Assessment of Joint Driving Configurations for Body Propulsion of an Orthogonal Legged Walker

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Abstract

Joint driving configurations for an orthogonal legged walker are assessed using a body propulsion model that simulates the dynamics of the body and leg members that move in a lateral plane; the inverse dynamic equations for the model are underspecified when more than three lateral joints are powered. Linear programming techniques are used to determine which lateral joints should be powered to minimize input power to the mechanism while satisfying traction and joint force constraints. The body propulsion model is applied to the AMBLER walking machine and a typical body move is simulated for different cycle times, degrees of body tilt, and foot-soil frictional coefficients.

1 Introduction

An orthogonal legged walker is a unique configuration with each leg consisting of two members that move with the body in a lateral plane and a third leg member that extends orthogonally from this plane. This configuration is potentially energy efficient because the body can be propelled in the lateral plane with minimal vertical excursions that expend power overcoming gravity. Vertical joints (orthogonal to the lateral plane) are braked while the body is propelled along a relatively level plane by the lateral joints.

A minimum of three joints in the lateral plane (out of twelve for a hexapod) must be powered to position and orient the body of an orthogonal legged walker during a body propulsion. An unpowered joint is forced to follow the overall mechanism motions which backdrives the corresponding drivetrain and actuator. There are numerous sets of powered joints in the lateral plane that can be used to propel the body, directly affecting the overall vehicle power consumption. A planar dynamic model and associated linear programming solution procedures have been developed to determine the optimum set of powered lateral joints for propelling the body of an orthogonal legged walker. This paper assesses joint driving configurations for body propulsions of the AMBLER walking machine.

2 AMBLER Walking Machine

The AMBLER (Figure 1) is an orthogonal legged walking machine being developed for planetary exploration [Bares 90], which imposes severe power constraints on its operation. The mechanism body consists of two posts whose upper ends are rigidly connected by a braced crossmember; three legs are attached to each body post. A leg consists of two members that move in a lateral plane and a vertical member that extends orthogonally from this plane (Figure 2). In outward order from a body post, the leg members are defined as inner, outer and vertical links, respectively.

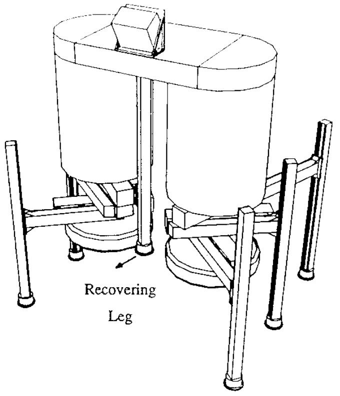


Figure 1: AMBLER Walking Machine Configuration

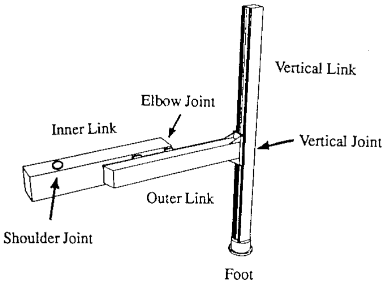


Figure 2: AMBLER Leg Design

A leg connects to the body by a rotational shoulder joint and the prismatic joint between lateral leg members is an elbow joint. The vertical link attaches to the outer link at the vertical prismatic joint and the ankle joint connects the foot to the leg. The ankle joint is free to rotate about the vertical axis to eliminate twisting of a foot on the soil; rotations of a foot about the lateral axes are prevented. The shoulder, elbow and vertical joints are powered by dc servo motors driving through torque multiplying gearboxes.

Circulating crawl gaits are the intended mode of walking for AMBLER, where only one leg is off the ground at a time ensuring maximum support stability should one or more footholds fail. Initial AMBLER gaits are composed of discrete body move and leg recovery motions. During the body move portion of a gait cycle, the mechanism body is propelled in the lateral plane by combinations of shoulder and elbow joints; vertical joint positions are held fixed. When body progress has completed, the foot of the recovering leg is lifted from the terrain and the leg circulates from the back to the front of the stance by passing between the body posts. Once the leg has recovered, the foot is planted and the cycle is repeated.

3 Modeling and Solution Procedures

During a body propulsion of the AMBLER walking machine, the vertical joints are braked while the lateral joints are used to propel the body. If the assumption is made that feet do not slip, motions that propel the body in the lateral plane can be considered independently of the mechanism's vertical weight distribution. A planar model has been formulated for the AMBLER mechanism [Manko 90c] that represents dynamics of the body and leg members that move in the lateral plane for simulation of the body move portion of a gait cycle. A set of generalized coordinates (which implicitly accommodates the mechanism closed-chains) consisting of the body orientation and positions in the lateral plane is used in conjunction with Kane's dynamics [Desa 85] to formulate an efficient set of dynamic equations for the planar model.

The body propulsion model is characterized by a set of inverse dynamic equations because the simulated body motions (specified by the gait planner) implicitly define trajectories for all lateral joints and the appropriate joint forces (and subsequent input power) required to generate the motions are being investigated. Substitution of joint trajectories into the planar equations of motion for the AMBLER mechanism produces three linear algebraic equations that are functions of twelve unknown joint forces. These inverse dynamic equations are underspecified and linear programming techniques are used to calculate optimal solutions [Guzzy 90].

Inequality constraints are specified to maintain joint forces below maximum limits, thus avoiding overloading of the actuators. The resultant of the generated traction forces cannot exceed the available traction force (otherwise foot slippage would occur) which is a non-linear relationship that is unsuitable for use with linear programming technique. Formulation of the generated traction forces and a conservative linearization of the traction force constraint are given in [Manko 90b].

The following linear objective function is defined to obtain solutions that minimize input power to the mechanism at each trajectory point.

$$P = \sum_{j=1}^{12} \{C_j + D_j v_j\} F_j \qquad (1)$$

where P - instantaneous input power,

F_j - joint force,

v_j - joint velocity, and

C_j, D_j - constants.

The velocity independent term represents the motor winding losses while the term dependent on both torque and velocity is the usable output power of a joint. Motor winding losses are a function of the motor current squared requiring a linearization of this relationship in the operating range of interest. Drivetrain inefficiencies increase (i.e., require more input power) the coefficient of the torque and velocity dependent term D_j, while amplifier inefficiencies increase both coefficients. The constant power required to energize an amplifier was not included in the objective function because this effect is essentially independent of the powered or backdriven state of a joint.

A limitation of using linear programming techniques for this application is the estimated joint states (i.e., powered or backdriven) at the start of a solution are used to determine the dynamic equations. The dynamic equations are held constant throughout the solution process, which does not recognize a possible change in joint states (and corresponding joint parameters) during the optimal selection of driven joints. The effect of this limitation is minimized by specifying joint parameters (i.e., damping or backdriving) that correspond with the majority of joint states predicted by the solution algorithm; a trial analysis is required to determine the number and identity of the lateral joints that compose an optimal driving configuration.

4 Body Move Simulations

The body propulsion model is used to simulate a typical body move, which is a .7 m translation along an inclined lateral plane (representing uneven vertical settlement). The initial mechanism state is shown in Figure 3 and the body trajectory follows a quintic profile which begins and ends with zero velocity and acceleration. Model parameters are given in Figure 4 and the vertical foot forces used in the body propulsion simulation were calculated using a model of legged locomotion on natural terrain [Manko 90a].

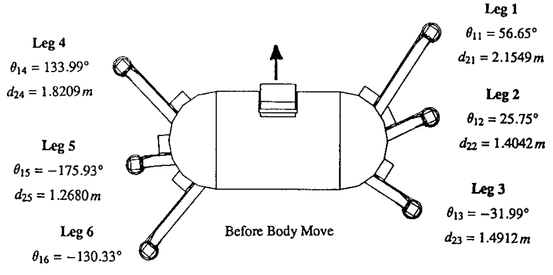


Figure 3: Initial Mechanism State

Member Properties				
Member	Mass (*kg*)	Inertia (*kg m*^{2})	Length (*m*)	CG Location (*m*)
body	907.20	1057.18	1.9304	.9652(1)
inner link	63.50	10.86	1.0160	.1270(2)
outer link	48.54	1.82	1.2954	.5334(3)

(1) Body cg is centered between posts.
(2) Measured from the body post outward.
(3) Measured from the vertical leg axis inward.

Joint Parameters					
Joint	Damping Force(1),(2)	Backdriving Force(1)	CT(3),(4)	DT(3),(5)	Maximum Joint Force(1)
shoulder	$27.12 + 1250v$	54.23	.0393	1.3889	1535.44
elbow	$222.4 + 6587v$	444.80	.0208	1.3889	3044.95
ankle	6.78	6.78	NA	NA	NA

(1) Units are *Nm*, *N*, and *Nm* for shoulder, elbow and ankle joints, respectively.
(2) v is the joint velocity.
(3) Refer to Equation 1 for parameter description.
(4) Units are *rad/sec* and *m/sec* for shoulder and elbow joints, respectively.
(5) DT is a non-dimensional parameter.

Figure 4: Model Parameters

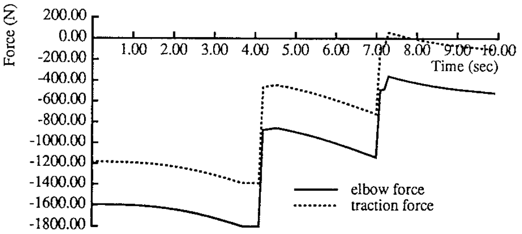
A description of the simulated cases and corresponding results are provided in Figure 5; different cycle times, degrees of body tilt, and foot- soil frictional coefficients were considered. Backdriving parameters are specified for all joints in Cases 1, 2 and 3 because trial analyses indicated a maximum of five lateral joints would be powered in these cases and the majority of joints would be backdriven. Conversely, damping parameters are specified for all joints in Case 5 because most joints are powered. The elbow joints for Legs 1, 3 and 6 are specified as being powered for Case 4 and joint parameters are defined accordingly.

Case Description					
Case(1)	Frictional Coefficient (2)	Body Tilt (*degrees*)	Cycle Time (*sec*)	Maximum Input Power (*watts*)	Total Energy Consumed (*joules*)
1	.77	5	10	595	3511
2	.77	5	5	1118	3125
3	.77	2	10	451	2636
4	NA	5	10	801	4206
5	.10	5	10	949	4975

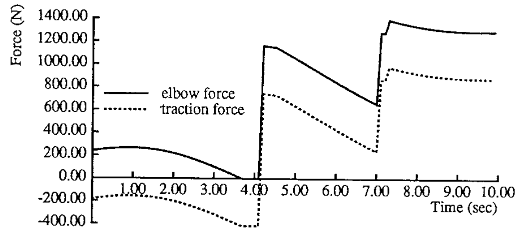
(1) All lateral joints were allowed to be powered except for Case 4 which had the elbow joints of Legs 1, 3 and 6 powered throughout the entire motion.
(2) Non-dimensional parameter.

Figure 5: Body Move Simulation Results

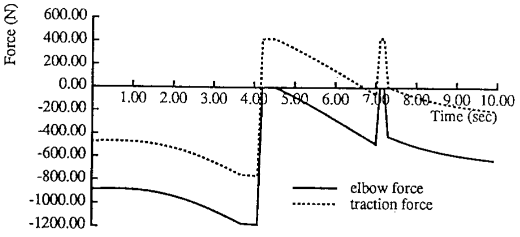
Case 1 is the base case with a 5° body tilt (a mechanism design limit), 10*sec* cycle time (typical rate of progress) and a relatively high foot-soil frictional coefficient of .77 for all legs; detailed results for this simulation are given in Figure 6. Between three and five elbow joints are selected as optimal driving configurations throughout the body propulsion. The minimum number of joints (i.e., three) are powered when traction force constraints are not limiting and additional joints are powered as available traction forces are exceeded.



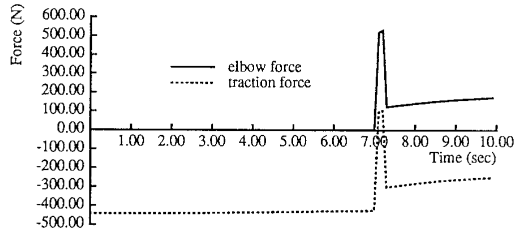
Elbow and Traction Forces for Leg 1



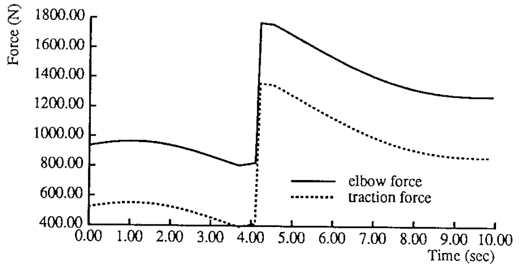
Elbow and Traction Forces for Leg 3



Elbow and Traction Forces for Leg 4



Elbow and Traction Forces for Leg 5



Elbow and Traction Forces for Leg 6

Figure 6: Detailed Results for Case 1

Reducing the cycle time to 5 *sec* for Case 2 results in a 88% increase in the maximum instantaneous input power to the mechanism. Between three and five elbow joints are again chosen as the optimal driving configurations for Case 2. The effect of gravity on AMBLER body propulsions is investigated in Case 3 which simulated a 2° tilt of the lateral plane; three elbow joints (alternating between leg sets 1-3-6, 1-4-6 and 3-4-6) are powered throughout the motion with an approximately 25% reduction in maximum input power and total energy consumed.

Switching actuators between powered and unpowered states (according to predicted optimal solutions) instantaneously releases stored potential energy in the leg members which could result in control system instabilities. Driving the same set of three joints throughout the gait cycle would avoid these impulse-like loadings, but at the expense of increased power consumption and violation of traction force constraints. Driving the elbow joints of Legs 1, 3 and 6 throughout the entire motion was simulated in Case 4 which enables the calculation of determinate solutions. The total power consumption and maximum input power increase by 20% and 35%, respectively, while available traction forces are exceeded for more than half of the trajectory.

Driving all lateral joints minimizes the generated traction forces and eliminates the need to backdrive joints which could cause control system instabilities. The effect on power consumption of driving all lateral joints is investigated in Case 4 by reducing the foot-soil frictional coefficients to .1 for all legs which requires that between ten and twelve lateral joints must be powered to satisfy the traction force constraints. Significant increases in power consumption and maximum input power of 42% and 60%, respectively, results when all lateral joints are powered.

5 Summary

An orthogonal legged walker is a unique configuration with each leg consisting of two members that move with the body in a lateral plane and a third leg member that extends orthogonally from this plane. There are many combinations of driven joints that are possible to propel the body since a minimum of three powered lateral joints (out of twelve for a hexapod walker) are required. Joint driving configurations are assessed using a body propulsion model that simulates the dynamics of the body and leg members in the lateral plane. The primary assumption of the model is the walker's feet do not slip which decouples the planar motions and the vertical force distribution of the mechanism.

The inverse dynamic equations of the body propulsion model are underspecified and linear programming techniques are used to calculate solutions that identify the set of driven joints which minimize input power to the mechanism at each trajectory point. Traction force constraints assure that mechanism feet do not slip and maximum joint force constraints prevent actuator overloading. Input power to the mechanism is minimized by defining a linear objective function that considers motor winding losses, output power, drivetrain inefficiencies and amplifier losses.

The body propulsion model is applied to the AMBLER walking machine constructed at CMU's Field Robotics Center. A typical body move is simulated for different cycle times, degrees of body tilt, and foot-soil friction coefficients. In general, a minimum number of lateral joints are determined as the optimal driving configuration when traction forces are not limiting and additional joints are powered as available traction forces are exceeded. Maximum joint force constraints were not restrictive in any of the cases that were considered. Powering all lateral joints minimizes the generated traction forces with significant increases in maximum input power and total energy consumed by the mechanism. Propulsion control schemes are being developed for the AMBLER walking machine based on the conclusions of these and other simulations.

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