Towards Articulated Mobility and Efficient Docking for the DuAxel Tethered Robot System

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***Abstract*—Sites of increasing interest for planetary science, such as craters, cold traps, and vents lie in terrains that are inaccessible to state-of-the-art rovers. The Jet Propulsion Laboratory, in collaboration with Caltech, is actively developing a tethered mobile robot, Axel, for traversing and exploring extremely steep terrain, such as Recurring Slope Lineae on Mars and vertical pits on the Moon. However, on Mars, where landing-site uncertainty is high due to the presence of an atmosphere, Axel may need to traverse several kilometers from its lander untethered due to a finite tether carrying capacity (∼300 m). This paper proposes a novel design for a hybrid mobility system that allows a pair of Axel rovers to dock, lock, and drive long distances as a four-wheeled, articulated steering vehicle. The design improves upon prior efforts to achieve DuAxel mobility by leveraging two actuated docking mechanisms attached on opposite ends of a central module to enable 'sit/stand' functionality; the prior DuAxel system was limited to skid steering, which was inefficient due to Axel's grouser-style, high-friction wheels. In the proposed system, the 'sit' configuration is achieved by aligning each dock parallel to the surface, allowing one Axel to detach and explore while the other remains docked and serves as a backup. While 'sitting', the central module rests on the ground and is outfitted with shovel-style wedges for passive anchoring to sandy terrain (an optional drill can be integrated for anchoring to rock). In order to 'stand', the exploring Axel reattaches, locks, and both docks are rotated until Axel's tether caster arm is upright and the central module is lifted off the ground. Once upright, each Axel rotates about a pivot point for articulated, all-wheel steering, which is accomplished by applying differential wheel torques. The main contributions of this paper are i) a detailed systems design of the docking mechanism and central module, ii) kinematic modeling of articulated mobility and 'sit/stand' docking functionality, and iii) initial testing in a relevant environment to characterize the mobility of the proposed system.**

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1. INTRODUCTION

As the domain of planetary exploration shifts towards increasingly extreme terrain, the application of tethered, mobile robots is of renewed interest [1], [2]. In contrast to traditional planetary rovers, like those currently exploring Mars, tethered robots allow enhanced mobility on extremely steep terrain and access to normally inaccessible science targets, e.g., in-place rock layers or water-ice deposits on crater walls. While tethered systems have been a topic of interest for several decades [3], recent work by NASA's Jet Propulsion Laboratory (JPL) and Caltech has lead to the development of the Axel rover, a two-wheeled mobile robot capable of traversing up to 300 m on a single tether, which provides continuous power, wired communication, and tensile support [4]. In order to explore, Axel starts out at the top[2] of a crater, cliff, or pit with one end of its tether anchored. Axel manages tether on board, which can be reeled in/out in order to descend/ascend steep areas while minimizing tether-surface drag. Due to a finite, tether-carrying capacity, Axel is constrained to drive within a circle defined by its tether length and anchor location. Consequently, Axel must either (i) be placed in proximity of a target and use its lander as a permanent anchor, or (ii) drive untethered and anchor upon arrival. Option (ii) has the advantage of leveraging a parent rover to allow untethered mobility and would be the preferred approach on Mars where the presence of a thin atmosphere implies increased landing site uncertainty [5].

Figure 1: *DuAxel*: The full DuAxel system is shown during initial testing; a pair of Axel rovers are docked in a standing configuration to a central module, which houses power electronics and features a camera mast for navigation.

Accordingly, JPL has developed the DuAxel system, which is comprised of two Axel rovers docked to a central module [6]. The system enables four-wheeled mobility over moderate terrain, undocking of Axel for exploring, and passive anchoring. This paper proposes a novel redesign of the DuAxel system, shown in Figure 1, which addresses a key limitation in mo-

[2] Axel can drive up moderate slopes, $< 30^\circ$, without tether support.

bility: inefficient turning. The original DuAxel design relied on skid-steer turning, i.e., wheel slip, which was limited by Axel's high friction wheels with protruding grousers. To enhance DuAxel mobility, we propose a 'sit/stand' central module with two actuated docking mechanisms that allow for articulated steering while standing and passive terrain anchoring while sitting. We show, through modeling and outdoor experiment, that the redesign enables new and enhanced mobility modes not previously possible.

The remainder of this paper is organized as follows. Section 2 summarizes past approaches in tethered robotics, Axel, and DuAxel. Section 3 presents the updated DuAxel system design. Section 4 outlines our kinematic model for DuAxel mobility. Section 5 offers results and lessons learned from initial, outdoor testing. Section 6 provides concluding marks and future work.

2. Related Work

Extreme Terrain Tethered Robots

Tethered robots for extreme terrain were first developed in the early 1990s, beginning with the Dante rover, a multi-limbed walker capable of descending into volcanic cones in Antarctica and Alaska [3]. In the early 2000s, JPL developed Teamed Robots for Exploration and Science, TRESSA, which leveraged a ground rover attached by twin tethers that were managed by discrete, anchor robots located at the slope ledge [7], [8]. Recently, the Tethered Robotic Explorer (TReX) was developed to enable automated mapping of steep areas such as mine sites, dams, and disaster areas [9]. For a detailed survey of tethered climbing robots see [10].

Axel Rover

The Axel rover has been in development at JPL since the mid 2000s and is, to date, the most robust, field-tested, tethered robot suited for planetary exploration. As shown in figure 2, the Axel rover system integrates a pair of hemispherical wheels, a central body with payload bays recessed into each wheel, and a caster arm [11], [6]. The symmetrical design is naturally self righting, and remains mobile regardless of orientation. Tether is managed on a central spool, which can rotate independently, and is paid out through the end of the caster arm. The wheels are outfitted with grousers, allowing for high traction on sandy terrain, in place trenching, and navigation over large rocks up to 0.5 m in height. The payload bay can rotate while Axel remains stationary, allowing up to eight instruments/sensors to be deployed in close proximity of the surface with millimeter accuracy.

DuAxel

DuAxel, first introduced in [6], has been deployed in field experiments to demonstrate untethered mobility, anchoring, and even autonomous docking [12]. Figure 2 shows DuAxel driving up to a cliff edge and anchoring. After the exploring Axel undocks, a kick stand deploys, and the central module, together with the backup Axel, serve as a passive anchor. Upon return, the exploring Axel's caster arm is retracted into the central module by reeling in tether. As a consequence of docking Axel to the central module with its caster arm parallel to the surface, articulated steering was not possible. Instead, the original DuAxel relied on slip/skid steering, which proved ineffective during field tests due to high surface-to-wheel friction and a non-square wheel base [6].

Figure 2: *Axel/DuAxel*: Images are from a 2011 field campaign to the Arizona desert are shown and illustrate the conceptual operation of the Axel/DuAxel system. DuAxel drives to a new location, anchors, and Axel undocks in order to deploy a sensor and measure the surface. Once science operations are complete, Axel retracts its tether and drives upslope in order to reattach with the central module.

3. DuAxel Design

This section describes the updated DuAxel design, which enables articulated steering, efficient docking, and improved anchoring. The mobility design is inspired by Carnegie Mellon's Zoë rover, a four wheeled platform with passively steered axles and an averaging roll joint [13]. Zoë's mobility relies on applying differential wheel velocities to each of four wheels to steer its axles and thereby control the robot's trajectory over undulating terrain [14].

Sit/Stand Design

To achieve Zoë-like mobility, the DuAxel has been re-designed to allow each Axel rover to rotate/steer about a pivot point centered on its body, which is achieved by positioning the caster arm upright, i.e., normal to the terrain, when docked to the central module. The stand configuration,

Figure 3: *DuAxel stand and drive*: As illustrated, Axel is docked upright to allow driving and articulated steering.

illustrated in Figure 3, allows the DuAxel system to drive both straight, i.e., both Axels are aligned perpendicular to the direction of motion and wheels are actuated with equal velocity, or turn, i.e., one or both Axels pivot about a point by driving wheels in opposite directions, as illustrated in Figure 4. Our current approach is to lock the steering direction

Figure 4: *DuAxel steering*: This illustration shows both Axels pivoting in place prior to driving an arc.

and later drive the wheels differentially to move along an arc with a minimum turn radius of 1.7 meters. While Zoë allowed for actively turning while driving, we simplify the design by adding an optional yaw brake to prevent undesirable yaw drift from occurring.

Once DuAxel arrives at its desired location, e.g., near the edge of a crater or cliff, a pair of actuated docking mechanisms rotate each caster arm downward while Axel's wheels are driven away from the central module. The sit configuration, illustrated in Figure 5, allows an Axel to undock and explore while the central module and spare Axel serve as an anchor.

Docking Mechanism

An actuated docking mechanism, shown in Figure 6, allows DuAxel to transition between sit/stand states and also serves as a tether anchor and passive averaging joint. The docking receptacle, inspired by designs used for both reconfigurable teams of robots [15] and module attachment on the International Space Station [16], uses a toothed alignment pattern to predictably dock Axel in a known configuration. We have modified the caster arm on Axel to have a matching docking

Figure 5: *DuAxel sit and anchor*: This illustration shows the result of actuating a pair of docking mechanisms downward while driving Axel wheels outward. The anchored 'sit' configuration allows Axel(s) to detach and explore.

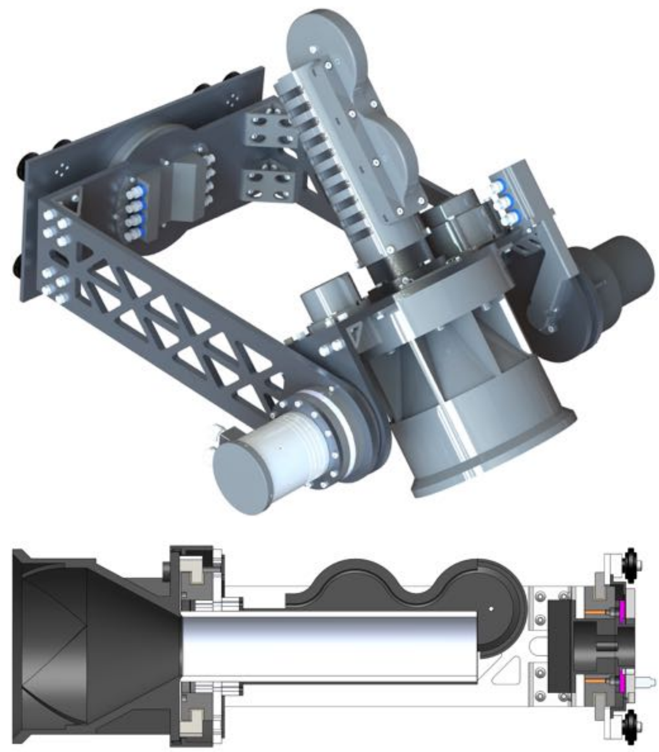

Figure 6: *Docking mechanism*: The illustrations above demonstrate the functions of the docking mechanism: actuated pitch control about a knee joint, passive yaw control through a docking cone with integrated brake, passive roll through an averaging joint, and tether anchoring using a capstan mechanism. The mechanism uses absolute angular encoders at each joint to accurately measure DuAxel's state. Note that electrical connections are routed through the rotating elements without slip rings. Instead rotational motion is constrained to limit potential wire damage.

cone that locks into place as tether is retracted. Caster arm misalignment is corrected by a gradually tapering dock tube.

Central Module

The central module, shown in Figure 7, is a structural frame that links each docking mechanism and accommodates power/electronics, a top-mounted camera mast, and a passive, shovel-style anchoring system. The custom design and shape of the central module result from the following considerations.

- Body height allows Axel arm to deploy at 0:15 degrees
- Body width fits within Axel's wheel baseline
- Turn radius is minimized and body storage is maximized

Figure 7: *Central module*: The key feature of the central module is that it can be lifted for clearance while driving and placed on the terrain for passive anchoring. The illustration shows storage for power/electronics, which are used to distribute power to, and communicate with, each Axel as well as a top mounted camera mast for DuAxel navigation.

- Docking mechanism length is minimized for strength
- Body cutouts accommodate Axel yaw and roll freedom
- Base footprint is stable and resists tipping on the ground
- Base allows for passive anchoring to the terrain

Anchoring

The central module is lowered to the terrain in the sit configuration, allowing for passive anchoring. Anchoring relies on four, angled aluminum plates located at the bottom of the central module frame, as shown in Figure 7. Each pair of plates form a shovel tip that dig downward into the surface as tension is applied on the tether of the exploring Axel. Additional resistance is applied by the remaining Axel's grouser wheels. In order detach, the returning Axel docks and both Axels are driven opposite of the anchor support direction until the shovel is no longer submerged. If the terrain is mostly rocky, the central module can be outfitted with an anchoring drill that is currently under development.

DuAxel System

Shown in Figures 1 and 8, the first prototype of the updated DuAxel system was recently completed. The key difference between the design presented thus far and the images shown is that one Axel has been modified with test hardware intended for evaluating a prototype tether management system [17]. As such, the rear docking mechanism appears larger than the front, right docking mechanism and unmodified Axel. Notwithstanding the changes made, the functionality of the DuAxel prototype is the same, with the exception that the modified dock cannot fully actuate to a horizontal position. We also note that the bottom image in Figure 1 shows a gap between the top of Axel and the docking cone attachment. The reason for the offset gap is to allot space for a future, miniaturized version of the tether management system. The end goal will be to converge each Axel to a common design so that the DuAxel system appears and performs symmetrically, which is a topic of future work, as discussed in Section 6.

Figure 8: *DuAxel prototype:* The initial configuration of the updated DuAxel system is shown from the side and front. Note that one of the Axels has been temporarily modified, which is why the docking design appears asymmetric.

4. Modeling Mobility

This section will discuss the kinematic models related to the control of DuAxel's driving, sit/stand, anchoring, and docking abilities. The generalized kinematic model formulated here is a velocity kinematic model relating the six degree-of-freedom velocity of the DuAxel's body frame relative to the world to each of the platform's joint rates. This model is then constrained to demonstrate the kinematic equations used to steer and drive the Axel in a variety of tele-operation modes.

Generalized Kinematic Model

The DuAxel system has a total of 8 points of actuation. The relevant coordinate frames for describing the system's kinematic model are shown in Figure 9. The kinematic tree extending from the rover's inertial frame to each of its wheel-ground contact points is described in Table 1. The rover moves relative to an inertial frame I. The frame aligned with DuAxel's central chassis is the D frame. DuAxel has two symmetric mobility components composed of an arm and a dockable Axel rover. The forward-facing arm relative to the D frame's x-axis is given the enumeration a, while the backward-facing arm is enumerated as b. A general expression for an arm is denoted using i. Each arm may roll about the the D frame's x-axis, at its averaging joint A_i. This joint is passive, yet may be constrained via a brake at the joint. The next frame along each arms' kinematic chains is the knee frame K_i. Motion about the y-axis of this frame acts to raise and lower the DuAxel body relative the wheel contact points. Rotation occurs about K_i's y-axis. The origin of the steering frame S_i is co-located with the K_i frame. Rotation about the S_i frame's z-axis acts to steer each Axel. This steering rotation, q_{S_i}, may be constrained via a brake. Each Axel mobility module has its own body frame, R_i. From the R_i frame the kinematic tree splits once again, leading to the two wheels. Each branch is enumerated with the sub-script l and r for left and right respectively. A wheel frame is therefore denoted as $W_{i,j}$, where j is either l or r. For example, the front left wheel's coordinate frame is $W_{a,l}$. A second wheel frame $W^*_{i,j}$ is used to describe a frame that rotates with the wheel as it is driven. The last frames are the wheel-ground contact frames $C_{i,j}$. This frame is located at the interface between the wheel surface and the point at which it contacts the terrain surface. The relative rotation between the $C_{i,j}$ frame and the static wheel frame $W_{i,j}$ frame is denoted as the wheel-ground contact angle $\delta_{i,j}$.

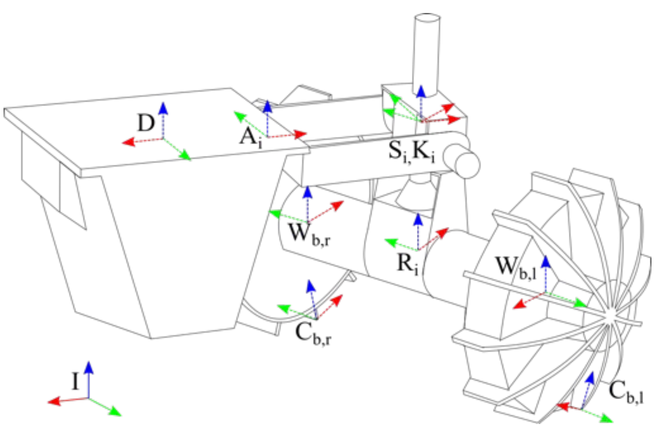

Figure 9: *Coordinate frames*: the generalized velocity kinematic mode of the DuAxel rover is shown.

For each arm of DuAxel, the generalized velocity kinematic model may be expressed as:

$$\boldsymbol{\zeta}^I_{C_{i,j}} = \boldsymbol{B}\begin{bmatrix}\boldsymbol{v}^I_B \\ \boldsymbol{\omega}^I_B\end{bmatrix} + \boldsymbol{H}_{i,j}\begin{bmatrix}\dot{q}_{A_i} \\ \dot{q}_{S_i} \\ \dot{q}_{K_i} \\ \dot{\delta}_{i,j}\end{bmatrix},$$

$$\boldsymbol{\zeta}^I_{C_{i,j}} = \boldsymbol{B}\boldsymbol{\zeta}^I_D + \boldsymbol{H}_{i,j}\boldsymbol{q_{i,j}}\,, \tag{1}$$

where $\boldsymbol{\zeta}^I_{C_{i,j}}$ is the twist of the wheel-ground contact frame relative to the inertial frame, $\boldsymbol{B}$ is the 'body' Jacobian that maps the motion of frame D relative to I and $\boldsymbol{H}_{i,j}$ is the arm to contact Jacobian, which maps the motion of the internal joint articulations to the overall platform motion. The full velocity kinematic model may therefore be written as:

Frame	Parent Frame	Translation Axis	Translation	Rotation Axis	Rotation
I	-	-	-	-	-
D	I	x, y, z	x, y, z	x, y, z	ϕ, θ, ψ
A_a	D	x	l_1	z	0
A_b	D	x	$-l_1$	z	π
K_a	A_a	x	l_2	x	q_{A_a}
K_b	A_b	x	l_2	x	q_{A_b}
S_a	K_a	-	-	y	q_{K_a}
S_b	K_b	-	-	y	q_{K_b}
R_a	S_a	z	l_3	z	q_{R_a}
R_b	S_b	z	l_3	z	q_{R_b}
$W_{a,l}$	R_a	y	l_4	-	-
$W_{a,r}$	R_a	y	$-l_4$	z	π
$W_{b,l}$	R_b	y	$-l_4$	z	π
$W_{b,r}$	R_b	y	l_4	-	-
$W^*_{a,l}$	$W_{a,l}$	-	-	y	$q_{W_{a,l}}$
$W^*_{a,r}$	$W_{a,r}$	-	-	y	$q_{W_{a,r}}$
$W^*_{b,l}$	$W_{b,l}$	-	-	y	$q_{W_{b,l}}$
$W^*_{b,r}$	$W_{b,r}$	-	-	y	$q_{W_{b,r}}$
$C_{a,l}$	$W_{a,l}$	z	$-l_5$	y	$\delta_{a,l}$
$C_{a,r}$	$W_{a,r}$	z	$-l_5$	y	$\delta_{a,r}$
$C_{b,l}$	$W_{b,l}$	z	$-l_5$	y	$\delta_{b,l}$
$C_{b,r}$	$W_{b,r}$	z	$-l_5$	y	$\delta_{b,r}$

Table 1: *Kinematic tree of coordinate frames*: For each frame, the parent frame, parent-child translation axis, translation amount, rotation axis, and rotation are listed.

$$\boldsymbol{\zeta}^I_{C_{i,j}} = \begin{bmatrix}\boldsymbol{B} \\ \boldsymbol{B} \\ \boldsymbol{B} \\ \boldsymbol{B}\end{bmatrix}\boldsymbol{\zeta}^I_D + \begin{bmatrix}\boldsymbol{H}_{a,l} & \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{H}_{a,r} & \boldsymbol{0} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{H}_{b,l} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{H}_{b,r}\end{bmatrix}\begin{bmatrix}\boldsymbol{q}_{a,l} \\ \boldsymbol{q}_{a,r} \\ \boldsymbol{q}_{b,l} \\ \boldsymbol{q}_{b,r}\end{bmatrix},$$

$$\boldsymbol{\zeta}^I_{C_{i,j}} = \boldsymbol{B}_f\boldsymbol{\zeta}^I_D + \boldsymbol{H}\boldsymbol{q}\,. \tag{2}$$

Steering and Driving

The DuAxel rover may steer and drive utilizing its two steerable Axel mobility units and independently drive each of the four Axel wheels. The objective of this section to is to develop expressions for steering angles q_{S_i} of each of the Axels as a function of the body twist ${}^B\boldsymbol{\zeta}^B_I = [v_x \quad v_y \quad 0 \quad 0 \quad 0 \quad \omega_z]$, as well as expressions for the Axel wheel speed as a function of ${}^B\boldsymbol{v}^B_I$. To develop these expressions we assume the motion of the DuAxel rover is over flat terrain so that all ground contact angles are $\delta_{i,j} = 0$ and that the internal articulation angles are held constant. In this case we will assume $q_{A_i} = 0$ and $q_{K_i} = 0$.

As shown in Figure 11 the steering angles q_{S_i} are a function of the velocity of each of the Axel's relative to the inertial frame, expressed in the steering frame, ${}^{S_i}v^I_{S_i}$. By applying the constraints listed above to the kinematic model in Eq. 2, we may develop the following expression for $v^I_{S_i}$:

$$v^I_{S_i} = \begin{bmatrix} v_x\cos\psi + v_y\sin\psi \\ -v_x\sin\psi + v_y\cos\psi + (\ell_1 + \ell_2)\omega \end{bmatrix}. \tag{3}$$

This can then be expressed in the S_i frame as:

$$^{S_i}v^I_{S_i} = \begin{bmatrix} v_x \\ v_y + (\ell_1 + \ell_2)\omega \end{bmatrix}. \tag{4}$$

Each steering angle is a function of this velocity vector:

$$q_{S_i} = \arctan \frac{^{S_i}v^I_{S_i,x}}{^{S_i}v^I_{S_i,x}}, \tag{5}$$

$$q_{S_1} = \arctan \frac{v_y + \omega(\ell_1 + \ell_2)}{v_x}, \tag{6}$$

$$q_{S_2} = \arctan \frac{v_y - \omega(\ell_1 + \ell_2)}{v_x}. \tag{7}$$

The angular velocities of each of the wheels, $\dot{q}_{W_{i,j}}$, are also a function of the DuAxel body velocities:

$$\dot{q}_{W_{i,j}} = \frac{v^{R_i}_{W_{i,j}}}{\ell_4}. \tag{8}$$

This leads to the following expressions for each of the four wheel speeds:

$$\dot{q}_{W_{a,l}} = \frac{\sqrt{v_x^2 + (v_y + \omega(\ell_1 + \ell_2))^2} + \omega\ell_4}{\ell_5}, \tag{9}$$

$$\dot{q}_{W_{a,r}} = \frac{-\left(\sqrt{v_x^2 + (v_y + \omega(\ell_1 + \ell_2))^2} - \omega\ell_4\right)}{\ell_5}, \tag{10}$$

$$\dot{q}_{W_{b,l}} = \frac{\sqrt{v_x^2 + (v_y - \omega(\ell_1 + \ell_2))^2} + \omega\ell_4}{\ell_5}, \tag{11}$$

$$\dot{q}_{W_{b,r}} = \frac{-\left(\sqrt{v_x^2 + (v_y - \omega(\ell_1 + \ell_2))^2} - \omega\ell_4\right)}{\ell_5}. \tag{12}$$

Sit/Stand

The sit/stand motion described in Section 3 may be modeled by expressing the relationship between the K_i frame rotation rate and the wheel $W_{i,j}$ frames' rotation rates:

$$\dot{q}_{W_{a,l}} = \frac{\ell_3 \dot{q}_{K_i} \cos q_{K_a}}{\ell_5}, \tag{13}$$

$$\dot{q}_{W_{a,r}} = \frac{-\ell_3 \dot{q}_{K_i} \cos q_{K_a}}{\ell_5}, \tag{14}$$

$$\dot{q}_{W_{b,r}} = \frac{-\ell_3 \dot{q}_{K_i} \cos q_{K_b}}{\ell_5}, \tag{15}$$

$$\dot{q}_{W_{b,l}} = \frac{\ell_3 \dot{q}_{K_i} \cos q_{K_b}}{\ell_5}. \tag{16}$$

5. Experiment

This section provides experimental results from testing DuAxel mobility in an outdoor environment. First, we evaluate the mobility model outlined in Section 4 to verify the stated steering and driving capabilities of DuAxel. Then we provide results demonstrating the sit/stand and docking functionality of the DuAxel and docking mechanism. Note that driving and sit/stand tests were performed separately due to time and hardware availability constraints. All experiments were conducted outdoors in our Mini Mars Yard on sandy, flat terrain.

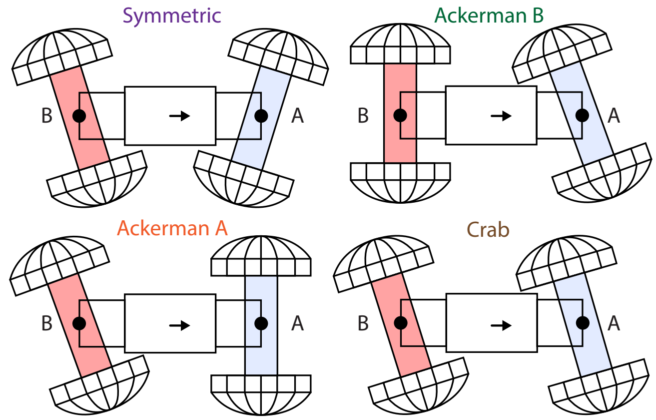

Figure 10: *Steering modes*: These top-down illustrations represent different options for steering DuAxel. Symmetric steering allows for the tightest turn radius (currently 1.7 m). Ackerman B steering aligns the rear Axel, B, with the central module, while the front Axel, A, is free to turn. Ackerman A is the opposite of B. Crab steering enforces that both Axels are always aligned parallel to one another allowing for simple linear trajectory following.

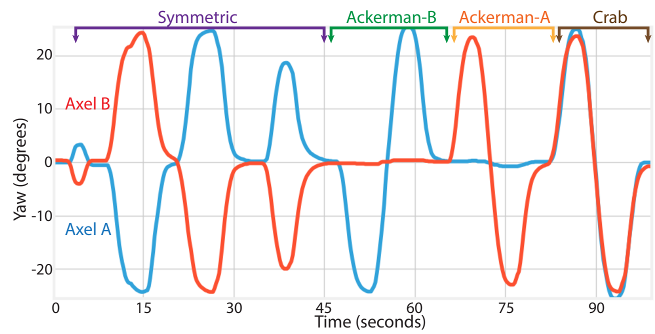

Figure 11: *Steering experiment*: The steering modes of DuAxel are shown. Yaw encoder values are plotted for each Axel as DuAxel is cycled through Symmetric, Ackerman, and Crab steering modes. Note that steering is limited to 25 degrees in either direction in order to prevent Axel's wheels from coming into contact with the central module.

Steering and Driving

The updated DuAxel system is capable of multiple steering modes as illustrated in Figure 10. For the experiment, we cycled though each of four steering modes while DuAxel remained stationary. Steering control was achieved through teleoperation; a user commanded DuAxel with a joystick. Figure 11 shows the yaw angle over time for each Axel with respect to the central module, as measured by an absolute encoder on the docking mechanism. Figure 12 shows all four steering modes demonstrated on the prototype DuAxel.

After verifying all steering modes, arc driving was evaluated. For each steering mode, we set the steer angle using a joystick, and drove the robot in an arc. The results of this test were qualitative and served to demonstrate the enhanced mobility of the proposed DuAxel design. A time-lapse, driving sequence from a test leveraging symmetric steering is shown in Figure 13. Overall, the result of the steer-and-drive experiment demonstrates that DuAxel can efficiently navigate on sandy terrain in order to avoid obstacles. The

(a) Symmetric

(b) Ackerman B

(c) Ackerman A

(d) Crab

Figure 12: *Steering modes*: This series of images demonstrate steering in place with the DuAxel prototype. All four steering modes are achieved on sandy, flat terrain.

only drawback of the current DuAxel design is that the docking mechanism 'knee' joint became loose after several runs. The issue will require revisiting the coupling design to see if a torsional spring can be added to stiffen the joint.

Sit/Stand

While we have not yet integrated sit/stand and steered drive functionalities on the completed DuAxel prototype, we have verified through test that the operation is viable with a single docking mechanism mounted on a slide rail. For the experiment, a single Axel is docked to the mechanism and coordinated sit/stand maneuvers are tested. Specifically, we control Axel to drive towards or away from the dock as the 'knee' joint is actuated [3] at a constant rate. Given the constant-velocity of the dock actuator, Axel must gradually decelerate during a stand in order to avoid unwanted wheel drag and excessive torque on the motor-gear coupling. Figure 14 illustrates Axel's ideal motion, i.e., displacement in the x direction and forward wheel velocity, while going from a sitting to standing state. As shown, Axel must first accelerate then slow gradually as the dock moves between horizontal and vertical states.

A robust control strategy was not used to demonstrate sit/stand during this test. Instead, Axel was teleoperated according to the strategy shown in Figure 14. Images collected during this test are shown in Figure 15. Although we successfully demonstrate sit/stand, the control was clumsy due to a lack of coordination and feedback control. The control strategy will be updated to use feedback control from both Axels in future work.

Docking

In this experiment we evaluate the Axel docking procedure. The Axel docks by reeling in it's tether and driving towards the docking mechanism. Once Axel's caster arm is nearby the docking receptacle, an operator can maneuver the arm by controlling its pitch and rotation through Axel's actuation and wheel rotation. After the caster arm clears the receptacle,

[3]Note that it is possible for both Axels to drive towards each other, causing the central module to lift off the ground without the aid of a motor. We have not tried this yet as the current dock actuator cannot be back driven due to a large gear reduction.

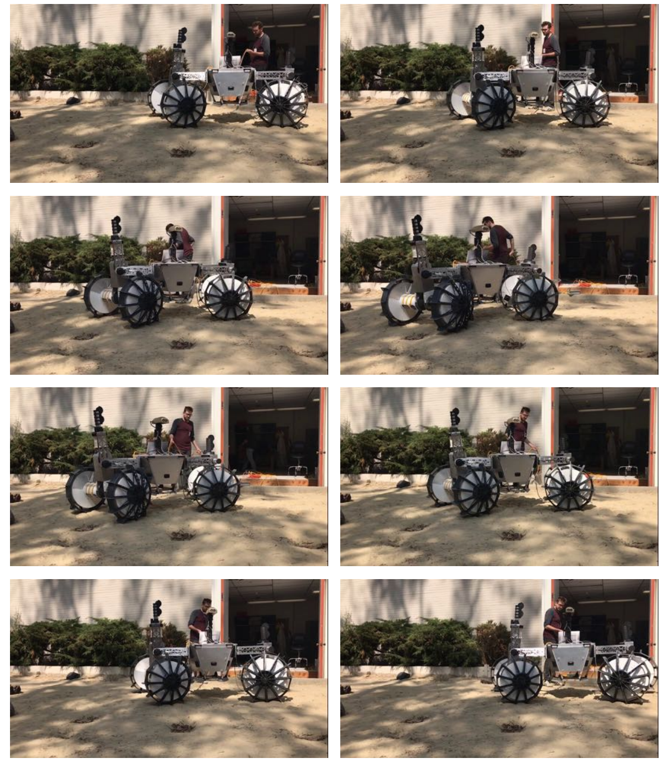

Figure 13: *Steered driving*: The following sequence shows steered driving over a small distance (~ 2 m) using symmetric steering. The test demonstrated arc driving with DuAxel for the first time, allowing a greater range of motion around obstacles in the environment.

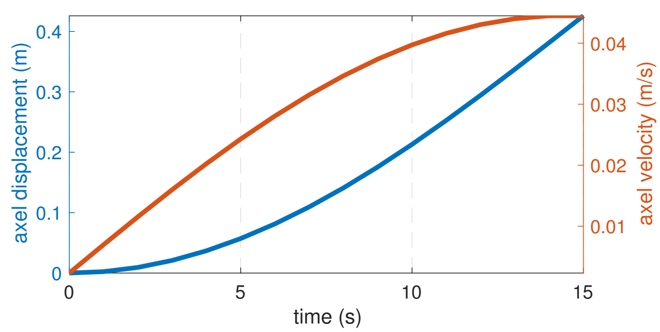

Figure 14: *Stand operation*: This plot shows the ideal motion of Axel during a stand operation in which the docking mechanism is rotated with constant velocity. We note that this plot was not generated from data collected during experiment.

Axel continues to drive and reel tether until its docking cone locks in place. Undocking simply involves repeating this operation in reverse. Figure 16 shows a successful docking test with a single Axel rover and a docking-mechanism mounted on a stand. The docking procedure is difficult to manually control due to the required synchronization of wheel, arm, and spool actions on Axel. For this reason, we will leverage ongoing research into automated tether management [17] and autonomous, vision-based docking [12] for future work.

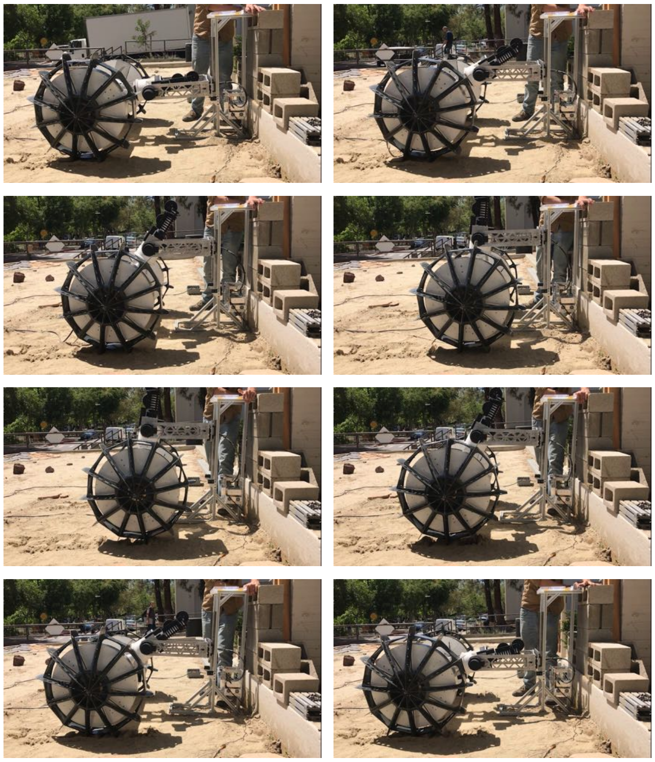

Figure 15: *Sit/Stand*: This sequence shows a test where a docking mechanism attached to Axel is cycled from sit to stand and back. During the test, a docking mechanism was mounted on a vertical slide rail, which allowed for verifying the approach with just one Axel; The sit/stand operation is more complicated for the full DuAxel system as each docking mechanism and Axel must be coordinated and account for wheel drag or slip if it occurs.

Figure 16: *Docking*: This sequence shows a teleoperated test of Axel driving towards the docking mechanism by retracting its tether and driving. Axel's caster arm is placed loosely inside the docking receptacle and the tether is reeled in. As the docking cone structure enters the receptacle, the alignment structure causes the receptacle to passively twist and align in a known configuration as the end of Axel's caster arm slides firmly in place.

6. CONCLUSION

This paper has detailed a novel design update to the DuAxel system, which enhances mobility and docking efficiency for a pair extreme terrain, Axel rovers. The improved system uses an articulated docking mechanism that enables sit/stand mobility. In the sit configuration, one Axel can undock and explore while the backup Axel and central module serve as a temporary anchor. In its stand configuration, each Axel can pivot independently for the purpose of articulated steering. We detail a kinematic model for DuAxel that accomplishes four different steering modes in addition to sit/stand functionality. We evaluate the proposed design and kinematic model in a series of outdoor experiments performed with a recently completed DuAxel prototype. The results demonstrate that the proposed system improves upon the prior DuAxel design and offers new functionality by incorporating just two additional actuators.

For future work, and prior to final publication, we will demonstrate end-to-end docking, sit/stand mobility, and steered driving with the prototype DuAxel in a relevant environment. A field test in the California desert is scheduled for December 2018. Future tests will involve DuAxel traversing to the edge of a steep area, anchoring, and allowing an Axel to undock and explore. Each Axel is currently undergoing design changes to allow for more sophisticated management of the tether. As such, the asymmetric design of the prototype DuAxel will be updated in the future to a symmetric system with identical Axel robots. Finally, we will incorporate autonomy into the DuAxel system by leveraging visual navigation and obstacle avoidance as well as automated sit/stand capability.

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Patrick McGarey *Ph.D. is a Robotics Technologist at JPL in the Robotic Mobility Group. Patrick received his PhD in Aerospace Engineering from the University of Toronto, where he was a visiting Fulbright Scholar. His research is focused on the development of tethered systems and autonomy functions for the exploration of extreme environments throughout the solar system.*

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Issa Nesnas *Ph.D. is a principal technologist and the supervisor of the Robotic Mobility group at the Jet Propulsion Laboratory with over two decades of research in space robotics and industrial automation. He is the principal investigator for the Axel robot and leads research in autonomy and mobility with a focus on extreme terrain access and micro-gravity mobility.*