Turning Efficiency Prediction for Skid Steer Robots Using Single Wheel Testing.

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Abstract To date, most field robots use wheels as their means of locomotion (especially true of planetary exploration robots). In many cases these robots are required to travel significant distances, with limited power, and over rough terrain. All of which make wheels a major component contributing to their performance. It is through experimentation and iteration that effective wheel design, for a given rover in a given mission, can be achieved. To do this, the SWEET (Suspension and Wheel Evaluation and Experimentation Testbed) simulates the rover environment using a single wheel methodology. The wheels currently being tested belong to the SR2 skid steer Mars rover designed and built at the University of Oklahoma. Simulating a skid steer turn with SWEET is achieved by varying the spinning rate of the platform under the wheel, which is rotating at a certain rate, and recording the forces incurred. These forces interact in such a way that the relevant mobility properties for a rover can be predicted. This experimentation method allows for cheap and timely iterative single wheel design.

1 Introduction

Compared with automotive wheels very little research has been done in the area of interplanetary wheel design. To fill the gap in the understanding of rover wheel design and wheel to soil interaction, testing machines have been designed by various institutions. In 1971, NASA tested a single Lunar Rover Vehicle wheel on a testing device called a dynamometer system [6] and now uses devices such as the variable

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terrain tilt platform (VTTP), at JPL, to gain a better understanding of entire rover systems in a sloped environment. The VTTP is a 16 x 16 ft table that can tilt up to 25 degrees and can be left bare or covered with terrain [4] but is meant to incorporate the total rover assembly and is used in a design validation role rather than an iterative design role. At the Massachusetts Institute of Technology a testing device (FSRL) tests a single driven wheel through different mediums to better understand wheel to soil interaction [3]. A similar device is used at Tohoku University to refine rover steering and other parameters [9]. Other comparable devices test wheels for Earth's terrain are [5, 8, 2]. The University of Oklahoma's testing apparatus named SWEET [1] is unique in that it allows for true turn testing.

All these test beds allow the simulation of aspects of real-life operations. Full assembly test beds are more difficult and expensive to use since they require the full rover, a full compliment of wheels, and much more space. Issues with the wheel design may also be conflated with other aspects of the rover design when a full system is tested, making iterative improvement of the wheel more difficult. Single wheel testing machines, on the other hand, allow a designer to iteratively design a wheel in a much less costly and timelier fashion than full assembly testing. For these single wheel testing machines to be of any use, the data that they give must have some significance in the real world. Their performance in the single wheel testing machine must transfer to predict the behavior exhibited on a multi-wheel rover doing typical maneuvers in field conditions.

Skid steering turn performance is an example of a typical maneuver, beyond the domain of most single wheel test systems. If it can be demonstrated that a model can transform data from a single wheel test to predict the turning efficiency of a rover, then skid steer turning is one more behavior that can be studied and improved upon cheaply and thoroughly using the single wheel testing method. This paper describes a method to test skid steer rover wheels on a single wheel test apparatus and then predict its real world turning performance on a skid steer rover. The predictions are then compared to full assembly tests fitted with four identical wheels to the one tested.

2 Theory of Single Wheel to Full Assembly Correlation

Skid steering is an unintuitive process in that there are multiple forces, due to the lateral sliding, that must take place for a skid steer rover to turn. When a rover initiates a turn its rotation (in the $X-Y$ plane) will accelerate up to a certain spin rate Ω (Fig. 1) at which point it will stabilize and the moment about its center (M_o) will equal zero.

$$\Sigma M_o = 0 \; . \tag{1}$$

$$\Sigma(F_y R\cos(\Theta)) - \Sigma(F_x R\sin(\Theta)) = 0 \; . \tag{2}$$

$$F_y = F_x \tan(\Theta) \; . \tag{3}$$

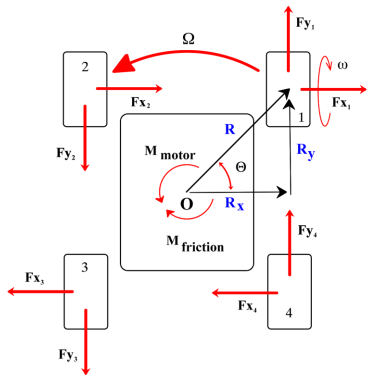

Fig. 1 Skid Steer Force Body Diagram

Equation 3 describes a relationship between F_x and F_y at the turning equilibrium point and is dependent upon the rover geometry (Θ). If the rover were slender (Fig. 2-a) then Θ would be larger than $\frac{\pi}{4}$ and F_x would be much smaller than F_y. If $\Theta = \frac{\pi}{2}$ then $F_y = \infty$. This would mean that no matter how much force a wheel could exert on the ground the rover's spin rate Ω would always be zero. If, on the other hand, Θ were equal to zero, as in Fig. 2-b, then F_y (which is really the net force of power and friction) would be equal to zero. This configuration is better known as Ackerman steering which means that the wheels have no lateral slip and if there is no longitudinal slip then the turning rate can be calculated by eq. 4.

$$\Omega = \frac{\omega r}{R}, F_y = 0\,. \tag{4}$$

where ω is the wheel angular velocity in radians per second, r is the wheel radius, and R is the distance from the center of the wheel to the center of rotation of the rover.

Equation 4 refers to the ideal turning rate Ω_{IDEAL} without longitudinal slipping for an Ackerman steering geometry. To calculate Ω_{IDEAL} for a skid steer rover ($\Theta \neq 0$), Θ must be taken into account and is reflected in eq. 5. Ω_{IDEAL} refers to the theoretical maximum a skid steer rover can spin, but F_y, at Ω_{IDEAL}, is still not zero.

$$\Omega_{IDEAL} = \frac{\omega r}{R}\cos(\Theta), F_y \neq 0\,. \tag{5}$$

To find the value of $\Omega_{F_y=0}$, which is the spin rate at which there is no longer a net force in the Y direction, the longitudinal velocity (V_y)(Fig. 2b) of the ground under the wheel must be equal to the velocity of the wheel rim (ωr) therefore making $F_y = 0$ (no slip). Equation 10 explains this relationship. Loose soils that cause more viscous friction, such as sand, will alter the slope of the force curves and decreasing the $\Omega_{Predicted}$ and $\Omega_{Fy=0}$ values.

$$V_y = \omega r\,. \tag{6}$$

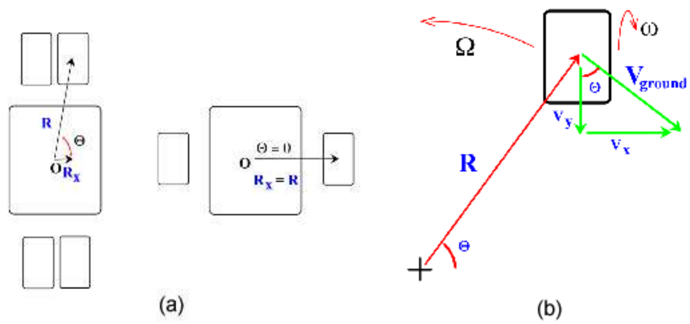

Fig. 2 a) Skid Steer Geometry Configurations; b) Skid Steer Kinematics

$$V_y = \cos(\Theta) V_{ground} \ . \tag{7}$$

$$V_{ground} = \Omega R \ . \tag{8}$$

$$\omega r = \Omega R \cos(\Theta) \ . \tag{9}$$

$$\Omega_{F_y=0} = \frac{\omega r}{R\cos(\Theta)} = \frac{\omega r}{R_x} \ . \tag{10}$$

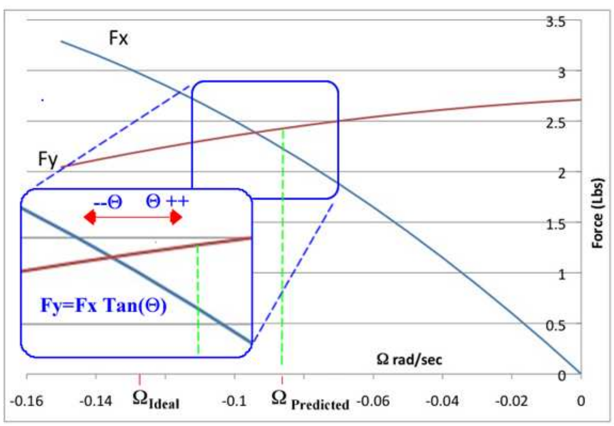

Fig. 3 Force vs Spin Rate Example

For the right front wheel of a rover pivoting in the counter clockwise direction, the ground must move under it in the opposite direction ($-\Omega \frac{rad}{sec}$) and the relationship of the forces on the wheel, as the spin rate (Ω) of the ground under the wheel increases, can be shown in illustration 3. When the simulated rover's spin rate (Ω) is equal to zero the wheel being tested rotates (ω) but does not move. This causes a force in the Y direction which is just the kinetic friction ($F_y = \mu_k N$) between the wheel and ground. For a blank wheel on smooth ground there is no F_x at $\Omega = 0$, but for a treaded wheel F_x could be non-zero which will be one value to focus on when testing new wheels. As the spin rate of the ground under the wheel, increases F_x increases while F_y decreases until they intersect. This meeting point would represent the equilibrium spin rate ($\Omega_{Predicted}$) of a square rover ($\Theta = \frac{\pi}{4}$). To find the equilibrium point, of a rectangular rover, eq. 3 adds the needed constraint between F_x and F_y. For the SR2 [7] rover $\Theta = .8477$ *rad* when combined with eq. 3 simplifies to eq. 11.

$$F_y = 1.133 F_x \,. \tag{11}$$

In essence what we are doing is operating the wheel and the ground under the wheel independently, by varying the ground speed (Ω) while keeping the wheel spin rate (ω) constant, and observing the behavior of the forces acting on the wheel. When the forces satisfy eq. 11 the corresponding Ω is the predicted rover spin rate. In Fig. 3 this relationship gives a point just right of the cross point and corresponds to a $\Omega_{Predicted}$ value which is the predicted spin rate of a rover fitted with four wheels with the same orientation, relative to the rover center, and identical tread to the wheel tested.

It should be noted how a rover's geometry affects this relationship. As Θ increases above $\frac{\pi}{4}$ the rover is more slender (Fig. 2) which makes turns less efficient and $\Omega_{Predicted}$ becomes smaller. If, on the other hand, Θ decreases its $\Omega_{Predicted}$ value increases until $\Theta = 0$ and $\Omega_{Predicted} = \frac{\omega r}{R}$ which is an Ackerman steering geometry.

3 Validation Experiments

To do single wheel testing the Suspension and Wheel Experimentation and Evaluation Testbed (SWEET) is used. The testbed (Fig. 4) has a 10 x 10 ft footprint and a weighted drop down test leg, incorporating a driven wheel and a six-axis, force torque sensor which stays stationary in the X and Y directions but allows movement along the Z-axis via a counterbalance system.

SWEET differs from most testbeds in that the table can move in the X and Y directions underneath the test stand, as well as rotate in the X,Y-plane. This added advantage gives the apparatus the unique ability to measure forces and torques in a true turn allowing the study of skid steer turning.

SWEET was programmed to simulate a skid steer turn and fitted with a .109 meter diameter blank wheel on simple carpet (Fig. 4). Parameters were set to mimic our in-house four wheel skid steer rover's (SR2 [7]) geometry and loading. The test variables were wheel spin rates (ω = .3, .4, and .5 $\frac{rad}{sec}$) and turn rates ($\Omega = 0$, -.01, -.02 .... -.12 $\frac{rad}{sec}$) with 5 trials of each. Post processing, of the data, was done with

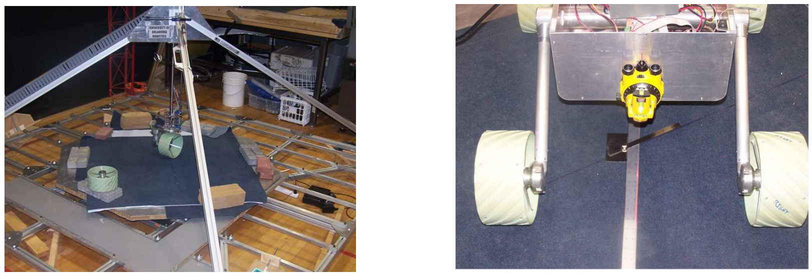

Fig. 4 a) SWEET Testbed; b) SR2 rover spin rate testing

several C programs that averaged all trials, performed 2nd and 3rd order regression curve fitting, and calculated $\Omega_{SWEET Predicted}$.

The results, for SWEET's skid steer turn test, are shown in Figs. 5, 6, and 7.

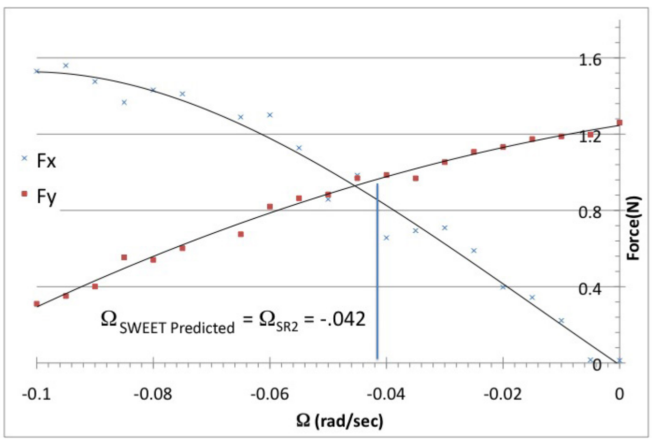

Fig. 5 Results for $\omega = .3 \frac{rad}{sec}$

SR2 (Fig. 4) was then fitted with four blank wheels and turned on the same carpet to validate the results. Tests were done for three different wheel speeds (ω =.3, .4, and .5 $\frac{rad}{sec}$) measuring the spin rate of the rover during the test (by measuring the angle between an onboard laser level mark and the initial position and dividing by the elapsed time), which are given in table 1 along with $\Omega_{SWEET Predicted}$ and percentage error. These results show a definite validation of the SWEET single wheel test within 3%.

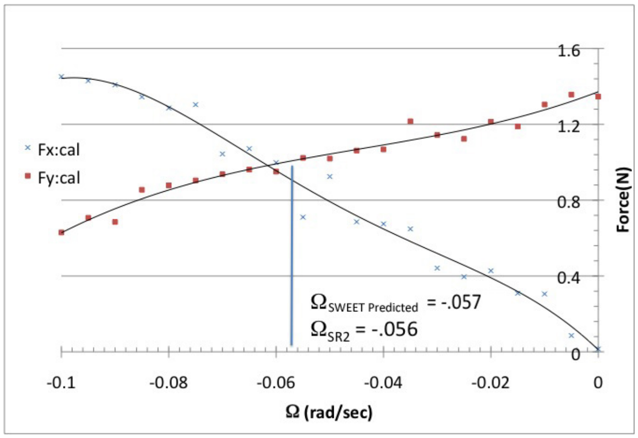

Fig. 6 Results for $\omega = .4\frac{rad}{sec}$

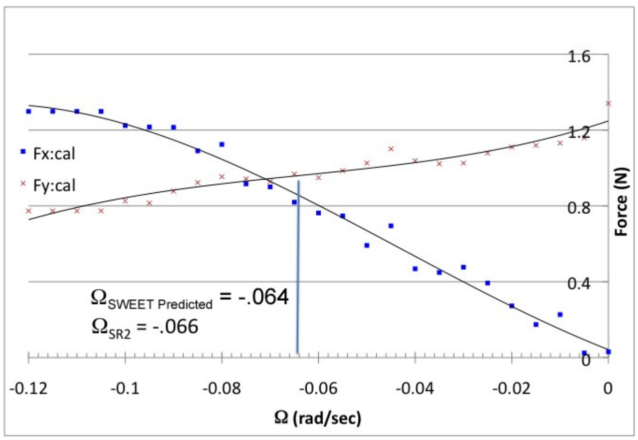

Fig. 7 Results for $\omega = .5\frac{rad}{sec}$

Table 1 Ω_{SR2} and $\Omega_{SWEET Predicted}$ results in $\frac{rad}{sec}$

ω	Ω_{SR2}	$\Omega_{SWEET Predicted}$	Error
0.3	-.042	-.042	0%
0.4	-.056	-.057	1.8%
0.5	-.066	-.064	3.0%

4 Skid Steer Experiments with Non-Blank Wheels

In considering a non-blank wheel, particularly a directional patterned wheel such as Fig. 8 there is a possibility of a force along the X axis induced by the tread pattern. If the wheel is mounted on the correct side then the additional force will benefit the turning efficiency by offsetting the frictional force produced by the turn. The theoretical ideal turning rate for a directional treaded wheel has to include any V_x produced by the tread.

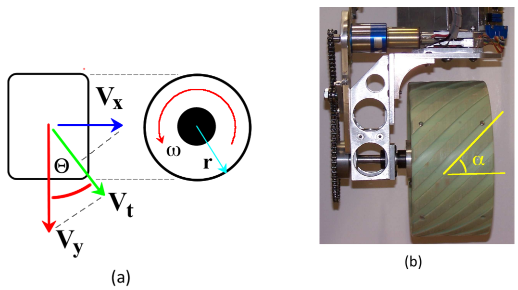

Fig. 8 a) Kinematic explanation of treaded wheel; b)Measuring α on a treaded wheel

$$V_t = V_y \cos(\Theta) + V_x \sin(\Theta)\ . \tag{12}$$

$$V_y = \omega r\ . \tag{13}$$

$$V_t = \Omega R\ . \tag{14}$$

$$\Omega_{IDEAL} = \frac{1}{R}(\omega r \cos(\Theta) + V_x \sin(\Theta))\ . \tag{15}$$

if Ω_{IDEAL} were related to the tread design only (such as a bolt screwing into a nut) and ignored any soil interaction V_x would be a function of ω, α, and r (equation 16 and Fig. 8). Which would give the Ω_{IDEAL} in equation 17.

$$V_x = \frac{\omega r}{\tan(\alpha)}\ . \tag{16}$$

$$\Omega_{IDEAL} = \frac{\omega r}{R}\left(\cos(\Theta) + \frac{\sin(\Theta)}{\tan(\alpha)}\right)\ . \tag{17}$$

Two directional patterned wheels, with diameter of .102 meters (Fig. 8b), were tested in SWEET. Figures 9 and 10 show the performance of the two oppositely patterned wheels dubbed 'left' and 'right' which correspond to their proper orientation on the rover. Again the tests were run simulating the right front side of a rover turning in a counter-clock-wise fashion. The tests were run on padded carpet, and not a hard surface, to focus on how the tread itself interacts with the surface and the treads affect on turning performance. Figure 10 shows the results of a left wheel in that position producing a $\Omega_{SWEETPredicted}$ value of -.037 $\frac{rad}{sec}$ while the right wheel gives a $\Omega_{Predicted}$ value of -.050 $\frac{rad}{sec}$ (table 2). The left wheel can be visualized as trying to screw itself to the right fighting against the turn when placed on the right side, the right wheel is trying to screw itself left benefiting the turn.

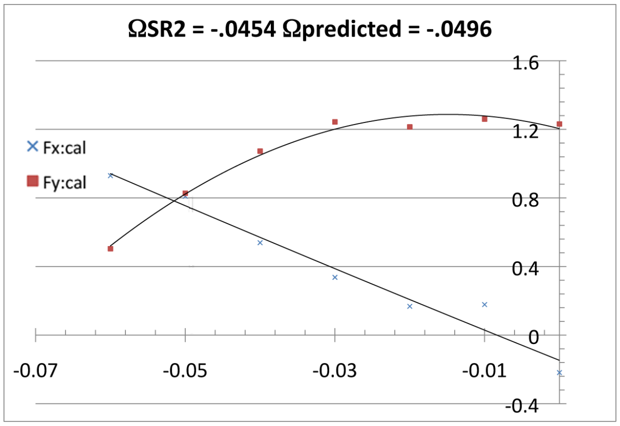

Fig. 9 Results for right treaded wheel rotating at $\omega = .3\frac{rad}{sec}$ in the right front position

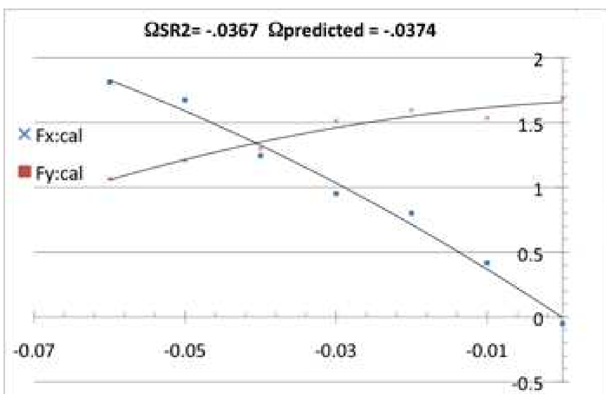

Fig. 10 Results for left treaded wheel rotating at $\omega = .3\frac{rad}{sec}$ in the right front position

Table 2 Ω_{SR2} and $\Omega_{Predicted}$ results for treaded wheels

Wheel	Ω_{SR2}	$\Omega_{Predicted}$	Error
Left	-.0367	-.0374	1.9%
Right	-.0454	-.0496	9.25%

5 Conclusions

This paper discusses and demonstrates a method that allows the results from a single wheel test to be used to predict turning efficiency for a full assembly skid steer rover. Three different wheels were tested and predicted turn rates were within 10% of full assembly tests which probably can be refined by increasing the sample size. Future work will be to test on sand and other terrain, test and evaluate interesting wheel types, and iterate tread design on conventional wheels to better ascertain a wheel's performance on different media all of which without the cost and time of full assembly tests.

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