A CASTOR WHEEL CONTROLLER FOR DIFFERENTIAL DRIVE WHEELCHAIRS

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Abstract: This paper describes a motion controller for differential drive vehicles with a compensation for castor wheel turn forces. The controller has been developed for electric wheelchairs with two front castor wheels, which require large steering forces to move into the direction given by the joystick in situations where a sharp turn of the castor wheels is needed. It computes the required forces to turn the castor wheels and modifies the drive request adequately. This also helps physical or cognitive impaired users who otherwise have to compensate castor turn forces manually using the joystick, which requires fast reaction time (e.g. when the castor wheels turn quickly into the driving direction) to avoid collisions.

1 INTRODUCTION

Figure 1 presents the intelligent wheelchair *ROLLAND* (Lankenau and Röfer, 2001) based on a Meyra wheelchair of the model CHAMP (Meyra Ortopedia, 2010). As many other electric wheelchairs, CHAMP uses pneumatic tires for both back differential drive wheels and front castor wheels to achieve comfortable indoor and outdoor driving. The configuration of back differential drive and two front castor wheels is probably the most frequently used one for electric wheelchairs. With the large ground contact area of the castor wheels, the high load (typical 160kg for the wheelchair with the driver, about one third on the front axis), and the tire material (rubber), the additional force to change the angle of the castor wheel is significant, especially when maneuvering at low speed in a narrow environment. Recently, an empirical study (*reference skipped*) on the evaluation of the safety assistant modul developed for *ROLLAND* was carried out, which monitors the surrounding environment using sensor data gathered by the equipped laser scanners and brakes in time if an obstacle is dangerously close to the wheelchair. During the experiment a common phenomenon was observed: after the intervention of the safety assistant, the participants attempted to regain control over the wheelchair by giving driving commands via the joystick, but the wheelchair did not drive in the direction they expected or did not move at all.

Figure 1: The intelligent wheelchair *ROLLAND*.

The primary reason for such problems is that the wheelchair requires a lot of motor force to turn the castor wheels, if the wheelchair starts in a standing position with castor wheels positioned in a blocking state (i.e., the two castor wheels stand transversely to the required drive direction). Moreover, users often change the joystick command if the wheelchair does not react to the previously given command, as most participants did in the above study. As a result they tried to give the wheelchair some arbitrary commands

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via the joystick or pressed the joystick powerfully, which caused an even less expected behaviour of the wheelchair. One solution to this problem, and as the focus of the current paper, is to apply a castor wheel controller, which enables the wheelchair to adjust castor wheels correctly, such that the time delay to realize the requested drive command can be reduced in those situations, and the joystick can remain in a stable position.

Castor wheels have been investigated in the literature mainly to model and minimize wheel shimmy (see (de Falco et al., 2009), (Brearley, 2009), (Kauzlarich et al., 2000)). In (Kauzlarich et al., 1984), castor turn forces are compared for different grounds and tire materials, but without a projection of these forces to the differential drive of an electric wheelchair. Therefore no compensation of these forces is discussed in that work.

This paper is structured as follows: We begin in Section 2 with the kinematic model for differential drive wheelchair with two front castor wheels, and introduce a model to predict castor turn forces and discuss possible compensation. Section 3 explains the integration of the castor force compensation into *ROLLAND*. Section 4 discusses some test results by comparing the wheelchair behaviour with and without the castor controller. Before concluding in Section 6 we discuss some related approaches in Section 5.

2 A KINEMATIC MODEL

We are going to present a kinematic model of castor turn forces for differential drive wheelchairs with two front castor wheels. The castor wheel angles are essential for the required turn forces, thus should be discussed first.

2.1 Castor Wheel Angles

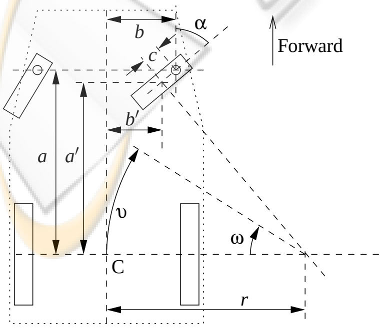

Figure 2: Determination of castor wheel angles.

To compute the required force to turn the castor wheels, the castor angles must be computed based on the current driving request. The motion state of differential drive vehicles can be described by its rotational speed ω (rad/s) and translational speed υ (m/s) measured at the center point C between the powered wheels. The radius r (see Figure 2) is determined by

$$\frac{\upsilon}{r} = \omega \Leftrightarrow r = \frac{\upsilon}{\omega} \quad (1)$$

However, there is always a small gap c between a castor's ground touch point and the intersection of its steering axis with the ground plane (also called *trail*). Furthermore, the steering axis inclination is usually 0 or almost 0 for castor wheels, and can be assumed to be 0. If c equals 0, the angle of the castor can be obtained (using trigonometry) by

$$\tan\alpha = \frac{r-b}{a} \quad (2)$$

For $0 < c \ll a$ (as usual), the castor wheel angle α obtained by Equation 2 is already a good approximation. However, a higher precision α' can be obtained using the ground touch point at distances a' and b' derived from the first estimation of the castor wheel angle α and the value of the gap c (see Equation 5), with which more precise castor turn forces can be calculated.

$$a' = a - c * \cos\alpha \quad (3)$$

$$b' = a - c * \sin\alpha \quad (4)$$

$$\tan\alpha' = \frac{r-b'}{a'} \quad (5)$$

2.2 Castor Turn Forces

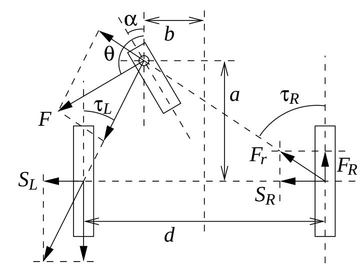

Figure 3: Castor turn force F projected to differential drive wheels.

Figure 3 shows the geometry of the *ROLLAND* electric wheelchair as an example for a differential drive robot with two castor wheels. Let the *castor turn force F* be the force that is required to start the castor wheel to swivel without rotating the wheel and applied at the castor steering joint. This force must be applied perpendicular to the driving direction of the castor wheel. F can be split into

$$F = F_{ground} + F_{joint} \quad (6)$$

where F_{ground} represents the friction between the ground and the tire at the ground touching point, and F_{joint} the friction inside the turning joint. The joint is typically so constructed that $F_{joint} \ll F_{ground}$. A difference between sticking and gliding forces could not be observed, due to the plasticity of the tire. As frictional forces grow proportionally with the normal force between the surfaces, the castor turn forces can be described as

$$F = c_{castor} L \tag{7}$$

where L is the load of the castor wheel and c_{castor} is constant for a given wheelchair and ground material. Equation 7 must be understood as an upper limit of the required castor force. A rolling castor wheel requires much smaller turn forces, which should be considered by the castor controller (see Section 3).

The castor turn force can be projected to the forces of the two differential drive wheels, F_L and F_R (see Figure 3):

$$\theta = \alpha \pm \frac{\pi}{2} \tag{8}$$

$$\overline{F} = \overline{F_l} + \overline{F_r} \tag{9}$$

$$F_L = F_l \cos\tau_l \tag{10}$$

$$\tan\tau_L = \frac{a}{b - \frac{d}{2}} \tag{11}$$

$$F_R = F_r \cos\tau_r \tag{12}$$

$$\tan\tau_R = \frac{a}{b + \frac{d}{2}} \tag{13}$$

$+$ or $-$ in Equation 8 is chosen depending on the intended castor steering direction (left or right swivel). Equation 9 splits the castor correction force $\overline{F}$ into forces of the differential drive wheels. The left engine produces $\overline{F_l}$ as the sum of the motor force $\overline{F_L}$ and a shearing force $\overline{S_L}$ (see Figure 3). The left engine force F_L is computed by Equations 10 and 11, and the right one by Equations 12 and 13.

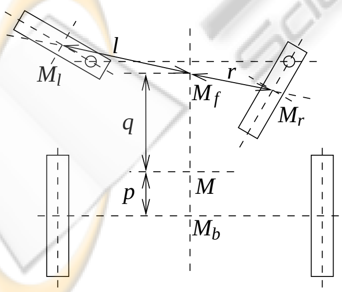

Figure 4: Mass distribution to castor and differential drive wheels.

Figure 4 shows the center of mass M of the wheelchair at the point with a distance of p to the back axis. The back wheels are connected with springs to the chassis, such that both wheels can be assumed to carry the same weight that sums up to M_b at the back axis center. The front wheels carry the remaining mass M_f, giving the following mass distribution:

$$M_f = M \frac{p}{p+q} \tag{14}$$

$$M_l = \frac{r}{l+r} M_f \tag{15}$$

$$M_r = \frac{l}{l+r} M_f \tag{16}$$

The values for p, l, and r can be obtained from the ground touch points as in Figure 2.

2.3 Maximal Castor Turn Forces

Using the kinematic model of Sections 2.1 and 2.2, Figure 5 gives an overview of the forces required by the differential drive vehicle using the geometry of the Meyra CHAMP wheelchair (in mm: $d = 585, p = 160, a = 470, b = 42$). For each value of the left castor angle (x-axis), the diagram shows the angle of the right castor wheel, which maximises the required correction force for one of the two differential drive motors. The force factor (right y-axis in Figure 5) is the relation between the required motor force and the standard situation in the left diagram of Figure 6, where castor turn forces and engine forces are all equal, and the castor wheels are in a blocking state when driving forward. The diagram in Figure 5 shows two symmetric maximal force factors -2.21 (left engine) and 2.21 (right engine). The -2.21 maximum for the left drive wheel is also shown in the right diagram of Figure 6 with castor angles $L = 46.08°$, $R = 8.28°$.

3 MOTION CONTROLLER

The kinematic model described in Section 2 has been implemented and integrated into the wheelchair *ROLLAND* in two ways:

- as an add-on for a classical proportional-integral (PI) controller using odometry information to control translational and rotational wheelchair speed (used for autonomous driving).
- as a pure castor force compensation controller to support joystick driving.

Although the tests reported in Section 4 have been run with the pure castor controller, both controllers have been implemented using the following principles:

1. The castor controller applies a slowly growing correction force. This helps to adapt to different

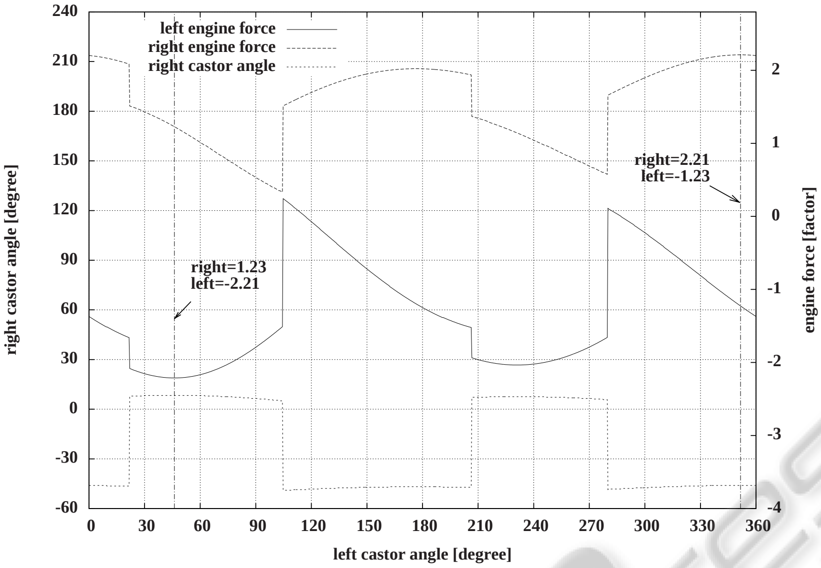

Figure 5: Castor angles with maximal differential drive load.

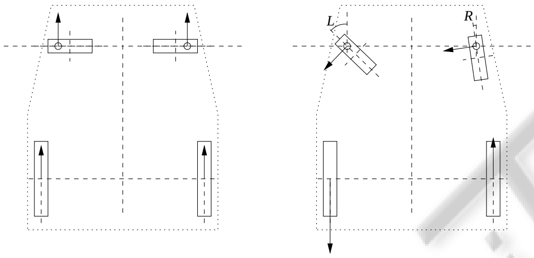

Figure 6: Castor correction forces in standard (left) and maximized situation (right).

frictional forces for varying undergrounds, standing or rolling castor wheels. It smoothly applies forces for the transition from *standing still* (no correction forces applied) to *driving* (correction applied).

2. The correction force will be significantly reduced, if the castor wheel turns too fast.
3. The correction force is reduced, when the difference between actual and requested castor angle is small.
4. If the given command changes the driving direction, the control intensity is reduced. A control intensity built for a specific driving direction should not be applied for a completely different driving direction.
5. The correction force of the controller is reduced to zero, if one of the castor correction forces changes its sign (the castor angle has crossed its target angle). This allows to reach the target castor angle exactly and reduces oscillations around the ideal castor angle.
6. The mass distribution to each individual wheel can be significantly influenced by the differential drive forces. The Meyra CHAMP, for example, has an independent wheel suspension using a trailing arm for each wheel. The forward torque of a wheel moves the trailing arm and its wheel downward, which increases the load of the castor wheel on the opposite side. The measurements of this effect have been used in the controller to correct the mass distribution described in Figure 4.
7. If the differential drive stands still, the engine torques grow nonlinear with the given driving command. The relation between them has been measured and recorded in a table to apply correct forces.

The combination of the castor controller with a PI-controller requires to join the drive requests produced by both controllers. A brief impression can be obtainded by the following two principles:

- For small deviating castor angles, the influence of the castor controller should be small. This gives priority to the PI-controller.
- Correction forces of the castor controller are subtracted from integral parts of the PI-controller. This gives priority to the castor controller, if castor wheels are in a blocking state.

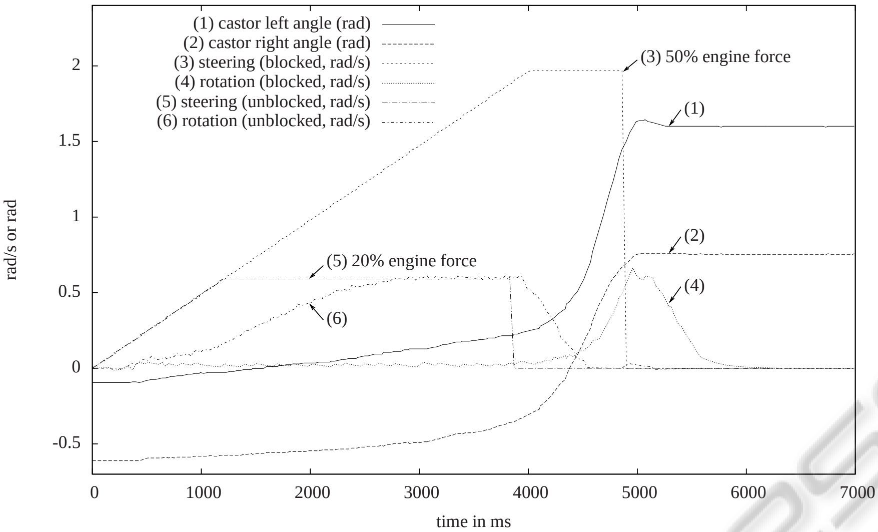

Figure 7: Wheelchair behaviour for a left turn with blocking or adjusted castor wheels.

4 TEST RESULTS

In order to evaluate the influence of the pure castor wheel controller, a number of tests have been carried out using the wheelchair *ROLLAND*. In the following we are going to discuss some test results.

The test shown in Figure 7 compares the reaction of the wheelchair between blocked and unblocked castor wheels while making a left turn without a castor controller. The steering command for blocked (3) and unblocked (5) castor wheels is slowly increased to a level that moves the wheelchair. With unblocked castor wheels, the engine force can be limited to 20% (5) to reach a wheelchair turn speed of about 0.6 rad/s (6). For blocked wheels, the engine force must be increased to 50% (3) to let the castor wheels turn around (angles are shown in (1) and (2)). In this case, the castor wheels start to swivel after about 5 seconds. The steering command is then reduced to zero (during this measurement) to avoid a too fast rotation of the wheelchair. Usually, the steering command must be reduced by the wheelchair user manually.

The adjustment of giving steering commands by the pure castor controller is demonstrated by Figure 8. The diagram shows a left-turn of the wheelchair starting with castor wheels in a blocking state using the castor controller. It compares the given steering command (5) from the user and the motor commands for steering (3) and forward motion (4) computed by the controller. The forward motor command is the mean value of left and right motor command, and the steering motor command the difference between them. The controller uses the driving command and the castor angles of the left (1) and right (2) wheels as input values. It produces a peak for the left engine of about 80% power (computed from forward (3) and steering (4) motor command), and will be reduced when the castor wheels start to swivel. The wheelchair starts to turn around significantly after the peak is reached, as indicated by curve (6) measured by the odometry of the wheelchair. The castor controller reacts much earlier than an odometry based controller and releases the user from doing this manually.

5 RELATED APPROACHES

An alternative approach is to turn the castor wheels using an additional actuator, as for the Toyota PM research vehicle (Toyota Motor Sales USA, 2009; Bonsor, 2004). The trail of the castor wheel can then be 0, which makes it 180° rotation symmetric. The wheelchair manufacturer Otto Bock recently presented the XENO wheelchair with a steering system called S^3 (Single Servo Steering, (Otto Bock HealthCare GmbH, 2010)) in combination with a differential drive using an approach similar to that of the PM research vehicle. For the additional cost of the castor turn servo engines, the Otto Bock system releases the differential drive from the burdon of castor turn forces, but the time to turn the front wheels can be significantly longer than the time needed to turn classical castor wheels. This can confuse a user who is unaware of this fact.

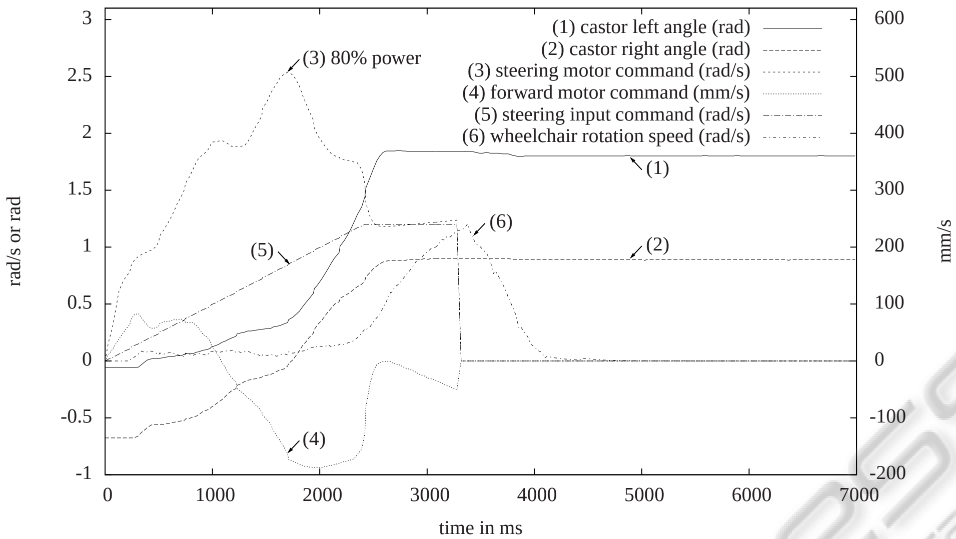

Figure 8: Castor controller for a left turn with blocking castor wheels.

6 CONCLUSIONS

In this paper we presented a castor wheel controller for differential drive wheelchairs with two front castor wheels (e.g., *ROLLAND* based on a Meyra wheelchair of type CHAMP). The controller uses the developed kinematic model to project turn forces of castor wheels to engine torques of differential drive vehicles. Some test data were given to compare the steering behaviour with and without the controller. The major benefit of the castor wheel controller is to release the user from the task to compensate the castor turn forces using the joystick to simplify the driving with the joystick.

One future work is to do more experimental evaluation and performance analysis of the pure and combined castor wheel controllers before carrying out real user studies. Moreover, the measurement of castor angles through potentiometers is unprecise in a certain range of angles. We will replace them by magnetic angle measurement sensors for full coverage.

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