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Reconfigurable Robots with Heterogeneous Drive Mechanisms: The Kinematics of the Heterogeneous Differential Drive

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ABSTRACT

Statically and dynamically reconfigurable robot mechanisms have been extensively studied by a number of researchers. Control formulations have been proposed for specific mechanisms and some researchers have tried to build unified frameworks for general robot control. This paper reports an extension of the differential drive mechanism that we call the Heterogeneous Differential Drive. Bridging the gap between differential drive mechanisms and skid-steered mechanisms, the heterogeneous differential drive permits the modular combination of different types of actuators with different capabilities under one unified framework. It is a step toward a unified framework for actuators we call Heterogeneous Drive Mechanisms that permits reconfigurable mechanisms with homogeneous or heterogeneous components.

The heterogeneous differential drive is a theoretical class of vehicles that lies in the gray area between pure differential drive vehicles and pure skid steered vehicles, yet represents either at the extremes. The heterogeneous differential drive also provides the basis for our preliminary development of the heterogeneous drive. This paper develops the kinematic model of the heterogeneous differential drive from the kinematic model of the differential drive formulation and describes an example mechanism.

INTRODUCTION

When one thinks of reconfigurable robots, modular projects such as PolyBot [23] typically come to mind. PolyBot is characterized by a collection of identical modules with a uniform interface that can "plug together" either manually or automatically, into various unique physical configurations. But reconfigurability has two aspects: static reconfigurability and dynamic reconfigurability [24]. Static reconfigurability refers to the offline configuration of a system for a particular task. Most robotic systems employ some level of static reconfigurability. Dynamic reconfigurability refers to the online configuration of a system for the particular conditions of the task at hand.

The Reconfigurable Modular Manipulator System (RMMS) [2] was a reconfigurable robot at the opposite end of the spectrum. RMMS was a rapidly-assembled, fixed-base manipulator that consisted of a suite of heterogeneous modules. A genetic algorithm searched the configuration space of possible configurations relative to a kinematic task metric and then the modules were manually assembled in the optimum configuration.

Historically, these types of reconfigurable actuator systems have been rare. There has been much more work on sensor reconfigurability, both static and dynamic, than actuator reconfigurability. Works like Polybot and RMMS have certainly contributed to this area, but their frameworks were specific to the mechanisms. Campion et al built a generic framework for actuator systems [1], but their framework focused more on dynamic simulations of generic robots than mechatronic actuator systems.

We are interested in extending the ability of mobile robots to deal with reconfigurable actuator systems, both static and dynamic. To achieve this, more generic models of actuator systems must be developed akin to those developed for sensor systems. This work is a step toward that goal.

While we ultimately want to develop the theoretical concept of a Heterogeneous Drive system, this paper focuses on the concept of the Heterogeneous Differential Drive. The Heterogeneous drive concept would provide a uniform framework to address the mobility of a robotic system with arbitrary combinations of arbitrary numbers of heterogeneous actuator mechanisms. An example robot system that stimulates this line of work is the multi-limbed TerminatorBot with water hammer-based active tether system [11][10]. Illustrated in Figure 1, this system mates two multi-degree of freedom limbs with an active tether that provides impulses of "bulk motive force" for applications in urban search and rescue (USAR).

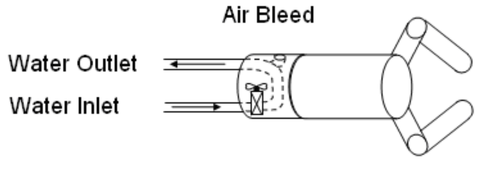

Figure 1: Schematic of a heterogeneous drive robot combining limbs and a novel water hammer actuator.

DIFFERENTIAL DRIVE

A review of the literature examining theoretical kinematic analyses of differential drive robots finds several

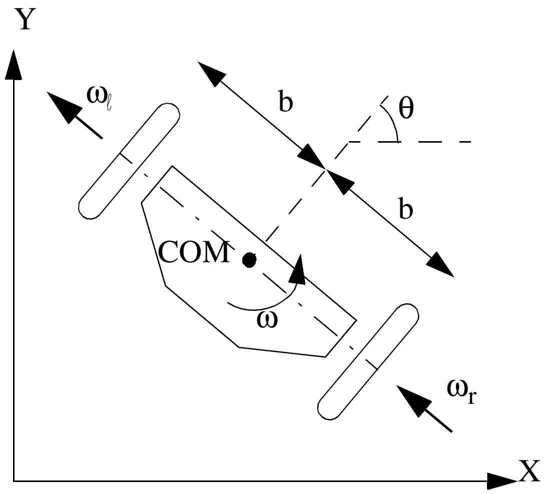

Figure 2: Most common model of differential drive robots that appears in the literature.

common assumptions (for example, see [3][4][5]). These assumptions, while rarely met in practice, provide a simplified theoretical kinematic model that is easy to analyze, yet proves to be surprisingly useful when applied to real examples of differential drive robots. In this simplified model taken from the literature (again, this is not our model), which appears in Figure 2, two drive wheels of effective radius, *r*, share a common axis of rotation and are separated by distance, *2b*. The center of mass (COM) is assumed to reside on the wheel axis of rotation and is assumed a distance *b* from either wheel. Both of these assumptions are rarely met in practice, but they serve to decouple the dynamics for a purely kinematic analysis and provide a convenient reference frame. The wheel angular velocities of the left and right wheels, respectively, ω_l and ω_r, are easily controlled by the vehicle and comprise the command inputs. The resulting motion of the center of mass of the robot is specified by

$$\begin{bmatrix} \dot{X} \\ \dot{Y} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} \frac{r}{2}\cos\theta & \frac{r}{2}\cos\theta \\ \frac{r}{2}\sin\theta & \frac{r}{2}\sin\theta \\ -\frac{r}{2b} & \frac{r}{2b} \end{bmatrix} \begin{bmatrix} \omega_l \\ \omega_r \end{bmatrix} \tag{1}$$

In the kinematic analyses appearing in the literature, it is assumed that the wheels don't slip so the translational velocity at the point of contact of each wheel is

$$v_l = -r\omega_l \qquad v_r = -r\omega_r \tag{2}$$

which allows (1) to be rewritten

$$\begin{bmatrix} \dot{X} \\ \dot{Y} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} -\frac{1}{2}\cos\theta & -\frac{1}{2}\cos\theta \\ -\frac{1}{2}\sin\theta & -\frac{1}{2}\sin\theta \\ \frac{1}{2b} & -\frac{1}{2b} \end{bmatrix} \begin{bmatrix} v_l \\ v_r \end{bmatrix} \tag{3}$$

The radius of curvature of the motion of the COM under this no-slip assumption is simply the distance, *k*, at which the instantaneous center of rotation (ICR) of the two wheels appears, which is a function of the differential velocities

$$(k-b)v_l = (k+b)v_r$$

so

$$k = b\frac{v_l + v_r}{v_l - v_r} \tag{4}$$

As the name implies, the ICR is never fixed. In fact, we control the robot's motion by adjusting the location of the ICR through the wheel velocities, from (4). This simplified kinematic model is used effectively for even highly dynamic differential drive robots such as the miniature rolling/hopping Scout robot described in [6].

SKID-STEERED DRIVE

Another popular form of drive mechanism for mobile robots is the skid-steered drive [7]. This is closely related to the differential drive as it steers by means of differential actuation of a pair of opposing sets of wheels. What sets the skid-steered drive apart is each set of opposing wheels includes more than one wheel, as shown in Figure 3 [8][9]. All wheels on the left rotate with angular velocity ω_l and all wheels on the right rotate with angular velocity ω_r. In this configuration, two or more wheels must skid sideways - perpendicular to the normal direction of travel - during turning maneuvers, violating an assumption of the differential drive described previously.

The key to the behavior of the skid-steered vehicle is the instantaneous center of rotation (ICR). By definition, there are more than two wheels and the ICR is over-constrained because the wheels lack the degree of freedom necessary to converge their axes of rotation. The resulting velocity at every wheel can possess a component that is perpendicular to the rolling direction and, therefore, causes the wheel to skid laterally (Figure 3).

In very aggressive driving conditions, the ICR can be located anywhere with respect to the robot. If it lies outside the wheelbase of the vehicle, extreme lateral slip is occurring and the vehicle is assumed to be out of control (a

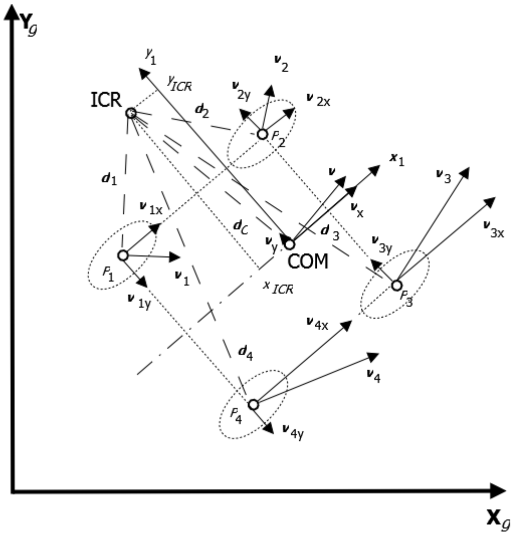

Figure 3: Most common model of a four-wheeled skid-steered vehicle that appears in the literature.

spin-out). Purely kinematic models are not useful for describing this type of driving, but in quasi-static conditions, x_{ICR}, the projection of the ICR onto the x-axis, lies between the COM and the centroid of the vehicle. It is important to note, however, that for any location of the ICR and any wheelbase, trigonometry dictates that $v_{1x} = v_{2x}$ and $v_{3x} = v_{4x}$.

While the kinematic models appearing in the literature expect the wheels to slip laterally during turning maneuvers, the wheels are assumed not to slip longitudinally, which is consistent with the trigonometric observation above, so (2) still holds. Writing the analogous equation to (3) produces

$$\begin{bmatrix} \dot{X} \\ \dot{Y} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} -\frac{1}{2}\cos\theta - \frac{x_{ICR}}{2b}\sin\theta & -\frac{1}{2}\cos\theta + \frac{x_{ICR}}{2b}\sin\theta \\ -\frac{1}{2}\sin\theta + \frac{x_{ICR}}{2b}\cos\theta & -\frac{1}{2}\sin\theta - \frac{x_{ICR}}{2b}\cos\theta \\ \frac{1}{2b} & -\frac{1}{2b} \end{bmatrix} \begin{bmatrix} v_l \\ v_r \end{bmatrix} \tag{5}$$

for the skid-steered case, where b is one-half the width of the vehicle.

Predicting the dynamic behavior of x_{ICR} can be difficult. Under most quasi-static conditions, however, x_{ICR} will remain at the centroid of the vehicle in an attempt to equalize the frictional forces caused by lateral wheel slip (assuming equal friction coefficients at each wheel, which is a strong assumption).

Incidentally, certain velocities must be identical as they are connected by the rigid structure so that

$$v_L = v_{1x} = v_{2x} \qquad v_F = v_{2y} = v_{3y}$$

$$v_R = v_{3x} = v_{4x} \qquad v_B = v_{1y} = v_{4y}$$

The inverse problem of finding command velocities given desired behavior of the COM reduces to

$$\begin{bmatrix} v_L \\ v_R \\ v_F \\ v_B \end{bmatrix} = \begin{bmatrix} 1 & -b \\ 1 & b \\ 0 & -x_{ICR} + c \\ 0 & -x_{ICR} - a \end{bmatrix} \begin{bmatrix} v_x \\ \omega \end{bmatrix} \tag{6}$$

where a is the distance from the COM to the back axle and c is the distance from the COM to the front axle. To complete the specification of the motion of the COM

$$v_y = x_{ICR}\omega$$

We must reiterate that the the above derivations of differential drive and skid-steered vehicles are not our own, but are summaries of the published literature. In the following sections, we will provide our own extensions to these prior works.

HETEROGENEOUS DIFFERENTIAL DRIVE

Given these two standard formulations of symmetric robotic drive mechanisms, we want to develop a formulation for asymmetric or heterogeneous drives. Using the traditional model of differential drive as a starting point, we derive what we call the *Heterogeneous Differential Drive* (HDD) by relaxing some of the assumptions of the differential drive. A trivial extension to the differential drive involves offsetting one wheel along the axis of rotation so the COM is not centered between the wheels as shown in Figure 4. To analyze this configuration, the frame x-y is placed at the COM, similar to the skid-steered drive, and the frame x'-y' is placed at the midpoint of the two wheels similar to the differential drive. v_ℓ and v_r now point along the x-direction of the body-centered frame and the velocities $v_{\ell y}$ and v_{ry} are introduced along the body-centered y-direction. Since wheels are generally not designed to slip sideways, $v_{\ell y} = v_{ry} = 0$ for this formulation of the heterogeneous differential drive.

From the standpoint of frame x'-y', this formulation is exactly the same as the traditional differential drive. In frame x-y, the linear and angular velocities of the COM are

$$\begin{aligned} \omega &= \omega' \\ v_x &= v_x' + \frac{b_r - b_l}{2}\omega' \\ v_y &= v_y' \end{aligned} \tag{7}$$

and the equivalent description of the motion of the COM becomes

$$\begin{bmatrix}\dot{X}\\ \dot{Y}\\ \dot{\theta}\end{bmatrix} = \begin{bmatrix}\frac{-b_l}{b_l+b_r}\cos\theta & \frac{-b_r}{b_l+b_r}\cos\theta\\ \frac{-b_l}{b_l+b_r}\sin\theta & \frac{-b_r}{b_l+b_r}\sin\theta\\ \frac{1}{b_l+b_r} & \frac{-1}{b_l+b_r}\end{bmatrix}\begin{bmatrix}v_l\\ v_r\end{bmatrix}$$

which clearly reduces to (2) when $b_l = b_r = b$. If we further displace the COM a distance, c, in the x-direction from the axis of rotation of the right wheel, the linear and angular velocities of the COM become

$$\begin{aligned}\omega &= \omega'\\ v_x &= v_x' + \frac{b_r - b_l}{2}\omega' \qquad (8)\\ v_y &= v_y' + c\omega'\end{aligned}$$

adding another straightforward term to the motion of the COM

$$\begin{bmatrix}\dot{X}\\ \dot{Y}\\ \dot{\theta}\end{bmatrix} = \begin{bmatrix}-\frac{b_l}{L}\cos\theta - \frac{c}{L}\sin\theta & -\frac{b_r}{L}\cos\theta + \frac{c}{L}\sin\theta\\ -\frac{b_l}{L}\sin\theta + \frac{c}{L}\cos\theta & -\frac{b_r}{L}\sin\theta - \frac{c}{L}\cos\theta\\ \frac{1}{L} & -\frac{1}{L}\end{bmatrix}\begin{bmatrix}v_l\\ v_r\end{bmatrix} \qquad (9)$$

where $L = b_l + b_r$ is the wheelbase.

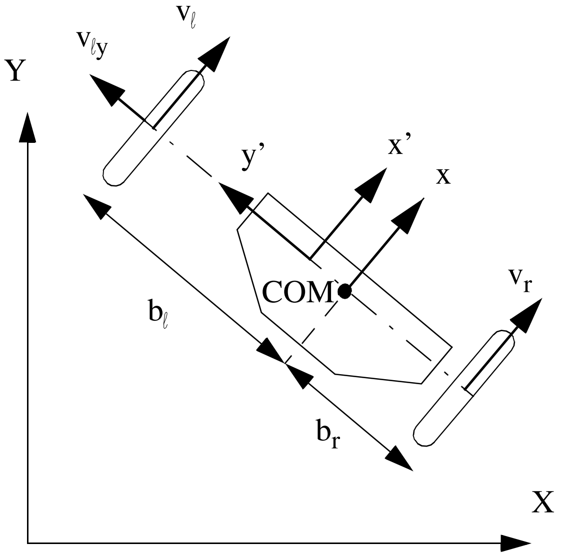

Figure 4: Toward heterogeneous differential drive: a trivial relaxation of one assumption of the differential drive.

In (7) and (8) v_y' is assumed zero, as the robot wheels are not allowed to slip sideways. Note, however, that v_y can take on non-zero values in (8) as it is offset from the robot centroid.

We have now relaxed some of the assumptions of the differential drive which has led to a more asymmetric mechanism, but not a fully heterogeneous one. By "heterogeneous drive," we mean we want completely different actuator types at the drive points. To represent this, we relax the final assumption that the drive points both lie on the same perpendicular to the drive velocities, v_l and v_r. We introduce an offset, d, into the left drive as shown in Figure 5.

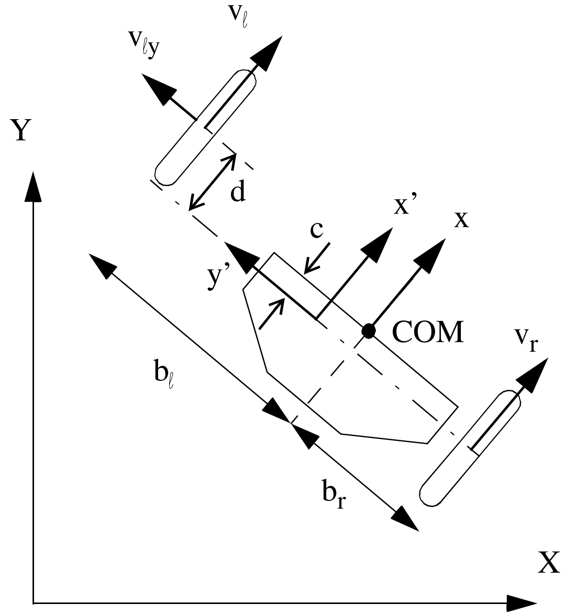

Figure 5: The heterogeneous differential drive: relaxation of all key assumptions of the differential drive.

For continuity, Figure 5 still looks like wheels, but we moved away from the angular velocities of (1) for a reason. The switch to linear velocities at the contact points was deliberate to consider any type of actuator that touches the ground, be they wheels, limbs, treads, or even exotic fluidic actuators. The mapping from actuator velocity space to COM velocity space becomes

$$\begin{bmatrix}\dot{X}\\ \dot{Y}\\ \dot{\theta}\end{bmatrix} = \begin{bmatrix}-\frac{b_l}{L}\cos\theta - \frac{2c-d}{2L}\sin\theta & -\frac{b_r}{L}\cos\theta + \frac{2c-d}{2L}\sin\theta\\ -\frac{b_l}{L}\sin\theta + \frac{2c-d}{2L}\cos\theta & -\frac{b_r}{L}\sin\theta - \frac{2c-d}{2L}\cos\theta\\ \frac{1}{L} & -\frac{1}{L}\end{bmatrix}\begin{bmatrix}v_l\\ v_r\end{bmatrix} \qquad (10)$$

With this formulation, we have introduced the potential for lateral velocities, just as in the skid-steered case, yet it still behaves much like the differential drive in control. If c=0, d=0, and $b_r = b_l$, it simplifies to the differential drive case, as expected. When mapping from desired motion to actuator space, we get

$$\begin{bmatrix} v_l \\ v_r \\ v_{ly} \\ v_{ry} \end{bmatrix} = \begin{bmatrix} -1 & \frac{2L}{2c-d} & -b_l \\ -1 & -\frac{2L}{2c-d} & b_r \\ 0 & -\frac{2d}{2c-d} & \frac{d}{2} \\ 0 & \frac{2d}{2c-d} & -\frac{d}{2} \end{bmatrix} \begin{bmatrix} v_x \\ v_y \\ \omega \end{bmatrix} \qquad (11)$$

which allows us to command velocities on the surface as actuator capability allows.

HDD EXAMPLE

In response to an actual mine disaster in which a search attempt had to be aborted because the robot could not move sideways [21][22], we developed the Crabinator [11][18] as a modular extension of the TerminatorBot [16][17]. Illustrated in Figure 6, the Crabinator uses a modular TerminatorBot body and statically adds a transverse tread actuator module. This configuration allows the robot to drag itself forward, normally (longitudinal motion) using its two limbs, or to locomote sideways using coordinated motion of the tread on one end the the arms in unison on the other end. (To visualize limb motion, it is important to realize that each limb end point moves with three degrees of freedom to facilitate body motion.)

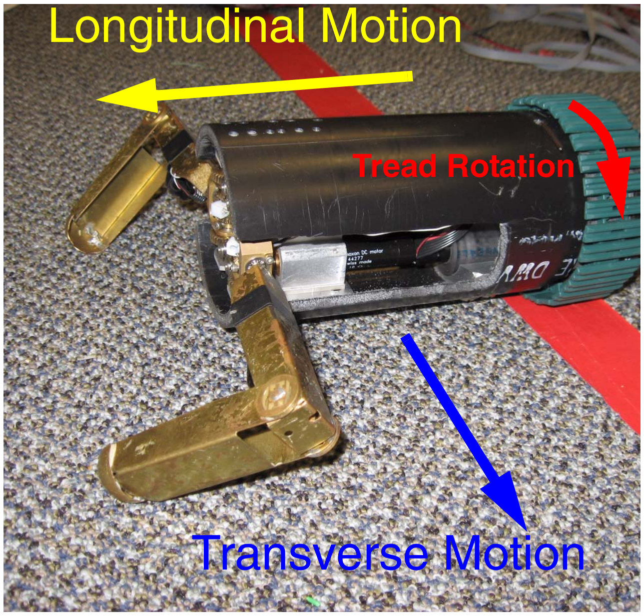

Figure 6: The Crabinator heterogeneous drive robot is capable of both side-slipping locomotion and longitudinal motion

The Crabinator behaves as a heterogeneous differential drive robot in both modes. In longitudinal mode, the two arms act as a differential pair with the COM offset from the line connecting the two tip contact points. The robot is controlled using (11), with parameters as shown in Table 1. (c is variable.) We use an inverse Jacobian controller to control the velocities of both the arm tips and the circular tread. The limbs can exert velocities in contact with the ground in two dimensions. During turns, the limbs are offset and require the full heterogeneous differential drive treatment to compute both the x- and y- components.

In transverse mode, the limbs act together as one actuator and the tread acts as another. Control remains the same, but transverse mode parameters are used from Table 1. (d varies.) The two actuators are obviously heterogeneous, yet the control is unified not only across heterogeneous actuators, but across both modes of operation. Simply changing the parameters for the desired mode and remapping actuator commands produces different motion.

Table 1: Unified control parameters for the Crabinator robot in two modes of locomotion.

Parameter	*Longitudinal mode*	*Transverse mode*
b_l ***(mm)***	111	130
b_r ***(mm)***	111	115
c ***(mm)***	-115	0
d ***(mm)***	33	0

CONCLUSIONS

This paper proposes a new theoretical class of mobile robot drive mechanism we call the Heterogeneous Differential Drive which is a step toward the more general Heterogeneous Drive. Heterogeneous differential drive robots can be controlled in a unified manner by commanding the desired vehicle's angular and linear velocities and simply adjusting the parameter values consistent with the desired mode of operation. Subsequent analyses maintain the benefit from the multitude of previous works analyzing their characerisitcs, such as time-optimal trajectories [5]. The heterogeneous differential drive bridges the gap between differential drive and skid-steer and unifies them.

In addition to the theoretical development, this paper presented an example application of the heterogeneous differential drive concept in the form of the TerminatorBot augmented with the Crabinator module. We have prototyped two versions of this drive mechanism and the heterogeneous differential drive formulation performed adequately. We also outlined a concept for a more ambitious heterogeneous drive mechanism, but the theoretical underpinnings are not fully developed.

FUTURE WORK

Our long term goal is to produce a framework for heterogeneous drive robots that encompass drive mechanisms that are generally asymmetric in form and asymmetric in actuation means. This will encompass, for example, robots with treads on one side and wheels on the other, hybrid legged/wheeled robots, and novel impulsive drive robots that may be assembled for very specific and unique operations in unknown environments.

We performed some initial planar tests of a prototype vehicle as shown in Figure 1. For this vehicle, the arms are the primary mode of actuation and steering and they operate independently at two points of contact to drag the robot forward. The water hammer actuator is a form of active tether that imparts a series of impulsive forces on the back of the robot to assist in propelling the robot forward. These impulsive forces result from the momentum transfer as fluid flowing in the tether is abruptly stopped by the valve.

From an analysis standpoint, this robot is certainly not an ackerman-steered vehicle and it is neither skid steered nor differential drive. Yet, the coordination of the multiple contact points (heterogeneous drive vehicles must have a minimum of two actuation points and actuation means) creates problems similar to the heterogeneous differential drive: the points of contact may not be precisely controllable with respect to their lines of action and with respect to induced motion. While this work is still preliminary, we believe we can create a generic framework for channeling such forces by computing the derivative of the velocities from the heterogeneous differential drive formulation (expanded for n points of contact) and using the multi-body dynamics of the entire robot to relate accelerations and forces. By deliberately shaping non-isotropic properties of the mass matrix through the manipulator configuration space, whole-body steering of the robot can be accomplished.

The multi-link limbs of the TerminatorBot create a complex mass matrix in the form of a closed kinematic chain when both limbs are in contact with the ground. The multi-body dynamics of the mechanism allow very complex shaping of the Cartesian mass matrix to exhibit non-isotropic characterisitcs. We compute the whole-body dynamics using the augmented object paradigm [20] of Khatib's Operational Space formulation [19]. From this we can build a reverse look-up table that maps desired acceleration vectors to specific joint configurations. This command structure is essentially the first derivative of the velocity commands we use for the heterogeneous differential drive and we are looking to unify the two.

ACKNOWLEDGEMENTS

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