track (Figure 5-1) would seem to be the toughest design for something that gets beat on as much as tracks do, but there are several drawbacks to this design. Debris can get caught in the spaces between the moving links and can jamb the track. A solution to this problem is to mount the hinge point as far out on the track as possible. This reduces the amount that the external surface of the track opens and closes, reducing the size of the pinch volume. This is a subtle but important part of steel track design. This lowered pivot is shown in Figure 5-2.

Tracked vehicles, even autonomous robots, will drive on finished roads at some point in their life, and all-steel tracks tear up macadam. The solution to this problem has been to install urethane pads in the links of the track. These pads are designed to be easily replaceable. The pads are bolted or attached with adhesive to pockets in special links on the track. This allows them to be removed and replaced as they wear out.

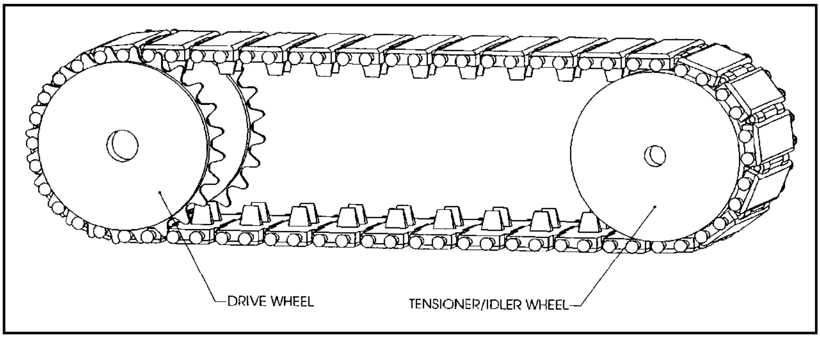


Figure 5-5d

usually mounted directly to the chassis through some common suspension system, but the idler wheel is mounted on an arm that can move through an arc that changes the shape of the front ramp. A second tensioning idler must be incorporated into the track system to maintain tension for all positions of the main arm.

This variability produces very good mobility when system height is included in the equation because the stowed height is relatively small compared to the negotiable obstacle height. The effectively longer track, in addition to a cg shifting mechanism, gives the vehicle the ability to cross wider crevasses. With simple implementations of this concept, the variable geometry track system is a good choice for a drive system for mobile robots. Figure 5-6 (a–b) shows one layout for a variable geometry track system. Many others are possible.

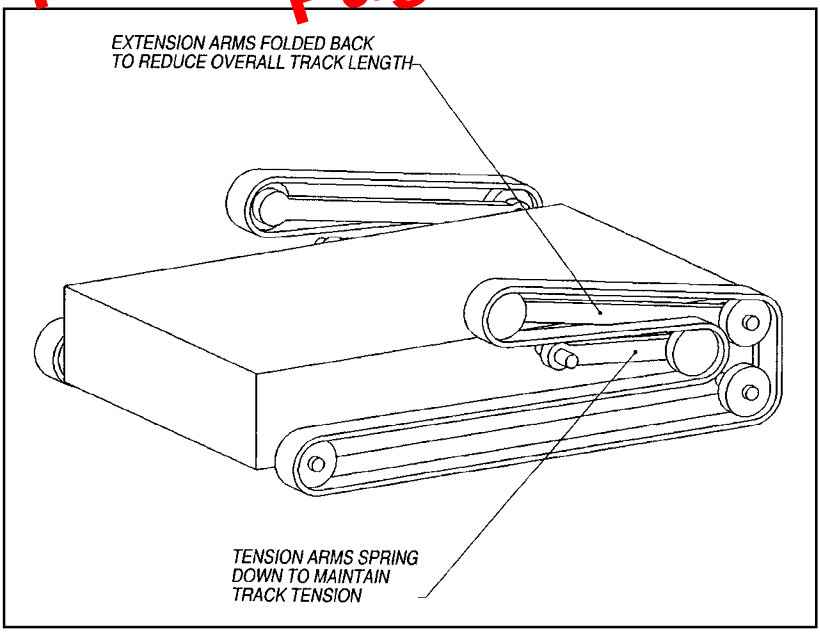


Figure 5-6a–b Variable track system

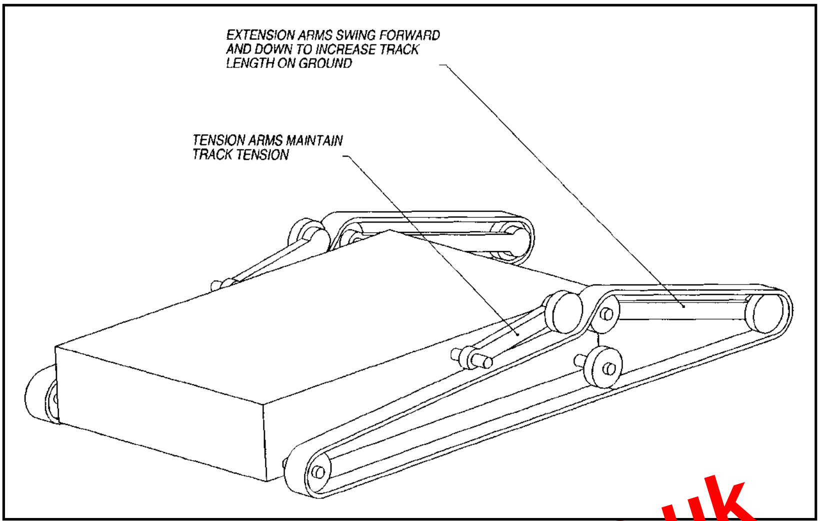


Figure 5-6b

Since it carries both the tension in the track and the drive torque, the drive sprocket (and associated drive mechanism) is the most vulnerable moving part of a track system. They can be located at either the front or rear of the track, though they are usually in the rear to keep them away from the inevitable bumps the front of an autonomous vehicle takes. Raising the sprocket up off the ground removes the sprocket from possible damage when hitting something on the road surface. These modifications result in a common track shape, shown in Figure 5-5c.

A simple method that extends the mobility of a tracked vehicle is to incorporate a ramp into the chassis or body of the vehicle. The static ramp extends in front and above the tracks and slides up obstacles that are taller than the track. This gives the vehicle the ability to negotiate obstacles that are taller than the mobility system using a non-moving part, a neat trick.

TRACK SUSPENSION SYSTEMS

The space between the drive sprocket and idler wheel needs to be uniformly supported on the ground to achieve the maximum benefit of tracks. This can be done in one of several ways. The main differences between these methods is drive efficiency, complexity, and ride characteristics. For especially long tracks, the top must also be supported, but

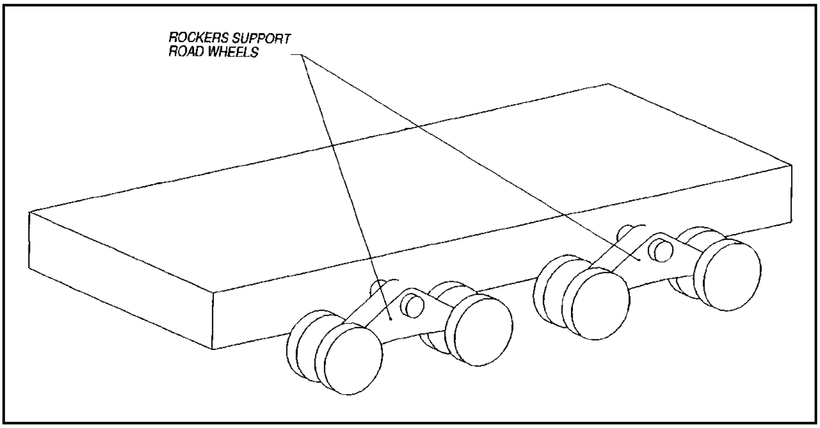


Figure 5-8 Road wheels on rockers

motion is especially beneficial at higher speeds, and the rocker layout used on wheeled vehicles is almost as effective on tracks. The rollers are mounted in pairs on rockers between the drive sprocket and the idler wheel. The rockers (Figure 5-8) allow the track to give a little when traversing bumpy terrain, which reduces vertical motion of the robot chassis. Careful tensioning of the track is essential with movable road wheels.

The most complex, efficient, and smooth ride is produced by mounting the road wheels on sprung axles. There are three main types of suspension systems in common use.

- Trailing arm on torsion spring
- Trailing arm with coil spring
- Leaf spring rocker

The trailing arm on a torsion spring is pictured in Figure 5-9. It is a simple device that relies on twisting a bunch of steel rods, to which the trailing arm is attached at one end. It gets its name because the arms that support the wheel trail behind the point where they attach, through the torsion springs, to the chassis. The road wheels mount to the end of the trailing arms and forces on the road wheel push up on the arm, twisting the steel rods. This system was quite popular in the 1940s and 1950s and was used on the venerable Volkswagen beetle to support the front wheels. It was also used on the Alvis Stalwart, described in more detail in Chapter Four.

You can also support the end of the trailing arm with a coil spring, or even a coil over-shock suspension system that can probably produce the smoothest ride of any track system (Figure 5-10). The shock can also be added to the torsion arm suspension system. The advantage of the coil

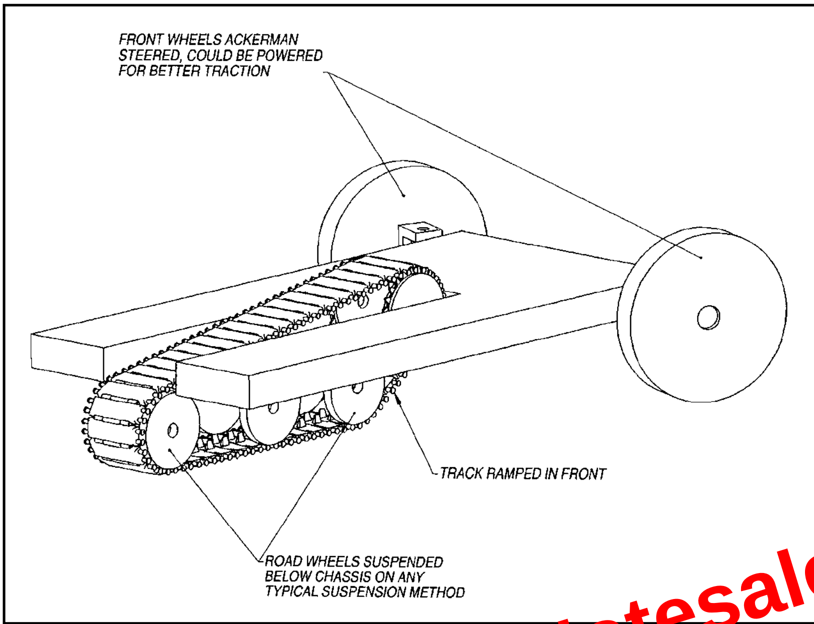


Figure 5-12 One track, two front wheels, Ackerman steer

which prevents turning in place. The first problem can be reduced by powering the wheels. There is no known existence of this layout, but it seems worth investigation. Figure 5-12 shows the typical ramped-front track common on snowmobiles because they normally do not go backwards. A track that is ramped both in front and back would increase mobility. It would be an interesting experiment to build a one-track, two-wheel drive, Ackerman steered robot and test its mobility.

Two-Tracked Drivetrains

The two-track layout is by far the most common. In its basic form, it is simple, easy to understand, and relatively easy to construct. Two tracks are attached to either side of the robot's main chassis, and each are powered by their own motor. Compact designs have the motor mounted substantially inside the track and attached directly to the drive sprocket. Since the drive sprocket must turn at a much lower rpm than the rpm's at which electric motors are most efficient, a speed reduction method almost always needs to be part of the drivetrain. Figure 5-13 shows a two-track layout, with drive motors, gearboxes, fixed track guide blades, and non-ramped tracks. This represents the simplest layout for a tracked vehicle.

Chapter 6 Steering History

The Romans extensively used two wheeled carts, pulled by horses. Pull on the right rein and the horse pulls the cart to the right, and vise versa. The two wheels on the cart were mounted on the same axle, but were attached in a way that each wheel could rotate at whatever speed was needed depending on whether the cart was going straight or around a corner. Carts got bigger and eventually had four wheels, two in front and two in back. It became apparent (though it is unclear if it was the Romans who figured this out) that this caused problems when trying to turn. One or the other set of wheels would skid. The simplest method for fixing this problem was to mount the front set of wheels on each end of an axle that could swivel in the middle (Figure 6-1). A tongue was attached to the axle and stuck out from the front of the vehicle, which in turn was attached to a horse. Pulling on the tongue aligned the front wheels with the turn. The back wheels followed. This method worked well and, indeed, still does for four wheeled horse drawn buggies and carriages.

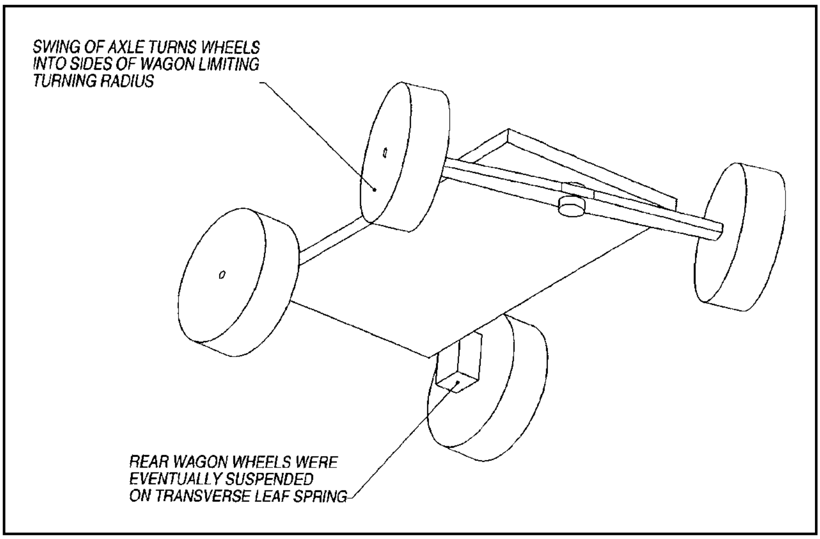


Figure 6-1 Pivot mounted front wheels

In the early 1800s, with the advent of steam engines (and, later, electric motors, gas engines, and diesel engines) this steering method began to show its problems. Vehicles were hard to control at speeds much faster than a few meters per second. The axle and tongue took up a lot of room swinging back and forth under the front of the vehicle. An attempt around this problem was to make the axle long enough so that the front wheels didn't hit the cart's sides when turning, but it was not very convenient having the front wheels wider than the rest of the vehicle.

The first effective fix was to mount the two front wheels on a mechanism that allowed each wheel to swivel closer to its own center. This saved space and was easier to control and it appeared to work well. In 1816, George Lankensperger realized that when turning a corner with the wheels mounted using that geometry the inside wheel swept a different curve than the outside one, and that there needed to be some other mechanical linkage that would allow this variation in alignment. He teamed with Rudolph Ackerman, whose name is now synonymous with this type of steering geometry. Although Ackerman steering is used on almost every human controlled vehicle designed for use on roads, it is actually not well suited for high-mobility vehicles controlled by computers, but it feels right to a human and works very well at higher speeds. It turns out there are many other methods for turning corners, some intuitive, some very complex and unintuitive.

STEERING BASICS

When a vehicle is going straight the wheels or tracks all point in the same direction and rotate at the same speed, but only if they are all the same diameter. Turning requires some change in this system. A two-wheeled bicycle (Figure 6-2) shows the most intuitive mechanism for performing this change. Turn the front wheel to a new heading and it rolls in that direction. The back wheel simply follows. Straighten out the front wheel, and the bicycle goes straight again.

Close observation of a tricycle's two rear wheels demonstrates another important fact when turning a corner: the wheel on the inside of the corner rotates slower than the outside wheel, since the inside wheel is going around a smaller circle in the same amount of time. This important detail, shown in Figure 6-3, occurs on all wheeled and tracked vehicles. If the vehicle's wheels are inline, there must be some way to allow the wheels to point in different directions. If there are wheels on either side, they must be able to rotate at different speeds. Any deviation from this

There are no multi-cell animals that use any form of continuously rolling mechanism for propulsion. Every single land animal uses jointed limbs or squirms for locomotion. Walking must be the best way to move then, right? Why aren't there more walking robots? It turns out that making a walking robot is far more difficult than making a wheeled or tracked one. Even the most basic walker requires more actuators, more degrees of freedom, and more moving parts.

Stability is a major concern in walking robots, because they tend to be tall and top heavy. Some types of leg geometries and walking gaits prevent the robot from falling over no matter where in the gait the robot stops. They are statically stable. Other geometries are called "dynamically stable." They fall over if they stop at the wrong point in a step. People are dynamically stable.

An example of a dynamically-stable walker in nature is, in fact, any two-legged animal. They must get their feet in the right place when they want to stop walking to prevent tipping over. Two-legged dinosaurs, humans, and birds are remarkably capable two legged walkers, but any child that has played Red-light/Green-light or Freeze Tag has figured out that it is quite difficult to stop mid-stride without falling over. For this reason, two legged walking robots, whether anthropomorphic (human-like) or birdlike (the knee bends the other way), are rather complicated devices requiring sensors that can detect if the robot is tipping over, and then calculate where to put a foot to stop it from falling.

Some animals with more than two legs are also dynamically stable during certain gait types. Horses are a good example. The only time they are statically stable is when they are standing absolutely still. All gaits they use for locomotion are dynamically stable. When they want to stop, they must plan where to put each foot to prevent falling over. When a horse's shoe needs to be lifted off the ground, it is a great effort for the horse to reposition itself to remain stable on three hooves, even though it is already standing still. Cats, on the other hand, can walk with a gait that allows them to stop at any point without tipping over. They do not need to plan in advance of stopping. This is called statically-stable independent leg walking. Elephants are known to use this technique

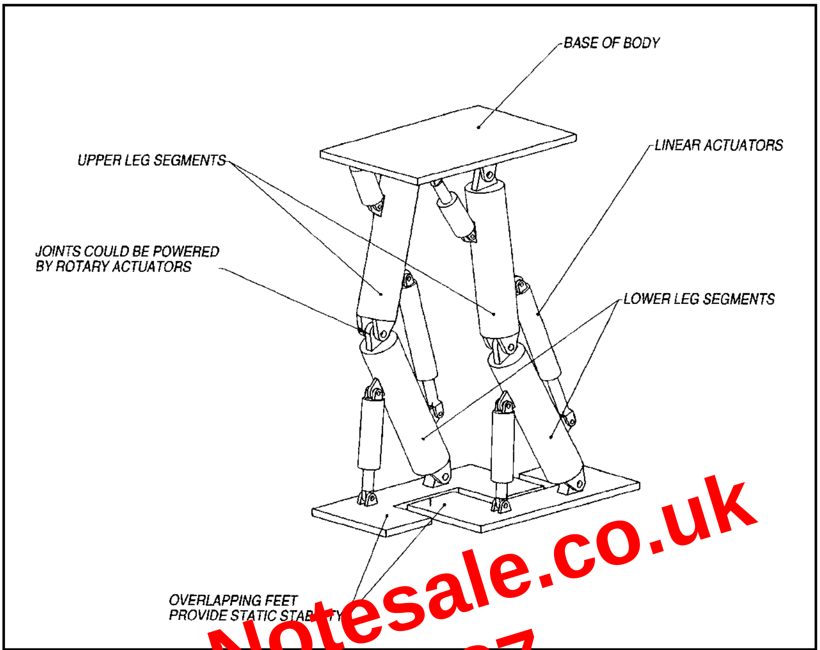


Figure 7-10 Extra wide feet provide two-legged stability

theoretically have very high mobility. Many research robots have been built that use four or six legs and are impressively agile, if very slow.

Although it would seem impossible to build a two-legged statically-stable robot, there is a trick that toys and some research robots use that gives the robot the appearance of being dynamically stable when they are actually statically stable. The trick is to have feet that are large enough to hold the robot upright on one foot without requiring the foot to be in exactly the right place. In effect, foot size reduces the required accuracy of foot placement so that the foot can be placed anywhere it can reach and the robot will not fall over.

The wide feet must also prevent tipping over sideways and are so wide that they overlap each other and must be carefully shaped and controlled so they don't step on each other. Two-legged walking, with oversized and overlapping feet, is simply picking up the back foot, bringing it forward, and putting it down. The hip joints require a second DOF in addition to swinging fore and aft, to allow rotation for turning. Each leg must have at least three DOF, and usually requires four. The layout shown in Figure 7-10 can only walk in a straight line because it lacks the hip rotation joint. Notice that even with only two legs and no ability to turn, this layout requires six actuators to control its six degrees of freedom.

This layout provides a good educational tool to learn about walking. Although in the final implementation it may have eight DOF and its

There are many less obvious applications for mobile robots. One particularly interesting problem is inspecting and repairing pipelines from the inside. Placing a robot inside a pipe reduces and, sometimes, removes the need to dig up a section of street or other obstruction blocking access to the pipe. The robot can be placed inside the pipe at a convenient location by simply separating the pipe at an existing joint or valve. These pipe robots, commonly called pipe crawlers, are very special designs due to the unique environment they must work in. Pipe crawlers already exist that inspect, clean, and/or repair pipes in nuclear reactors, water mains under city streets, and even down five-mile-long oil wells.

Though the shape of the environment may be round and predictable, there are many problems facing the locomotion system of a pipe crawler. The vehicle might be required to go around very sharp bends, through welded, sweated, or glued joints. Some pipes are very strong and the crawlers can push hard against the walls for traction, some are very soft like heating ducts requiring the crawler to be both light and gentle. Some pipes transport slippery oil or very hot water. Some pipes, like water mains and oil pipelines, can be as large as several meters in diameter; other pipes are as small as a few centimeters. Some pipes change size along their length or have sections with odd shapes.

All these pipe types have a need for autonomous robots. In fact, pipe crawling robots are frequently completely autonomous because of the distance they must travel, which can be so far that it is nearly impossible to drag a tether or communicate by radio to the robot when it is inside the pipe. Other pipe crawlers do drag a tether which can place a large load on the crawler, forcing it to be designed to pull very hard, especially while going straight up a vertical pipe. All of these problems place unusual and difficult demands on the crawler's mechanical components and locomotion system.

End effectors on these types of robots are usually inspection tools that measure wall thickness or cameras to visually inspect surface conditions. Sometimes mechanical tools are employed to scrape off surface rust or other corrosion, plug holes in the pipe wall, or, in the case of oil wells, blow holes in the walls. These effectors are not complex mechanically

Traction Techniques for Vertical Pipe Crawlers

There are at least four tread treatments designed to deal with the traction problem.

- spikes, studs, or teeth
- magnets
- abrasives or nonskid coating
- high-friction material like neoprene

Each type has its own pros and cons, and each should be studied carefully before deploying a robot inside a pipe because getting a stuck robot out of a pipe can be very difficult. The surface conditions of the pipe walls and any active or residual material in the pipe should also be investigated and understood well to assure the treatment or material is not chemically attacked.

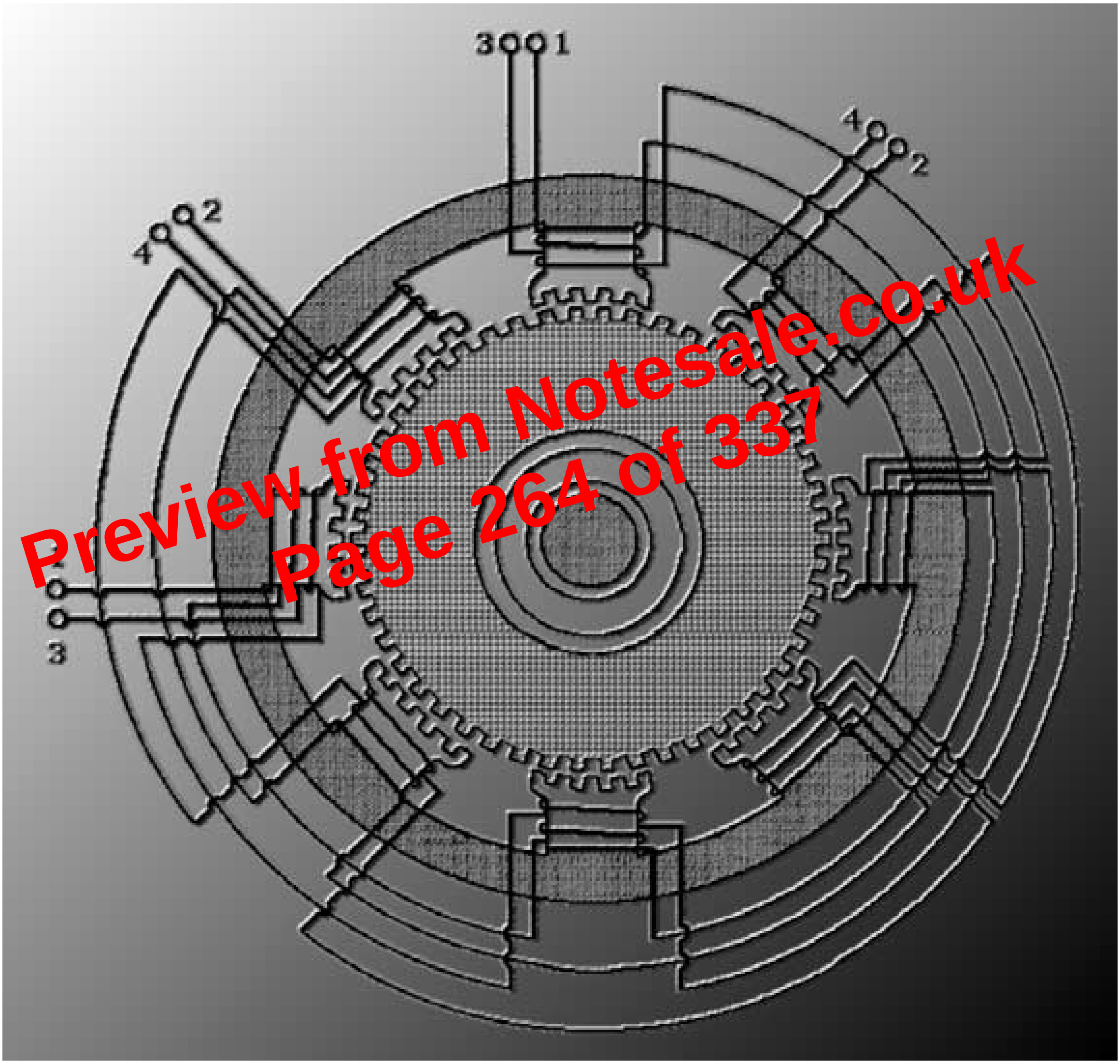
Spiked, studded, or toothed wheels or treads can only be used where damage to the interior of the pipe can be tolerated. Galvanized pipe would be scratched leading to corrosion and some hard plastic pipe material might stress crack along a scratch. Their advantage is that they can generate very high traction. Spiked wheels do find use in oil wells, which can stand the abuse. They require the crawler to span the inside of the pipe so they can push against opposing walls.

The advantage of magnetic wheels is that the wheels pull themselves against the pipe walls; the disadvantage is that the pipe must be made of a ferrous metal. Magnets remove the need to have the locomotion system provide the force on the walls, which reduces strain on the pipe. They also have the advantage that the crawler can be smaller since it no longer must reach across the whole of a large pipe. Use of magnetic wheels is not limited to pipe crawlers and should be considered for any robot that will spend most of its life driving on a ferrous surface.

Tires made of abrasive impregnated rubber hold well to iron and plastic pipe, but these types loose effectiveness if the abrasive is loaded with gunk or worn off. Certain types of abrasives can grip the surface of clean dry pipes nearly as well as toothed treads, and cause less damage.

High-friction rubber treads work in many applications, but care must be taken to use the right rubber compound. Some rubbers maintain much of their stickiness even when wet, but others become very slippery. Some compounds may also corrode rapidly in fluids that might be found in pipes. They cause no damage to pipe walls and are a simple and effective traction technique.

Chapter 9 Comparing Locomotion Methods



ume of everything on the robot not related to the mobility system (including the power supply), and define this volume with a realistic ratio of length, width, and height. A good place to start for the size ratios is to make the width 62 percent of the length, and the height one quarter of the length. This box represents the volume of everything the mobility system must carry.

The next step is to define the mobility requirements, allowing substantial leeway if the operating environment is not well known. The basic six parameters discussed above are a good place to start.

- Step or wall height
- Minimum tunnel height
- Crevasse width
- Maximum terrain slope
- Minimum spacing of immovable objects
- Maximum soil density

All of these need to be studied carefully to aid in determining the most effective mobility system layout to use. The more time spent doing this study, the better the mobility system choice will match the terrain's requirements.

When this study is completed, selecting and designing the mobility system is then a combination of scaling the system to the robot's box size, and meeting the mobility constraints. It should be remembered that this process will include several iterations, trial and error, and perseverance to guarantee that the best system is being incorporated. The more information that can be obtained about the operating environment, the more likely the robot will be successful. In the end, one of the more capable and versatile mobility systems, like the six-wheeled rocker bogie or the four-tracked front-flipper layouts will probably work well enough even without complete knowledge of the environment.

A generic rule of thumb for mobility system design can be extracted from the investigations done in this chapter. Relative to the size and weight of the vehicle the mobility system is carrying, make the mobility system big, light, slow, low (or movable) cg, and be sure it has sufficient treads. If all these are maximized, they will make your robot a high mobility robot.

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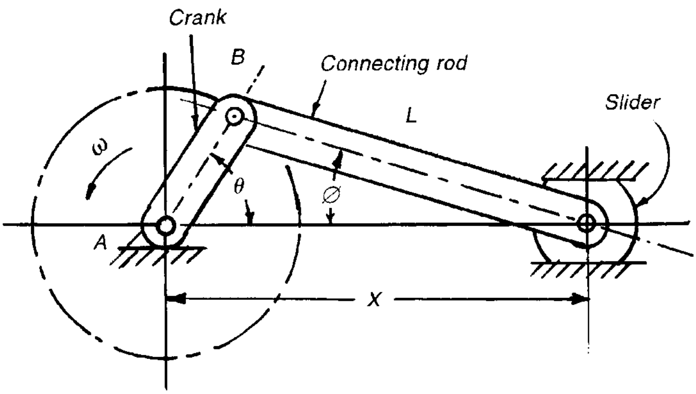

SYMBOLS

L = length of connecting rod

R = crank length; radius of crank circle

x = distance from center of crankshaft A to wrist pin C

x' = slider velocity (linear velocity of point C)

x'' = slider acceleration

θ = crank angle measured from dead center (when slider is fully extended)

ϕ = angular position of connecting rod: $\phi = 0$ when $\theta = 0$

ϕ' = connecting-rod angular velocity = $d\phi/dt$

ϕ'' = connecting-rod angular acceleration = $d^2\phi/dt^2$

ω = constant crank angle velocity

Displacement of slider

$x = L\cos\phi + R\cos\phi$

Also:

$$\cos\phi = \left[1 - \left(\frac{R}{L}\right)^2 \sin^2\theta\right]^{1/2}$$

Angular velocity of the connecting rod

$$\phi' = \omega\left[\frac{(R/L)\cos\theta}{[1-(R/L)^2\sin^2\theta]^{1/2}}\right]$$

Linear velocity of the piston

$$\frac{x'}{L} = -\omega\left[1 + \frac{\phi'}{\omega}\right]\left(\frac{R}{L}\right)\sin\theta$$

Angular acceleration of the connecting rod

$$\phi'' = \frac{\omega^2(R/L)\sin\theta[(R/L)^2 - 1]}{[1-(R/L)^2\sin^2\theta]^{3/2}}$$

Slider acceleration

$$\frac{x''}{L} = -\omega^2\left(\frac{R}{L}\right)\left[\cos\theta + \frac{\phi''}{\omega^2}\sin\theta + \frac{\phi'}{\omega}\cos\theta\right]$$

Figure 10-2 Slider Crank

linear motion from rotary, but the slider crank is particularly effective for use in walking robots.

The motion of the slider is not linear in velocity over its full range of motion. Near the ends of its stroke the slider slows down, but the force produced by the crank goes up. This effect can be put to good use as a clamp. It can also be used to move the legs of walkers. The slider crank should be considered if linear motion is needed in a design.

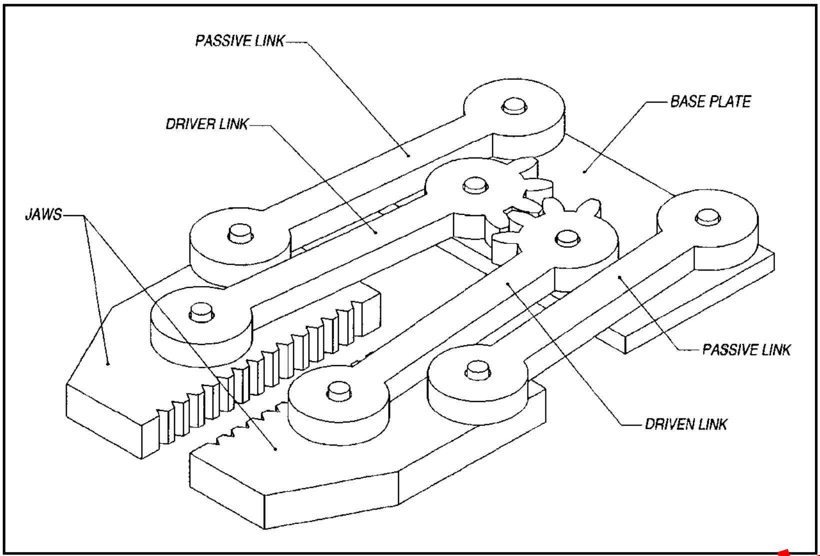

Figure 10-22 Parallel jaw using four-bar linkage

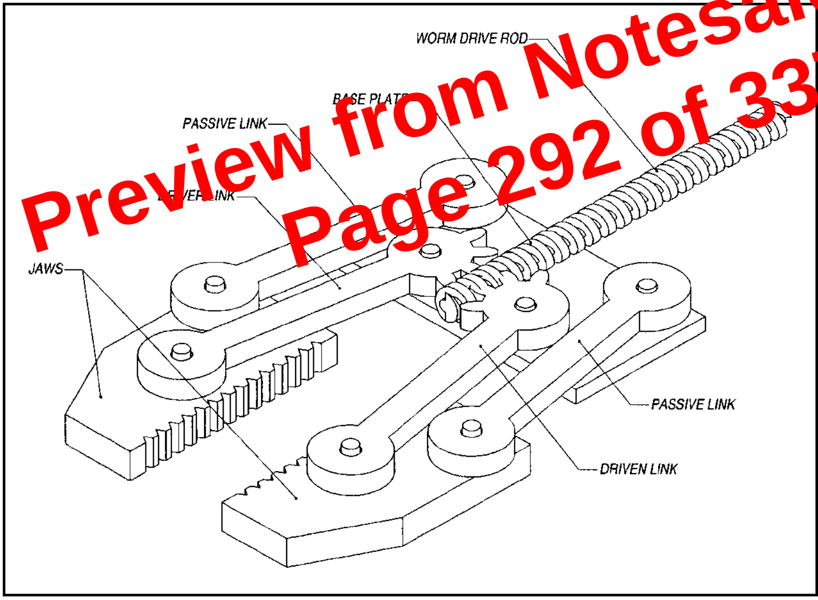

Figure 10-23 Parallel jaw using four-bar linkage and linear actuator

PASSIVE PARALLEL JAW USING CROSS TIE

Twin four-bar linkages are the key components in this long mechanism that can grip with a constant weight-to-grip force ratio any object that fits

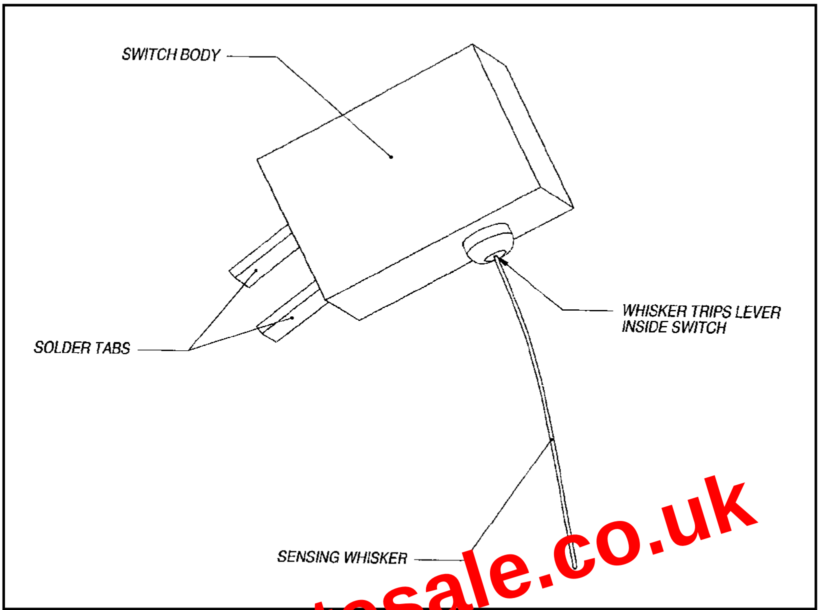

Figure 11-3 Whisker Switch

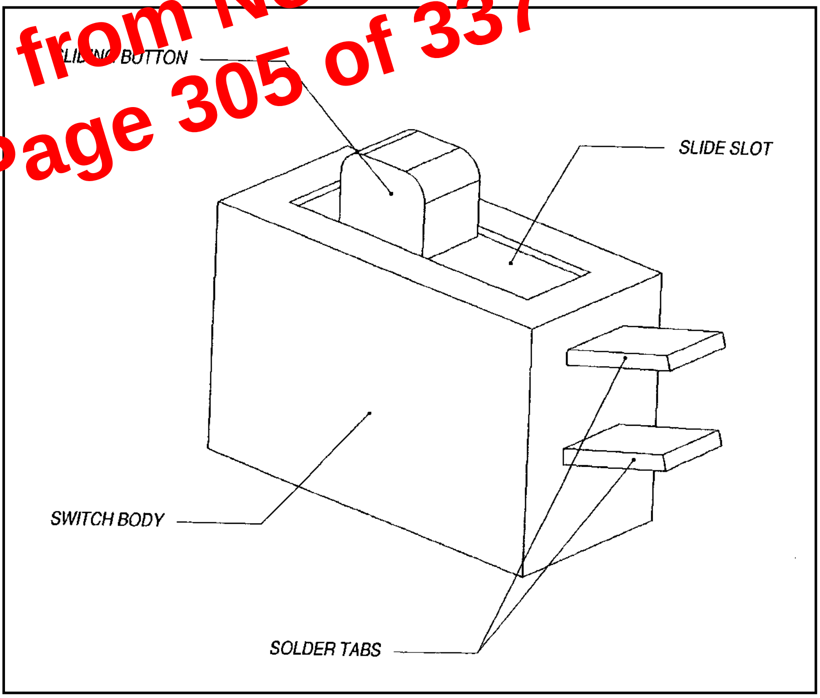

Figure 11-4 Slide Switch

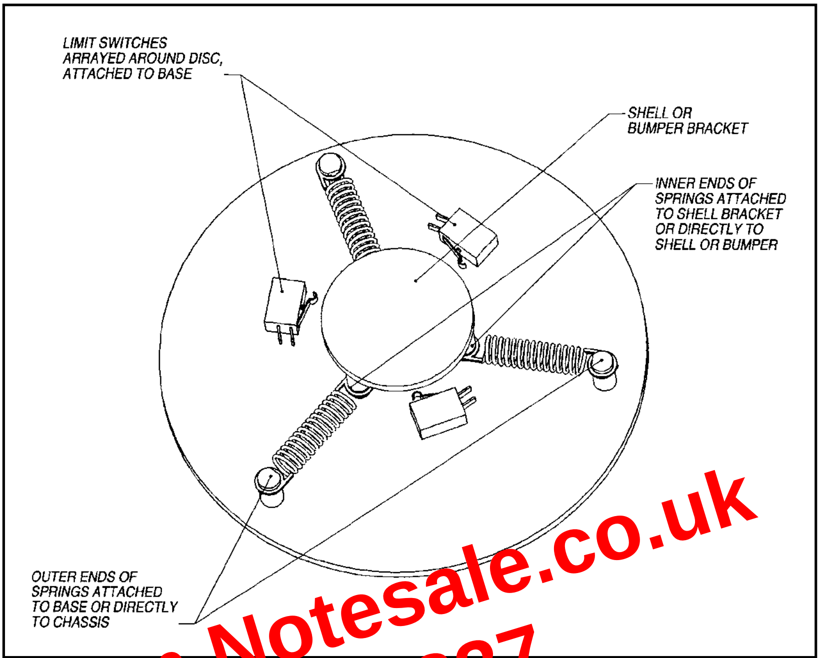

Figure 11-14 Tension spring star layout

other components to keep it centered, like the V-groove device discussed previously, and some sort of spring to hold the top plate in the groove.

Tension Spring Star

A simple to understand spring-centering layout uses three tension springs in a star layout (Figure 11-14). The outer ends of the springs are attached to the chassis and the inner three ends all attach to a plate or other point on the frame that supports the bumper. This layout is easy to adjust and very robust. It can be used for robot bumpers that must detect bumps from all directions, provided there is an array of sensors around the inner edge of the bumper, setup as a switch-as-hard-stop layout. This layout requires a damper between the chassis and plate to reduce wobbling.

Torsion Swing Arm

The torsion or trailing arm car suspension system (Figure 11-15) first appeared in the early 1930s and was used for more than 25 years on the

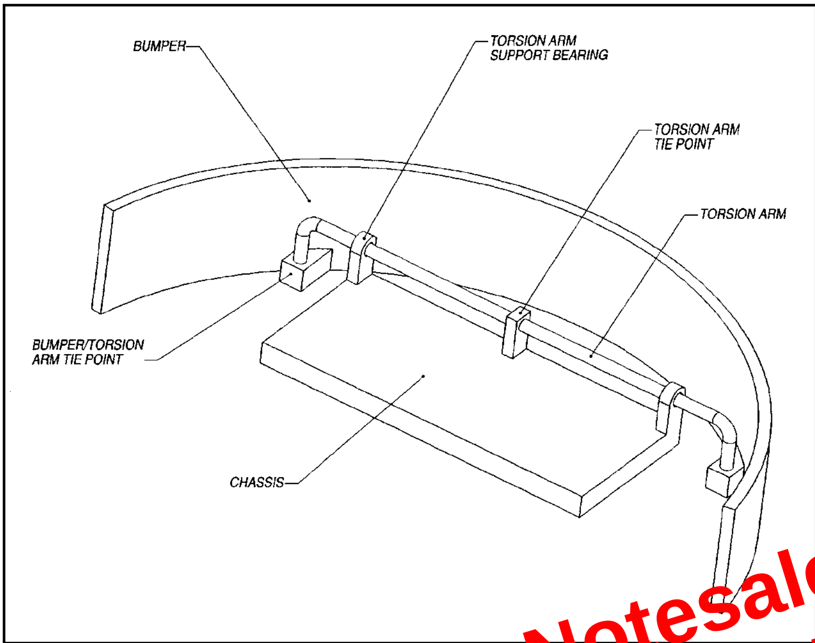

Figure 11-15 Torsion swing arm

VW Beetle. It is similar in complexity to the sideways leaf spring shown in the next section, but is somewhat more difficult to understand because it uses the less common property of twisting a rod to produce a spring. The mechanism consists of a simple bar with trailing links at each end. The center of the beam is attached to the chassis, and each end of the trailing links supports the bumper. If the beam is properly sized and sufficiently flexible, it can act as both support and spring with proper passive suspension points.

Horizontal Loose Footed Leaf Spring

Another suspension system, used since the days of horse drawn buggies, that can be applied to robot bumper suspensions is a leaf spring turned on it side. This design has great simplicity and reliability. In a car, the leaf spring performs the task of springs, but it also holds the axles in place, with very few moving parts. The usual layout on a car has one end attached to the frame through a simple pivot joint and the other end attached through either a pivoting link, or a robust slot to allow for that end to move back and forth in addition to rotating. The center of the spring is attached to the axle, allowing it to move up and down but not in any other direction. Two springs are required to hold the axle horizontal.

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Note: Figures and tables are indicated by an italic *f* and *t*, respectively.

About the Author

Paul E. Sandin is a robotocist with iRobot Corporation, where he designs and builds systems for the Consumer Robotics Division. Previously, he worked for RedZone Robotics, where he designed suspension components for large-scale toxic waste cleanup robots. He has an intimate knowledge of robots, both large and small. He lives with his family in a suburb of Boston, Massachusetts.