

Advanced Control Strategies for a Roll Simulator - A Feedback Linearization Technique Explored

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ABSTRACT

This paper presents a feedback linearization control technique as applied to a Roll Simulator. The purpose of the Roll Simulator is to reproduce in-field rollovers of ROVs and study occupant kinematics in a laboratory setting. For a system with known parameters, non-linear dynamics and trajectories, the feedback linearization algorithm cancels out the non-linearities such that the closed-loop dynamics behave in a linear fashion. The control inputs are computed values that are needed to attain certain desired motions. The computed values are a form of inverse dynamics or feed-forward calculation. With increasing system eigenvalue, the controller exhibits greater response time. This, however, puts a greater demand on the translational actuator. The controller also demonstrates that it is able to compensate for and reject a disturbance in force level. The feedback linearization controller demonstrates that with the limitation of the current actuators and track length removed, the simulator could reproduce the motions for an entire rollover maneuver.

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INTRODUCTION

The popularity of Recreational Off-Highway Vehicles (ROVs) has increased significantly in recent years. The number of ROVs sold annually in the USA has increased from 20,000 in 2003 to over 126,000 in 2008, an increase of over 500 percent [1]. Accompanying this increased usage has been increased ROV related injuries. As such, the Consumer Product Safety Commission (CPSC) has become concerned with the safety of these vehicles. These concerns include the ROV's rollover propensity and in the case of a rollover, occupant injury mitigation. Injury concerns include the interaction of the occupants with the vehicle and the ability of the vehicle's restraint system to contain an occupant at the onset and during a rollover event.

Limited published work exists on studying the rollover propensity of ROVs. What is more, even less work exists on investigating the occupant kinematics of ROVs during a rollover event. Some work has been performed on ROVs and All-Terrain Vehicles (ATVs) in [2], [3], [4], [5], [6] and [7]. The research in these studies, however, was either limited in that it did not show results for motion beyond 10-15 degrees of roll or it contains events well beyond 90 degrees of roll. Furthermore, none of this work investigated the occupant kinematics during the roll event. Because of the relatively high frequency of quarter-turn rollovers that occur with ROVs, and the nature of occupant injuries during quarter-turn

rollovers, the ability to conduct laboratory tests to study the interaction of the occupant with the vehicle and/or road surface at 90 degrees of vehicle roll is desired.

A Roll Simulator has been designed and constructed to reproduce in-field rollovers of recreational off-highway vehicles (ROVs) and study occupant kinematics in a laboratory setting. Figures 11 and 12 in the Appendix illustrate a typical configuration for the Roll Simulator. The simulator consists of a sled (cart)-platform assembly where the ROV is attached to a platform, placed nominally perpendicular to the rail, and rotates about a roll axis. A complete description of the Roll Simulator can be found in [9], [10] and [13]. Validation of the Roll Simulator has been performed in [8] and [12]. A model of the Roll Simulator has been developed and validated in [10] and [13]. The Roll Simulator has also been used in parametric studies, which are described in [11]. The validation conducted in [8] used experimental tests where J-turn maneuvers were performed to attain the minimum energy rollover threshold. For these tests, minimum energy indicated the least amount of steering input needed to induce two-wheel lift-off (TWLO) during dropped-throttle J-turn tests with an initial speed of 30 mph. Tests were performed with safety outriggers (roll motion up to 10-15 degrees) and autonomously without outriggers (roll motion up to 90 degrees of roll). Important vehicle dynamic states including lateral and longitudinal acceleration, roll rate

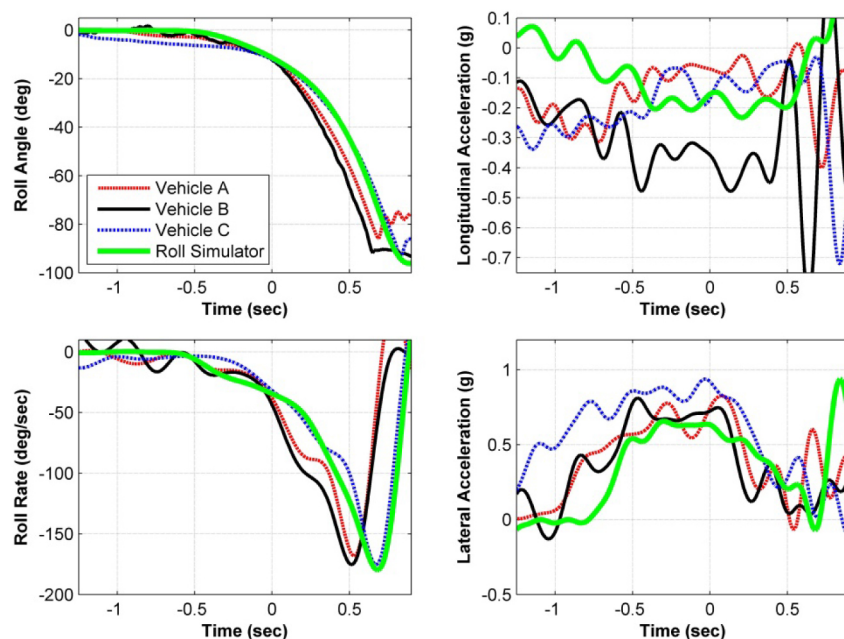


Figure 1. Roll Simulator vs. Autonomous Data, Courtesy of [1]

and roll angle were used as input conditions to be reproduced on the Roll Simulator.

In this paper, it is the intention to investigate a modification of the Roll Simulator, where the limitations of the system are removed.

Currently, the actuators for the Roll Simulator are configured such that they limit the overall performance of the machine. It is not to say that the simulator cannot meet the desired motions, but the versatility of the system is hindered by the size and arrangements of the actuators. The main aspect of the machine that prohibits the application of more sophisticated control algorithms is the cable and drum system, which transmits the forces from the hydraulic motor and particle brake. Because tension needs to be maintained in the cables (wire ropes) at all times, specific attention is dedicated to this aspect. As such, the translational actuators, i.e., the particle brake and hydraulic motor, can and are only applied in a one-way fashion. In other words, the hydraulic motor accelerates the sled-platform assembly and the brake decelerates it. Fine tuning of the speed and/or acceleration would require proper coordination of the hydraulic motor and particle brake. This would prove to be difficult. The control strategy described in [9] and [13] developed an algorithm that primarily used feed-forward calculations to control the sled-platform assembly. To date, this strategy has been successful at maintaining tension in the cables at all times while meeting the intended goals of the Roll Simulator; i.e., emulating the inertial forces that an ROV exhibits during a J-turn maneuver where full rollover occurs, in a laboratory setting.

Another limiting factor in the Roll Simulator's design is the roll motor. At 725 lb-ft of maximum torque, the original intention was to meet only 20 percent of the torque load; and the helper spring and inertial forces would contribute the

remaining moments needed to achieve a particular roll motion. However, to achieve a specific roll motion, a roll motor with significant reserve torque is needed to "tune" to a desired roll motion.

Research performed in [8] made comparisons between the Roll Simulator and in-field autonomous tests. Results shown in Figure 1 validate the Roll Simulator's performance. It can be seen here that the Roll Simulator is able to track the roll motion of in-field tests. For the acceleration profiles, however, the Roll Simulator cannot track the in-field test for the entire maneuver. Depending on the vehicle you compare with, there is between 0.3 and 0.5 seconds duration (near time equal 1.0 seconds on Figure 1) where the Roll Simulator cannot attain the desired accelerations. Reasons why the Roll Simulator cannot follow the entire acceleration trajectory are due mostly to track length. The physical length of the track is not long enough such that the sled cannot gain enough speed where during the braking the phase, the lateral acceleration can develop over a longer period of time. It is important to point out at this time that during the period where the Roll Simulator cannot meet the acceleration demands, the measured roll rate and angle, from the in-field tests, are at lower levels. Based on only a few field rollover tests compared to Roll Simulator tests, researchers have concluded that up until to the point where the roll rate increases significantly (around -0.5 seconds), the acceleration has little influence on the occupant kinematics. Ideally, further investigations, where the duration of the lateral acceleration was extended on the Roll Simulator, could strengthen this conclusion regarding occupant motion. Also note that the maneuver chosen to reproduce on the Roll Simulator was a J-turn maneuver. In the future, a different maneuver, such as a fishhook maneuver or sine with dwell maneuver may need to

be performed on the Roll Simulator. The current setup of the Roll Simulator would prohibit the implementation of these types of maneuvers mainly because of track length and arrangement of actuators.

To study the Roll Simulator with the limitations of its actuators removed, a feedback linearization technique will be introduced in this paper to show the force and torque levels required to meet desired translational (acceleration) and rotational (roll) trajectories.

FEEDBACK LINEARIZATION

Feedback linearization is a technique used in a control system to cancel out non-linearities found in the system, such that the closed-loop dynamics behave in a linear fashion. Usually the non-linearities and parameters within the system are well known. Figure 2 illustrates an example of a tank with a non-linear orifice and cross-sectional area that is a function of fluid height. The goal is to control the fluid to a desired level h_d using the control input u . The non-linear first-order equation governing the height of the tank is:

$$A(h) \frac{dh}{dt} + a\sqrt{2gh} = u \quad (1)$$

Where, $A(h)$ is the cross-section of the tank and a is the cross-section of the pipe. To cancel the non-linearities of the system, an appropriate control input would be:

$$u = a\sqrt{2gh} + A(h)v \quad (2)$$

Where, v is an equivalent input and is chosen to be:

$$v = -\gamma \tilde{h} \quad (3)$$

The error level is $\tilde{h} = h(t) - h_d$ and γ is a positive constant.

Substituting Equations 3 and 2 in Equation 1 the resulting closed-loop dynamics are:

$$\frac{d\tilde{h}}{dt} + \gamma \tilde{h} = 0 \quad (4)$$

This implies that as $t \rightarrow \infty$, $\tilde{h} \rightarrow 0$. The total input flow is:

$$u = a\sqrt{2gh} - \gamma A(h)\tilde{h} \quad (5)$$

If a desired trajectory is sought, then the equivalent input would be $v = \dot{h}_d - \gamma \tilde{h}$ and the closed-loop dynamics become:

$$\frac{d\tilde{h}}{dt} + \gamma \tilde{h} = 0 \quad \text{which implies, again, that as } t \rightarrow \infty, \tilde{h} \rightarrow 0.$$

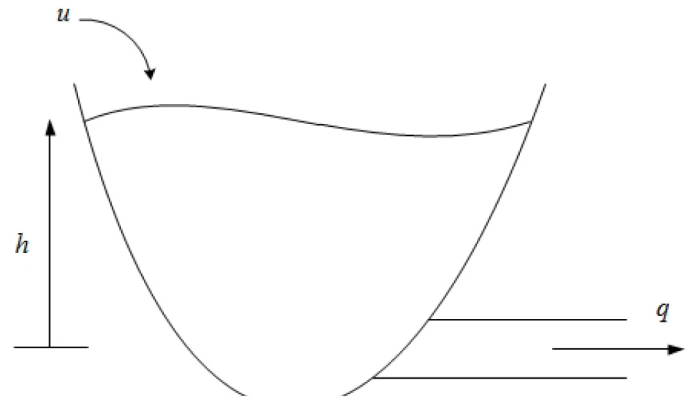


Figure 2. Height Control of Non-Linear Tank

This simple example, found in Slotine [14], illustrates how choosing the appropriate control input can cancel out the non-linearities of a simple first-order dynamic system. It is recognized that for this simple system the non-linearities and all system parameters are well known. Since the Roll Simulator's parameters (inertias, masses, CG location, etc.) and non-linearities (gravitational terms, centripetal terms, etc.) are also well known, it is considered a good candidate to use feedback linearization. Furthermore, as is shown in many examples in [14] and [15], feedback linearization can be used for tracking control. Ultimately, a controller is to be designed such that the Roll Simulator can follow a particular trajectory.

FEEDBACK LINEARIZATION AS APPLIED TO THE ROLL SIMULATOR

To extend this approach to the Roll Simulator, which is considered a multi-input multi-output (MIMO) system, a modified method needs to be used. For this exercise, we will only study the dynamics of the sled-platform assembly. The dynamics of the hydraulic system and particle brake will be replaced by one actuator. This actuator, for example, could be an electric motor with a tire attached to its shaft such that the delays in the system are minimized. The motor would apply torque to the shaft and the tire would translate the torque into a linear force applied along the floor. Because the electric motor would be "fast" acting and be able to apply torque in both directions, it would be more responsive than the hydraulic motor and particle brake with the current cable and drum system, see [9] and [13]. For the roll motor, an electric motor will still be used, but the torque limits of 725 lb-ft would be higher.

In matrix form, the dynamic equations developed in [10] and [13] for the sled-platform assembly are:

$$\begin{bmatrix} M_t & M_p C_3 \\ M_p C_3 & I_t \end{bmatrix} \begin{Bmatrix} \ddot{Y} \\ \ddot{\theta} \end{Bmatrix} + \begin{bmatrix} 0 & M_p C_4 \dot{\theta} \\ 0 & 0 \end{bmatrix} \begin{Bmatrix} \dot{Y} \\ \dot{\theta} \end{Bmatrix} + \dots \\ + \begin{bmatrix} 0 \\ M_p g C_2 \end{bmatrix} = \begin{bmatrix} F \\ T \end{bmatrix} \quad (6)$$

Where,

$$I_t = I_p + M_p (L_p^2 + H_p^2),$$

$$M_t = M_p + M_s,$$

$$C_1 = L_p \sin \theta + H_p \cos \theta,$$

$$C_2 = L_p \cos \theta - H_p \sin \theta,$$

$$C_3 = \cos \psi C_1,$$

$$C_4 = \cos \psi C_2$$

Equation 6 can be written in short form:

$$M(q)\ddot{q} + C(q)\dot{q} + G(q) = U \quad (7)$$

Where,

$$M(q) \triangleq \text{Mass Matrix},$$

$$C(q) \triangleq \text{Centripetal Matrix},$$

$$G(q) \triangleq \text{Gravitational Vector},$$

$$U \triangleq \text{Force Vector},$$

$$q \triangleq \text{State Vector} = \begin{bmatrix} q_1 \\ q_2 \end{bmatrix} = \begin{bmatrix} Y \\ \theta \end{bmatrix}$$

Writing equations of motion in this fashion help in designing an input that “cancels” out the non-linear dynamics of the system. An example shown in Slotine [14] illustrates a controller for a two-degree-of-freedom articulated manipulator for trajectory control. The input torques are written in such a fashion that the closed-loop dynamics behave in a linear fashion and the tracking error is reduced. In a similar manner, a suitable control input for the Roll Simulator is:

$$U = \begin{bmatrix} F \\ T \end{bmatrix} = M(q)v + C(q)\dot{q} + G(q) \quad (8)$$

The equivalent inputs are:

$$v = \begin{bmatrix} v_1 \\ v_2 \end{bmatrix} = \ddot{q}_d - 2\lambda\dot{\tilde{q}} - \lambda^2\tilde{q} \quad (9)$$

Where,

$$\tilde{q} \triangleq \text{Tracking Error} = q(t) - q_d(t)$$

Note that the desired trajectory $q_d(t)$ is a function of time and is not a particular position. Also, λ is a positive constant and is the system closed-loop eigenvalue. The inputs shown in Equation 8 are considered the “computed” force and torques. That is, the controller is performing inverse dynamics, where it is computing the torque and force to meet the desired motions. Of course, the assumption is made that the dynamics, system parameters and trajectories are all well known.

Substituting Equation 8 in Equation 7, the system dynamics become:

$$M(q)\ddot{q} + C(q)\dot{q} + G(q) = M(q)v + C(q)\dot{q} + G(q) \quad (10)$$

Simplifying, the resulting equation is:

$$M(q)(\ddot{q} - v) = 0 \quad (11)$$

Substituting Equation 9 in Equation 11, the closed-loop system dynamics are:

$$\begin{aligned} M(q)(\ddot{q} - \ddot{q}_d + 2\lambda\dot{\tilde{q}} + \lambda^2\tilde{q}) &= 0 \\ M(q)(\ddot{\tilde{q}} + 2\lambda\dot{\tilde{q}} + \lambda^2\tilde{q}) &= 0 \end{aligned} \quad (12)$$

Since the mass matrix is symmetric and positive-definite for all $q(t)$, the second term on the left hand side of the equation leads to exponentially stable closed-loop dynamics. In other words as $t \rightarrow \infty$, $\tilde{q}(\text{tracking error}) \rightarrow 0$ for all positive values of λ .

Trajectory Tracking

In order to properly implement a feedback linearization algorithm with tracking control, the desired motions must be continuous, bounded and differentiable. Figure 3 shows desired motions currently used on the Roll Simulator. It is obvious that these are continuous and meet the criteria to be used in a feedback linearization controller.

Figure 4 illustrates simulation results with the feedback linearization implemented on the desired motions described in Figure 3. The simulation was performed using Matlab's Simulink [16]. A depiction of this model used for this study is included in the Appendix (Figure 13). Table 1 lists the parameters used in this study. The top two panes of Figure 4 represent the “computed” torques and forces. It can be seen here that the controller tracks the desired trajectories for the entire motion. In the bottom right pane, the lateral acceleration of the sled is shown, not the center of gravity (CG) of the ROV. Comparisons with the results illustrated in Figure 5, which displays experimental data derived from the actual Roll Simulator, show that the sled's acceleration does