Locomotion Emulator: A Robot Testbed For Navigation Research

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Abstract

The Locomotion Emulator (LE) is a mobile robot testbed that overcomes limitations of previous testbeds. The LE consists of a *locomotor*, a mechanism capable of completely general locomotion on a surface, and an *emulator*, a software environment that specializes this mechanism to mimic the characteristics of different vehicles. The LE's general locomotion can subtend all the trajectories important to navigation research. This paper discusses the need for such a vehicle and describes the LE mechanism and software.

INTRODUCTION

In a common paradigm of robotic navigation research, laboratory simulation dominates the initial stages of the development cycle. When the demands of the research exceed the capabilities of the simulation system, the burden of development and experimentation shifts to the real-world implementation. However, development on the target vehicle is not optimal: in general, such machines are cumbersome, and require large technician and facility support.

Mobile testbeds are often introduced into the research program to overcome problems of on-target development. Testbeds go beyond simulation by providing a mobile platform for extensive experimentation. While very beneficial, robotic testbeds present their own set of problems: differences between the testbed and the target vehicle, such as size, power, and physical configuration, force the researchers to address the unique traits and characteristics of both systems. Otherwise, the system being developed may become testbed-specific and necessitate extensive retrofit and modification upon implementation on the target vehicle.

To lessen the risk and cost of the testbed-to-target crossover, the Field Robotics Center has constructed the Locomotion Emulator (Figure 1), a mobile robot testbed that can emulate the functionality of any target vehicle such that the two machines are indistinguishable to the system under development. The LE consists of a locomotor, a mechanism capable of completely general locomotion on a surface, and an emulator, a software environment that specializes this mechanism to mimic the characteristics of different vehicles. Each of these is described in detail below.

LOCOMOTOR

The locomotor is a powerful all-wheel steer, all-wheel drive base with a rotating payload platform. Comprised of four subsystems -- chassis, powertrain, electronics, and turret -- the locomotor is reliable, extensible, maintainable and controllable. A general specification sheet for the locomotor is included as Appendix A and an explanation of the vehicle kinematics is included as Appendix B.

Figure 1: Locomotion Emulator

Chassis

The LE chassis performs three primary functions: it is a rigid structure that transmits the forces and moments of the rotating turret to the ground; it supports and protects the two LE electronics enclosures; it supports and protects the electrical and mechanical components of the powertrain.

While the LE itself has a circular appearance, the chassis is triangular with wheel modules at the vertices. The area under two of the triangular legs of the chassis is used as a mount point for the electronics enclosure while the area encompassed by the third leg is used as a mount point for the powertrain components. Figure 2 shows the LE with the turret plate removed.

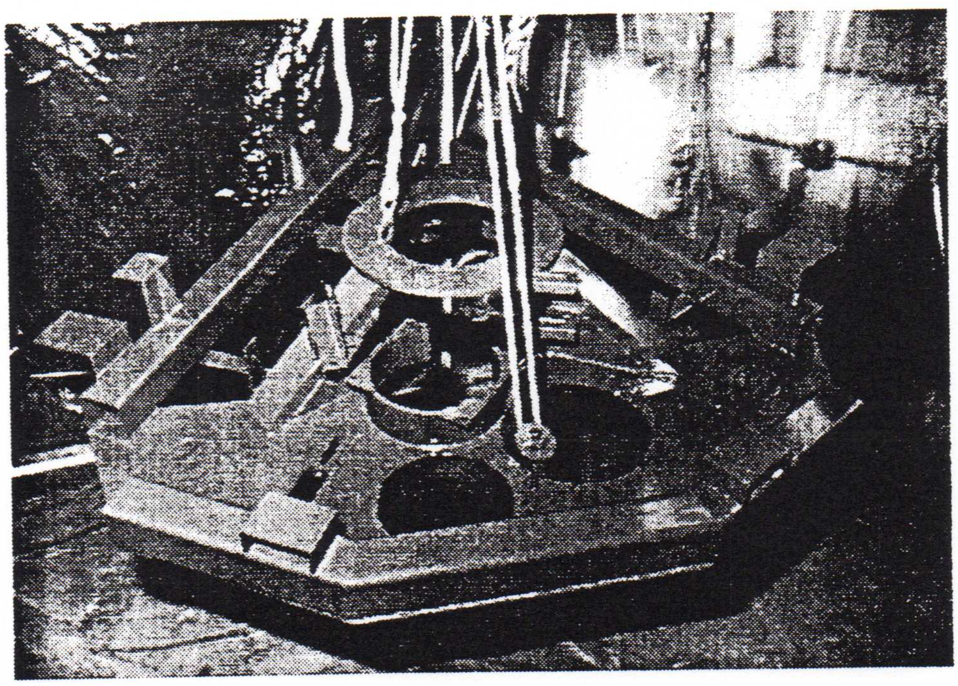

Figure 2: Vehicle Chassis

Powertrain

The LE powertrain is comprised of three subsystems -- wheel modules, steer, and propulsion -- consisting of both electrical and mechanical components. The design of the powertrain system is such that maintenance or component replacement requires a minimal amount of disassembly. The configuration precludes the complexity of actuating and coordinating six individual motions, and apportions steering and propulsive power to wheel modules as circumstances demand. Refer to Figure 3 for illustration of the powertrain.

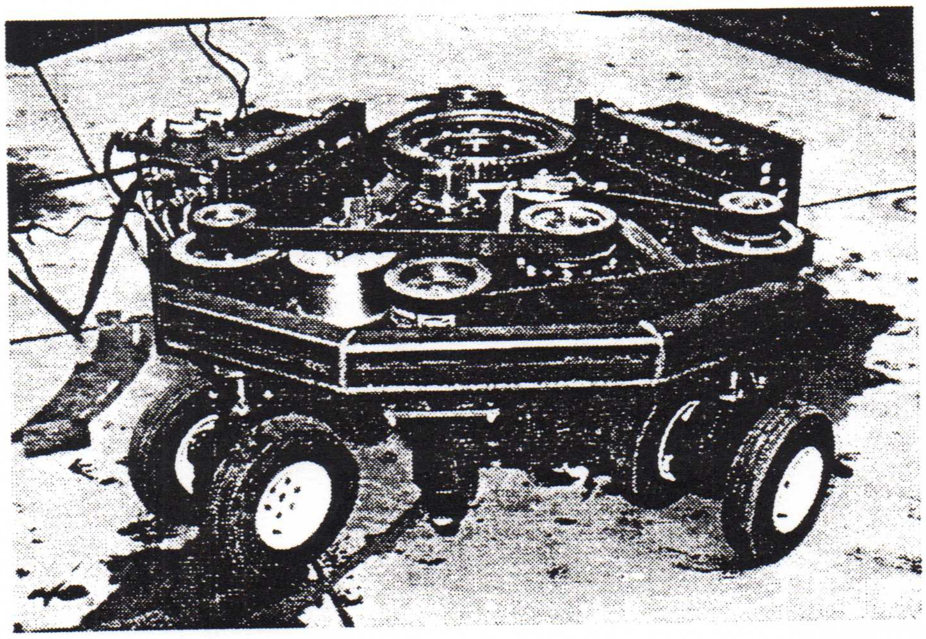

Figure 3: Powertrain

The wheel modules utilize a tube-in-tube design for transmission of steering and propulsion power from the belt systems to an automotive differential. The steer tube is mounted by sliding through sleeves at the vertices of the chassis with snap rings preventing the modules from falling out. Removal of the snap rings allows the entire wheel module assembly (minus steer and propulsion sprockets) to drop out for maintenance or repair.

The steer subsystem utilizes a single electric servomotor and gearing combination to drive a synchronous belt. Standard synchronous sprockets are attached to each of the individual wheel module steer tubes. Because alignment of the wheel modules is important to vehicle performance (minimize power loss to scuffing and the dead-reckoning error incurred with slippage), all steer tubes have slotted holes where they attach to the differentials. The slotted holes in combination with the adjustment available in the sprocket allow for perfect alignment of the wheel modules. A homing switch that provides feedback directly to one of the motion control boards is mounted on one of the wheel modules. The belt operating at the lower elevation in Figure 3 is the steer belt.

The propulsion subsystem is similar to the steer subsystem, but it is located at a higher elevation (refer to Figure 3). The differences between the steer and propulsion are that alignment is not an issue, belt speed is higher, and therefore a smaller belt can be utilized, and a higher horsepower servomotor is used.

Electronics

The LE electronics have been designed to be functional, extensible and maintainable. Vehicle electronics are located in three enclosures - the amplifier enclosure, the controller enclosure, and the turret enclosure - based on function. All vehicle power and communications with remote hosts/equipment are carried through a tether to the amplifier enclosure. The LE requires 35 A of 230 VAC 3Ø for the servomotors and 25 A of 120 VAC 1Ø for computing. As a general rule MIL-SPEC connectors have been used everywhere except the DB series of connectors.

Amplifier Enclosure

The amplifier enclosure serves as the distribution point for all power and signal carried through the tether. To simplify maintenance and troubleshooting, the servoamplifiers and their power supply are mounted on rack slides.

Terminal strips mounted on the inside of the enclosure door provide for quick, simple reconfiguration of where the signal lines are redistributed. A Safety and Logic printed circuit board (PCB) also mounts to the inside of the enclosure door. A series of six potentiometers mount along one edge of the PCB allowing easy adjustment of the amplifier gains away from the high voltage power. A duplicate set of the LEDs mounted on the exterior is located on the center of the door for troubleshooting fault conditions. Custom programmable logic array (PAL) chips to simplify addition of various electronic devices and some switching logic are also contained on the PCB.

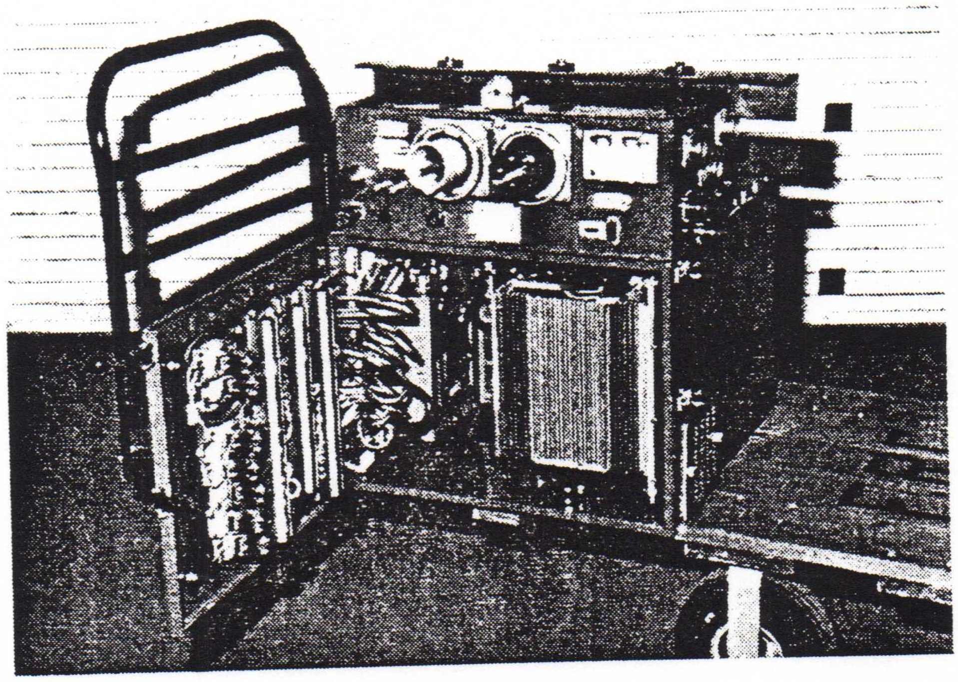

Figure 4: Amplifier Enclosure

Controller Enclosure

The controller enclosure provides a temperate, shock-isolated enclosure for the control computing. Fans for cooling are mounted on the back of the enclosure and are powered at the same time as the computing. Similar to the amplifier enclosure, the computing chassis has been mounted on rack slides and features a removable top panel for operator access. The LE computing is comprised of the following hardware:

- a 12 slot Multibus I chassis
- 2 - Intel 80286 CPU boards
- a fixed disk/floppy disk controller board
- 2 - Creonics 2 axis motion control boards
- a 360 kB floppy
- a 20 Mb fixed disk

Turret Enclosure

The turret enclosure, a NEMA-4 box that mounts on top of the turret plate, facilitates the integration of third party sensors and computing into the LE system. Within the enclosure are terminal strips that allow routing of power and signal through an electrical slip ring to the amplifier enclosure. The turret enclosure also provides a protected environment for the single axis gyro and its power supply.

To connect additional equipment on the turret and route its signal back through the terminal lines in the tether, the following tasks must be performed:

- mount equipment to turret
- configure for available connectors
- jumper the terminal block in the turret enclosure
- jumper the terminal block in the amplifier enclosure

Turret

The turret serves a dual purpose as both an important degree of freedom for emulation and as a mounting platform for payload such as sensors or computing. In this section only its use as a payload platform is discussed.

The turret plate, a circular aluminum disk 78 inches in diameter, provides a continuous rotating mounting surface for third-party sensors and equipment. A bolt pattern has been pre-drilled to facilitate the mounting of such devices. At slow speeds the turret is capable of supporting large normal forces but cannot handle equipment that develops large forces in the positive vertical direction.

EMULATOR

The emulator, the software component of the Locomotion Emulator, can replicate the motions of three target configurations: skid-steer, articulated, and Ackerman (see Figure 5). Implemented on a real-time, multiprocessor computer, the emulator supports communication interfaces for command description, performs the internal modelling and control algorithms, coordinates the individual axis actuators, and monitors the subsystems of the LE.

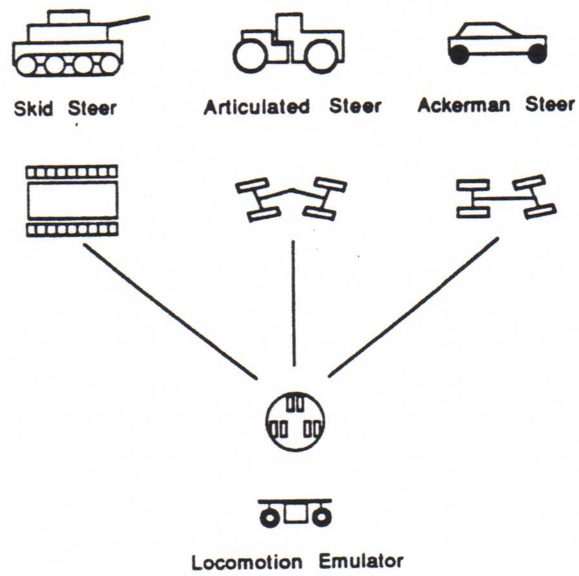

Figure 5: Target Vehicle Configurations

Emulation Issues

The task of locomotion emulation demands more than the duplication of the target vehicle's mobility functions; it calls for the replication of the information exchange that the host computer would experience while interacting with the target vehicle. This exchange consists of the feedback data from the onboard sensing mechanisms and the command interface between the host computer and the testbed's controller.

Since onboard sensing is the host computer's source of perception, the data recorded by the testbed sensors must be identical to the data recorded from the target vehicle. Onboard sensing is partitioned into two categories: external, which involves measurement of the local environment, and internal, which pertains to the robot itself.

For external sensing devices such as sonar rings, video cameras, and laser scanners, the positioning and orientation of the equipment are transferred from the target vehicle to the Locomotion Emulator. As the LE executes a motion directive, these sensors sweep through the same trajectories as those induced by the target vehicle and, therefore, report identical readings. The instrumentation can be mounted directly on the LE's payload platform. If the space requirements for the sensor location exceed the LE's physical size, frame mock-ups, resembling all or portions of the actual vehicle, can be constructed and attached to the LE.

Internal sensors, such as position encoders, are very dependent on the physical configuration of the vehicle, making the replication of the feedback data difficult to achieve. Internal sensing for an emulated vehicle requires a more involved process than installing additional sensors. The Locomotor Emulator utilizes its own internal sensing resources to generate the internal sensing for the target vehicle. For example, the LE position encoders are used to calculate the positions, velocities, and accelerations of the target vehicle's axes of motion.

The command interface between the LE controller and the system architecture plays an important role in the emulation process. The interface represents not only the communication protocols but also the level of responsibility the LE controller has within the overall system. Since the Locomotion Emulator is a tool for developing autonomous navigation systems, the controller should assume as small a role as possible and yet have the flexibility to accommodate a range of vehicle configurations and software architectures. Although the internal structure and organization may vary greatly from system to system, at some level of every architecture the motion directives are translated into axis-specific data. Since axis-based information represents a common denominator among navigational architectures, the interface for the LE resides at this level and incorporates axis commands that are specific to the emulated vehicle.

Command Interface

The command interface for the LE controller is similar to interfaces found on conventional motion controllers. Through this interface the host can control the emulated axis of the target vehicle in either position or velocity modes. For velocity control, the command describes a desired final velocity for the emulated axis. The specified axis will 'ramp' to the target velocity under the constraints of the programmable acceleration. Once the velocity goal is achieved, the emulated axis will continue at that velocity until instructed otherwise. With the position control mode, the motion command designates a final position for the emulated axis. The axis will perform a trapezoid motion profile with user-selected acceleration and cruise velocity values. The axis will achieve the final position goal and maintain that position until a new command is issued.

An axis-specific command structure allows the host to control the individual axis of motion on the emulated vehicle. For the Ackerman and articulated configurations, the controllable motions are the steer and drive axes. The designated axes on a skid-steer vehicle are the left and right tracks. Similarly, the axes for the unicycle, which is the LE's natural configuration, are the steer, drive, and turret axes.

Approach to Vehicle Emulation

The core of the LE controller is the emulation algorithms. The basic principle of the algorithms is to construct an internal model of the emulated vehicle and calculate the model's responses to motion commands generated by the host. The behavior of the model is then translated into motion directives for the locomotor. Presently, the internal models are based solely on the kinematic characteristics of the vehicle configurations.

Key to our approach to emulation is the concept of coincidal control points. We define a control point as a point in space from which the equations of motions are referenced. The axis or joint commands generated by the host are used with the Jacobian matrix for the emulated vehicle to calculate the motion characteristics of that vehicle's control point, (i.e., the forward solution). The control point for the emulated vehicle is then mapped directly onto the control point of the LE (i.e., the two control points are coincidal in space and possess identical motion attributes). Once the motion characteristics for the LE's control point are known, they are applied with the inverse Jacobian matrix for the LE to calculate the motions of the LE's steer, drive, and turret axes (i.e., the inverse solution).

The planar location of control points for the LE and the target vehicle are both user-programmable. If the operator is interested in mimicking the motion of a particular device, such as a laser scanner or a camera mounted on the the actual vehicle, he can specify the device location to be the control point of the target vehicle. When the device is physically installed on the LE, the mounting location can be chosen as the LE control point. As the LE emulates the motion of a vehicle, the device (i.e., the coincidal control points) moves through space with the identical reference frame (see Figure 6).

Architecture

The architecture for the controller consists of two functional partitions: the *communication* module interacts with the host identities, both humans and computers, and the *control* module performs the emulation algorithms and coordinates the individual axis actuators (see Figure 7).

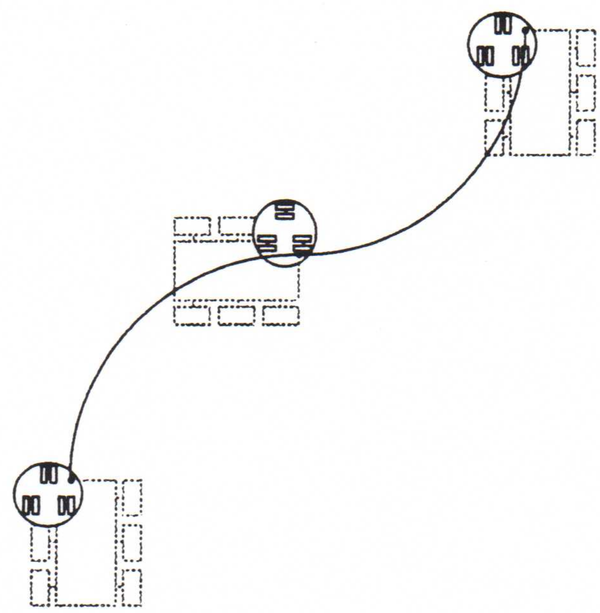

Figure 6: Skid-Steer Emulation

The communications module manages all interactions between the controller and the outside world. This module supports a communications protocol that facilitates the detection of errors during data transmission. The module also performs validation tests to ensure all new commands are within the acceptable limits. Queries to the controller are answered and returned to the originator.

The human interface to the controller is a menu-driven display. From the terminal, the operator can select the configuration parameters for the LE and the target vehicle. Once the configuration is selected and the system is initialized, the operator can enable the communications channel to the host computer or he can enter commands directly from the console. The commands include velocity and position goals for the axes of the emulated vehicle. The feedback information includes current velocity and position of axes and the current heading of the vehicle. The human interface also supports a software joystick that facilitates the transportation and setup of the LE for experimentation.

The computer host communicates with the controller through an RS232 serial line. The parameters of the serial line are programmable via the operator console. A simple but effective communications protocol organizes the transmitted data into ASCII packets. By utilizing a common serial line and a communication protocol, the LE becomes accessible to a wide range of host computers.

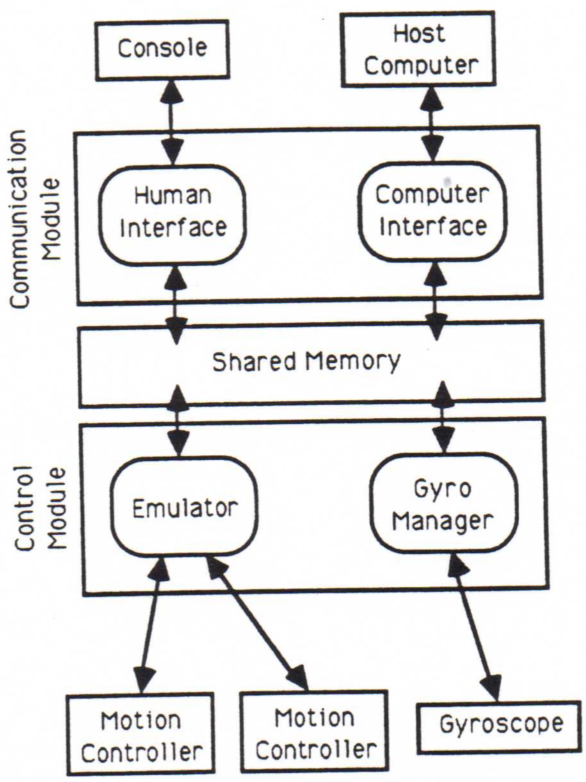

Figure 7: Controller Architecture

The control module is responsible for all actions of the Locomotor Emulator. The module receives motion commands from the communications module, performs the emulation calculations, and coordinates the individual actuators. The control module samples the low-level motion control boards for the state of the LE axes. An onboard gyroscope provides heading information.

The system architecture was designed incorporating the features of a real-time operating system. A key characteristic of a real-time OS is multi-tasking with preemptive, priority-based scheduling. Multi-tasking allows the software program to be broken into several subprograms called tasks. Each task is assigned a specific function such as reading a serial port or printing to the terminal screen. The tasks can incorporate communication with other tasks or operate totally oblivious to any other

Although a multi-tasking system allows multiple processes on the same CPU, the execution of the processes remains sequential. To increase the overall speed, decrease the response latency, and take full advantage of the software modularity, the LE controller incorporates multiprocessing by implementing the control and communication modules on separate single board processors. Other hardware components include two motion control boards for low-level control of the actuators and a peripheral controller with a bubble memory cartridge for mass storage.

CONCLUSION

The LE's first application is the emulation of mining equipment for unmanned operation underground. The power, scale and imprecision of this class of heavy equipment motivates the use of an emulation device with the generality, robustness and convenience that the LE provides. Our own research is evolving the LE mechanism, control computing and command protocol for applicability within and beyond underground mining. The LE is a significant accomplishment within our larger commitment to develop mobile work robots for industries such as surface mining, construction and hazardous waste management.

APPENDIX A - LOCOMOTION EMULATOR SPECIFICATIONS

General Specifications

Top Speed	3 MPH
Acceleration	1.7 FT/S^2
Drawbar Pull	2000 LBS
Vehicle Weight	2670 LBS
Shore Power.	60A 230 VAC 3Ø
[35A of 120 VAC available to operator]	60A 120 VAC 1Ø

Powertrain Specifications

Power Supply	18kW
Steer Motor [2500 ppm encoder]	4.5kW

Propulsion Motor [2500 ppm encoder, 360 in. lb. brake]	9kW
Max. Steering Rotational Speed	15 RPM

Turret Specifications

Turret Motor [2500 ppm encoder]	4.5kW
Max. Turret Rotational Speed	15 RPM
Turret Payload	1500 LBS

APPENDIX B[1]: LOCOMOTION EMULATOR KINEMATICS

A kinematic description of a mobile robot relates the motions of the steering and driving mechanisms to motions of the robot in some fixed (world) coordinate frame. From this, the inverse solution of the equations of motion can be developed as a basis for control. Given a specified robot trajectory, kinematics determine actuations necessary to achieve the desired trajectory.

We present a kinematic model of the proposed testbed using the methodology of Muir and Neuman[2]. Their treatment assumes single point contact between driving mechanisms and planar surfaces, about which rotational slip is possible, but translational slip is disallowed. Coordinate frames are assigned to links of the robot and transformations between frames written, from which a set of transformation equations are formulated. The fundamental differential relationship between robot motion in the world frame and motions of each wheel - the wheel Jacobian - is then derived. The differential relationships for each wheel are combined to form a composite robot equation. Under certain conditions, this equation can be solved for actuator velocities in terms of world frame robot velocities and used as a control scheme.

Our design objective is to create a mechanism that kinematically emulates a variety of other rolling vehicles. We will accomplish this by formulating kinematic descriptions of three target configurations (skid-steered vehicles, articulated vehicles, and Ackerman-steered vehicles). The Locomotion Emulator relates actuator commands to resulting vehicle motions in world coordinates for each configuration. The LE will accept geometric parameters of the target configuration (e.g., tire diameter and track separation) and commands to the actuators from a user interface and calculate the resulting motions in world coordinates. The equations of motion for the LE will then be solved in the inverse sense to derive LE actuator commands that achieve the same movement in the world frame.

The steering and drive actuations for all wheel pairs are performed with one pair of motors, making the kinematic description of all wheel pairs identical and independent of locomotor geometry. (Each wheel pair is modeled as a single equivalent wheel whose steering axis intersects the point of ground contact.) This

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1 An unpublished paper by J.F. Osborn, Field Robotics Center, Carnegie Mellon University, July, 1987.

2 Muir, P.F. and C.P. Neuman, "Kinematic Modeling of Wheeled Mobile Robots," Technical Report, The Robotics Institute, Carnegie Mellon University, June 1986.

reduces the kinematic description of the LE to that of a single conventional steered wheel below a rotating platform, represented by the following matrix equation

$$\dot{p} = J\dot{q}$$

or

$$\begin{bmatrix} v_x \\ v_y \\ w \end{bmatrix} = \begin{bmatrix} -R\sin q_s & 0 \\ R\cos q_s & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} w_x \\ w_T \end{bmatrix}$$

The left hand side is the vector of robot velocities in the fixed world frame, where

v_x = x component of robot linear velocity
v_y = y component of robot linear velocity
w = rotational robot velocity

The physical (actuated) robot velocities are:

w_x = rotational velocity of the wheel about its axle
w_T = rotational velocity of the turret with respect to the chassis

The relationship between the two is given by J, the robot Jacobian, for which:

R = wheel diameter
q_s = steering angle

The LE has a simple kinematic description because 1) the Jacobian is of low order and 2) linear and rotational velocities expressed in world coordinates are independent.