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DEVELOPMENT AND USE OF DRIVING ROBOTS FOR CONDUCTING UNMANNED TESTS OF OFF-ROAD VEHICLES

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ABSTRACT

This paper contains descriptions and demonstrations of automated test drivers (ATDs) for several different style off-road vehicles. These robotic ATDs can be used without a human operator, to drive vehicles in scenarios that are unsafe for human drivers. Full-scale vehicle tests including rollovers, pitchovers, and crashes involving Recreational Off-Highway Vehicles (ROVs), All-Terrain Vehicles (ATVs), and Zero-Turn Riding Mowers (ZTMs) are included in the paper. The mechanical actuators used to control steering, throttle, and braking differ for the different ATDs. However, they use similar control strategies, network architecture, and electronics. Using these similar items as a starting point would be beneficial for developing ATDs for different styles of military vehicles.

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1. INTRODUCTION

This paper contains descriptions and demonstrations of automated test drivers (ATDs) for several different style off-road vehicles. These off-road version ATDs grew out of the need to conduct full-scale dynamic tests that would likely cause injuries to human drivers, including rollovers, pitchovers, and crashes. These dangerous maneuvers are conducted to evaluate potential benefits of safety features such as occupant protection devices (OPDs), rollover protection structures (ROPS), and reinforced firewalls to mitigate injuries caused by debris penetrating the occupant compartment of a moving vehicle.

The unmanned ATDs can be used in path-following (full autonomous) mode or remote control (joystick driving) mode. The basic control strategies, network architecture, and electronics for these off-road ATDs are similar, and these emerged from similar systems used on passenger vehicle ATDs. The following section briefly describes the basic features inherent to all these ATDs.

Sections are then included for each of the three off-road ATDs presented, Recreational Off-Highway Vehicles (ROVs), All-Terrain Vehicles (ATVs), and Zero-Turn Riding

Mowers (ZTMs). An overview of the mechanical actuators used to control steering, throttle, and braking for each vehicle type is provided, as are example results from some of the potentially dangerous off-road tests conducted.

The ATD features and hazardous test types presented in these examples could be extended for different styles of vehicles, including both on-road and off-road commercial and military vehicles.

2. BACKGROUND

The authors and their colleagues at S-E-A, Ltd. began developing automated steering controllers (ASCs) for passenger vehicles nearly 20 years ago [1]. These early version steering robots were designed to generate prescribed open-loop steering maneuvers with better repeatability, precision, speed, and torque than a human driver [2]. Models with electric motor steering actuators that replace the OEM steering wheel were designed as were steering ring models that are airbag compatible.

Path following algorithms were added to the ASCs to provide closed-loop steering control around GPS based paths. For many automotive path following applications, algorithms using proportional-derivative heading error control methods work well [3]. This path-follower consists of two functions, the path planner and the control law.

The path planner smooths the desired trajectory into one the vehicle can follow, and emulates the forward-looking function of a human driver, comparing the current vehicle orientation with the intended path to calculate an achievable "goal point" ahead (Figure 1). Once the goal point is determined by the path planner, the control law calculates the steering command, δ, necessary to reach it. The controller first determines the angle between the vehicle heading and the goal point bearing, θ, termed the heading error. Then proportional-derivative control (with gains K_p and K_d respectively) is applied to this heading error, and the result becomes the steering command given below.

$$\delta = K_p\theta + K_d\frac{d\theta}{dt}$$

This controller acts to drive the difference between vehicle heading and goal point bearing to zero. This controller strategy is the basis for the path following controllers used for off-road vehicles. However, there are numerous other subtleties that must be included to adapt the controller for different speeds, path curvatures, and different vehicles.

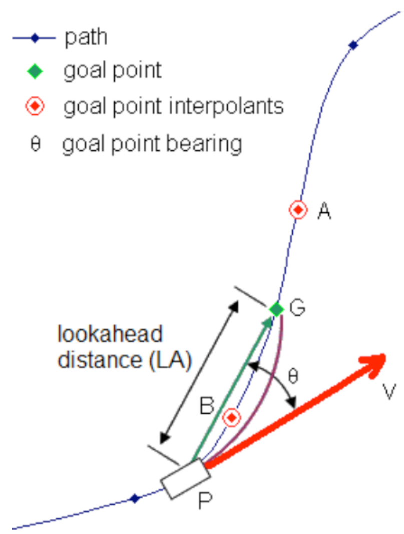

Figure 1: Concept of Goal Point Seeking

The development of brake and throttle robots (BTRs) to control vehicle longitudinal motion soon followed initial developments of the steering robots. Fully developed versions of BTRs are capable of throttle pedal position control, brake pedal position and force control, vehicle speed control, and vehicle deceleration control [4].

Integration of the BTR with the ASC and a GPS system, for position sensing, provided the basis for the growth of the automated test driver (ATD) for passenger vehicles. The ATD provides vehicle speed (longitudinal) control and path following (lateral) control. Linkage between the low-level and local path and speed controllers is shown in Figure 2 [5]. The left column is the steering control and the right column is the brake and throttle control.

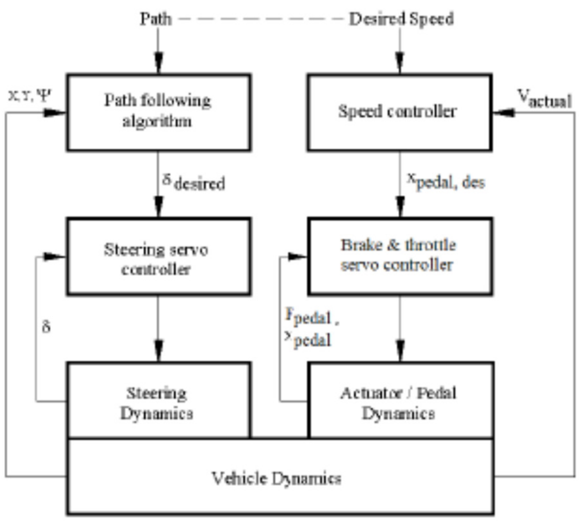

Figure 2: ATD Control System Overview

This strategy is the basis for the ATD controllers used for off-road vehicles. However, there are again numerous other subtleties that must be included to adapt the controller for the different types of off-road vehicles.

Enhancements to the essential ATD controller have provided the capability for conducting vehicle-to-vehicle interaction maneuvers [6]. These features have been used to conduct crashes involving two moving passenger vehicles, both equipped with ATDs.

The passenger vehicle ATDs and off-road ATDs presented in the following three sections are all designed to be operated with a human driver on the test vehicle or unmanned, thus providing the autonomous mode needed for conducting crashes and dangerous maneuvers. The steering, brake, and throttle controllers can react faster and more repeatably than a human driver. The path following algorithms have matured to the point they can be tuned to provide human-driver-like path following ability even on rough terrains.

3. RECREATIONAL OFF-HIGHWAY VEHICLE (ROV) ATD

Figure 3 shows an ROV equipped with the ROV ATD. ROVs have steering wheels, throttle pedals, and brake pedals like passenger vehicles. The ASC used for this ROV testing is shown attached to the top of the steering column. Numerous antennas for GPS, communications, and safety wireless networks are shown on the vehicle. The ATD electronics box (with controller and data acquisition computers) and batteries are in the rear bed of the vehicle. Figure 4 shows the BTR used for ROVs, which is the same version of BTR used for passenger vehicles.

Figure 3: Vehicle Equipped with ROV ATD

Figure 4: BTR used with ROV ATD

The example study presented here using the ROV ATD was one conducted for the

Consumer Product Safety Commission (CPSC) to demonstrate how tree branches can penetrate ROV floorboards, and potentially cause a serious or fatal injury to an occupant [7]. The demonstration specified using an autonomously controlled ROV to impact a stick while traveling at 16.1 kph (10 mph).

Figure 5: Stick in Wooden Box

Figure 6: Two Stick Penetration Zones

Figure 5 shows the stick, a 2" diameter red oak dowel, resting in box below ground level. Figure 6 shows two impact zones selected for testing using this vehicle. The impact zones were selected to represent spaces in the suspension where the tip of a stick could enter the wheel well area of the vehicle and penetrate the occupant compartment.

The test vehicle was started from rest about 20 m from the impact point. The GPS coordinates of a nominally straight-line path were recorded by driving the test vehicle slowly to the impact position. This recorded path was then followed during the actual test runs. The vehicle reached the test speed of 16.1 kph in about 4.0 sec and the total run-up time to impact was about 16.5 sec.

At the point of impact, vehicle speeds were within one percent of 16.1 kph, and the lateral position offsets (lateral path errors) were less than 3 cm. A high-quality GPS and a well-tuned ATD were necessary to achieve this level of speed and position control.

Figure 7 shows time lapse images of the stick penetration into Zone 1. The images shown were taken from video shot at 240 frames per sec, and the sequential images shown are five frames apart. With the vehicle traveling 16.1 kph, the vehicle travels about 9.3 cm between the sequential images shown. The total distance traveled between the first image and last image shown is about 1.82 m.

In addition to the stick penetration study, ROV ATDs have been used in other instances involving driving unmanned ROVs in hazardous maneuvers. One case involved conducting full-scale, unmanned ROV rollovers to evaluate rollover vehicle dynamics and occupant (test dummy) kinematics. In another case, an ROV ATD has been deployed to drive ROVs over an off-road durability test course that is too rough for a human driver to withstand for extended periods of time.

4. ALL-TERRAIN VEHICLE (ATV) ATD

An ATV equipped with an ATV ATD is shown in Figure 8. ATVs have straddle seating and handlebar steering. This vehicle was used in a study to determine the feasibility and effectiveness of using occupant protection devices (OPDs) on ATVs [8].

The tests consisted of conducting low-energy lateral rollovers, with up to 180 degrees of maximum roll angle, and moderate-energy lateral rollovers, with more than 180 degrees of maximum roll angle. The fully autonomous test maneuvers involved driving the ATVs along a straight path at 32.2 kph (20 mph) and then rapidly turning the handlebars with enough steering magnitude and steering rate to result in low to moderate energy rollover events.

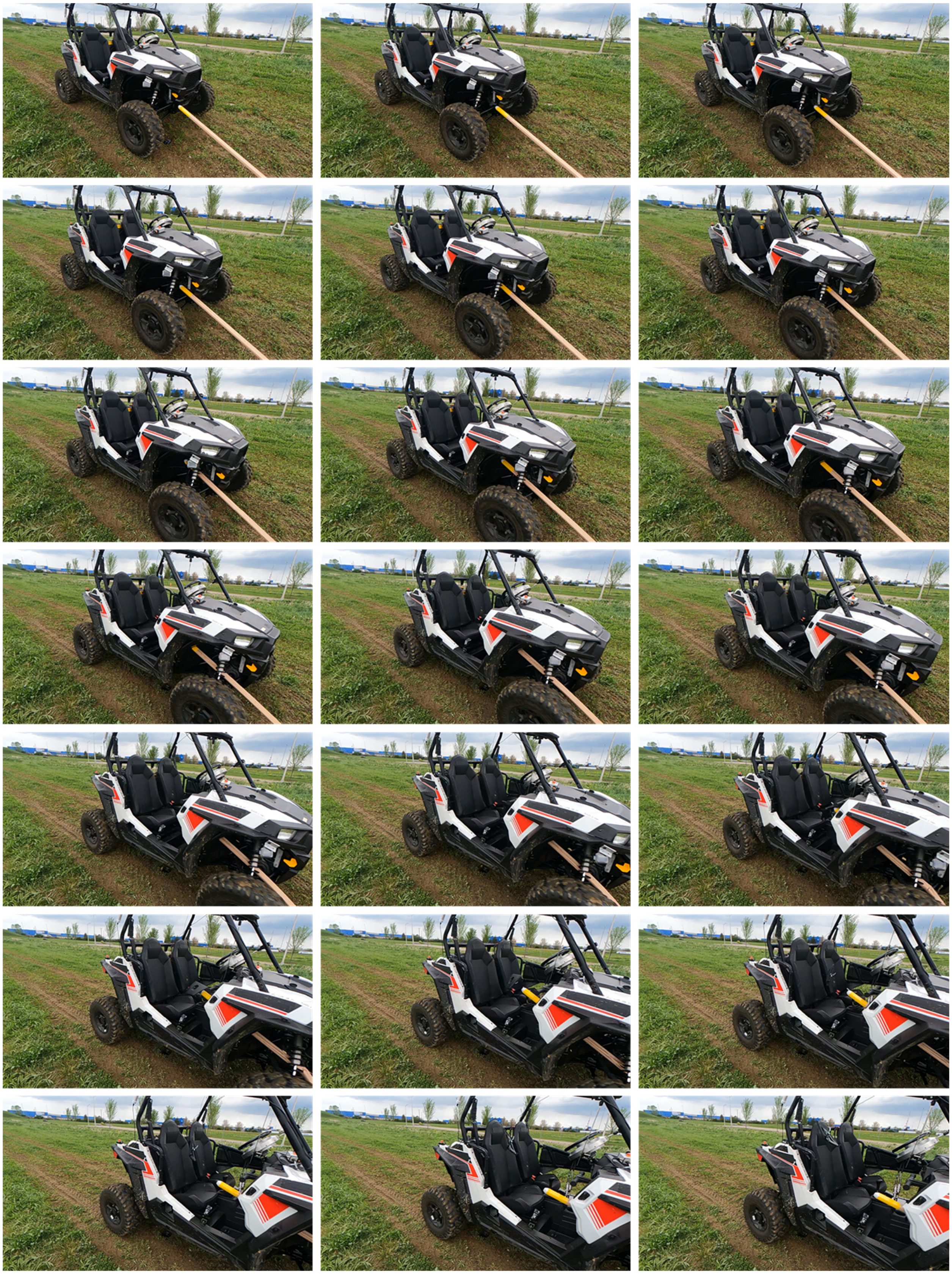

Figure 7: Time Lapse Images of ROV Zone 1 Penetration

Figure 8: Vehicle Equipped with ATV ATD

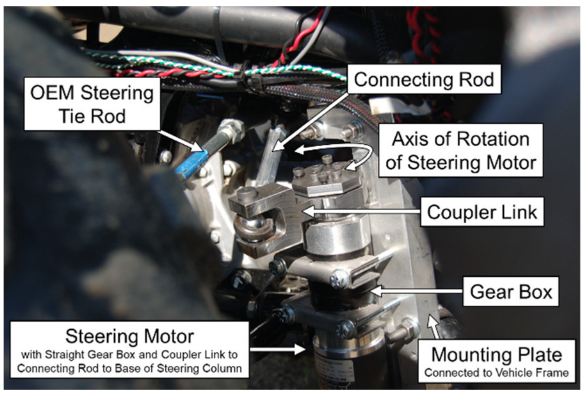

Figure 9: ATV ATD Steering Actuator

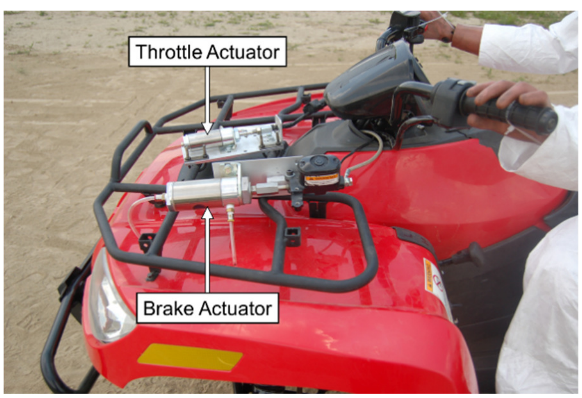

Figure 10: ATV Throttle and Brake Actuators

ATD steering was actuated using an electric servo-controlled motor with a coupler link and connecting rod to the vehicle's steering tie rod, as shown in Figure 9. This hardware was mounted beneath the front rack of the vehicle, so it would not disrupt the rollover dynamics of the vehicle.

Pneumatic cylinders were used to actuate the ATV's throttle thumb lever and brake hand-grasp lever, as shown in Figure 10. These levers were removed from the handlebars and mounted on the front rack of the vehicle, to mitigate potential damage caused during the rollover events.

Tests conducted for this study used a Hybrid III, 50th percentile male anthropomorphic test device (test dummy) as a surrogate rider. A dummy secure-and-release system was developed to secure the dummy in an upright position while accelerating forward and through the start of the turn, and then releasing the dummy at a point in the maneuver that would represent the point when a human rider could no longer hold onto the ATV. The dummy secure-and-release system used nylon cable ties to secure the dummy's hands to the handlebars, and a pair of steel cables, one to the neck and one to the hip, that could be released simultaneously using a pneumatic actuator (Figure 11). For these turning-induced rollover maneuvers, releasing the cables when the vehicle reached a roll angle of 30 degrees provided results believed to be representative of how a human might be unable to hold on the vehicle during such an event. Roll angle monitoring and the trigger signal to release the pneumatic actuator were incorporated into the ATV ATD software.

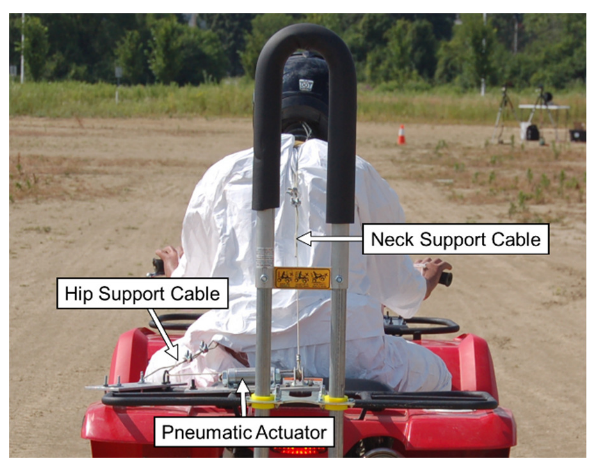

Figure 11: Secure-and-Release System Cables

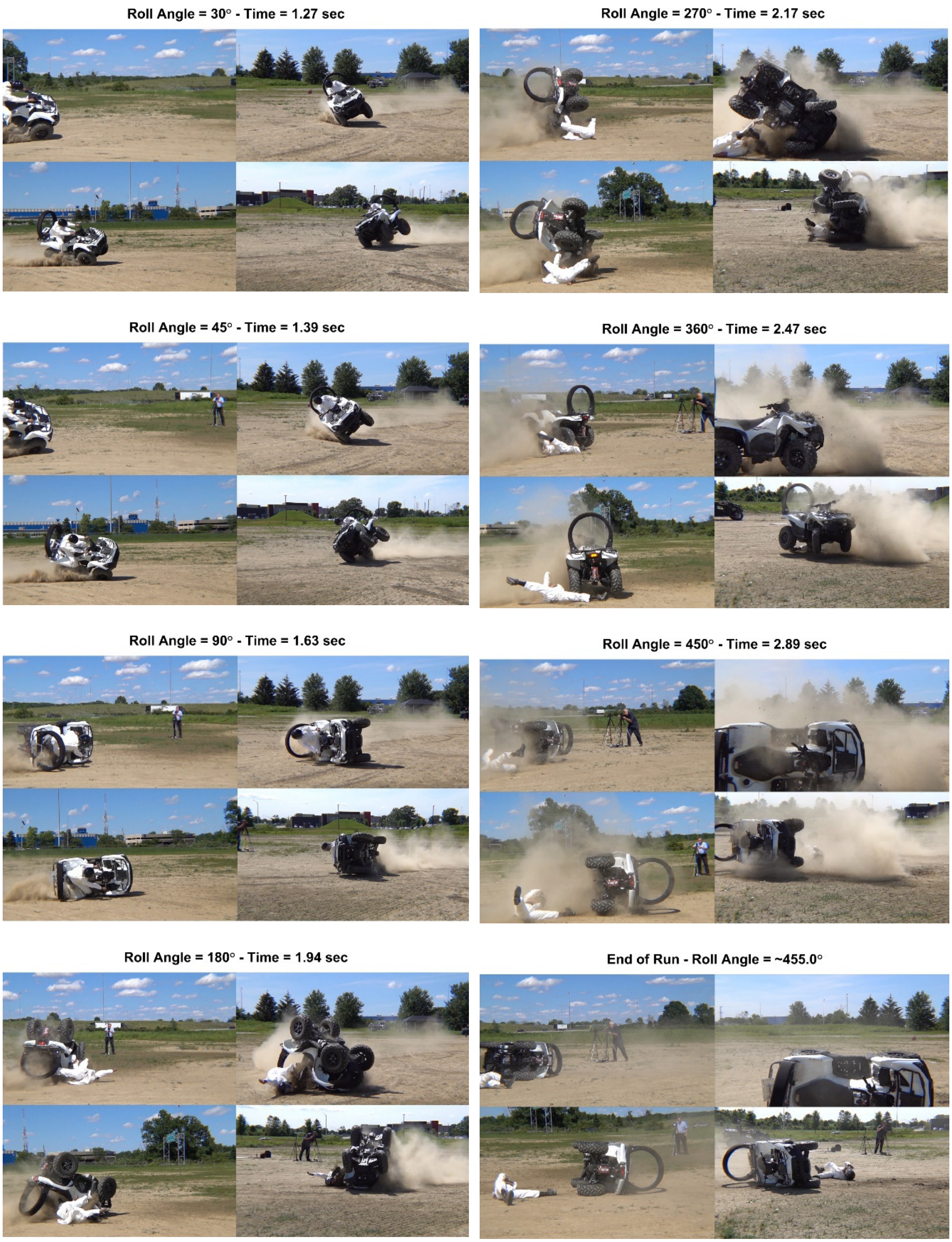

Figure 12: Rollover Sequence Images from a Moderate Energy Rollover Event

Figure 12 shows rollover sequence images taken from four video cameras during a moderate energy rollover event that resulted in a final roll angle of 455 degrees. The titles above each image list the roll angle and the time from the start of the steering input. Images for 30, 45, and 90 degrees are shown, and then every 90 degrees up to 450 degrees. The final image shows the final roll angle of 455 degrees.

The ATV ATD provided the tool needed to conduct full speed rollovers to study how the ATV interacts with a rider (dummy) throughout the rollover sequence. Tests with various OPDs showed that some OPDs offered the capacity to provide survival space for a rider during and at the end of some rollover events. This study highlighted the importance of running full speed tests representative of possible real-world accident types. These tests provided representative three-dimensional dynamics for the ATV and the dummy.

In addition to the OPD study, ATV ATDs have been used in other ATV studies intended to evaluate ATV dynamic responses in the absences of human driver weight shift during the test maneuvers. In these other studies, fixed ballast was attached to the seat of the ATV to represent the load of a human rider(s). Example of these studies include one to evaluate effects of rider lean angles on ATV response [9], one to study the effects of two people riding an ATV [10], one to evaluate anti-lock brake system (ABS) technology on ATV stability [11], and one to evaluate a proof-of-concept electronic stability control (ESC) system for ATV stability [12].

5. ZERO-TURN MOWER (ZTM) ATD

Currently, industry safety standards for ride-on mowers do not require a rollover protective structure (ROPS) for any mower weighing less 400 kg (882 lb) [13]. Most residential riding mowers weigh less than this, and CPSC has initiated a study to evaluate the effectiveness of using ROPS on residential riding mowers to reduce injuries and deaths during overturn events.

The best way to evaluate ROPS effectiveness on a vehicle is to conduct full-scale dynamic tests that overturn the vehicle in a real-world-like manner. The motivation for the development of the ZTM ATD is to conduct overturn tests that would be harmful to a human driver.

Zero-turn mowers (ZTMs) have differential rear wheel drive systems and front wheels on non-steerable, free-floating casters. They typically have two driver activated hand tillers for speed (longitudinal) and steering (lateral) control. If the right-side and left-side tillers are pushed forward simultaneously by the same amount, the ZTM will speed up in the forward direction. Pushing both tillers all the way forward will generate full speed for the given throttle setting. Pulling simultaneously rearward on the tillers causes the ZTM to travel in reverse.

Steering (directional control) is achieved by moving the tillers different amounts. For instance, if the right tiller is pushed forward further than the left tiller, the vehicle will turn to the left.

A ZTM equipped with a ZTM ATD is shown in Figure 13. The photo shows an electronic servo-controlled tiller actuator on the left tiller, and a similar actuator is attached to the right tiller. ZTM speed and steering are regulated by the ATD-controlled coordination of the two tiller positions. Figure 14 also shows a test dummy on the ZTM, used as a surrogate driver.

Tests conducted using a human test driver on a ZTM outfitted with safety outriggers to prevent it from overturning were conducted to explore possible maneuvers that would be used for studies designed to evaluate ROPS effectiveness [14]. Two types of test maneuvers were selected for the study using the ZTM ATD.

Figure 13: ZTM ATD Tiller Actuator

One of the tests is a throttle-on maneuver on an uphill slope. Figure 14 is a frame from a video taken from a representative rearward pitch-over test conducted with a test dummy as a surrogate driver. This maneuver resulted in a complete rearward pitchover event, with the ZTM ultimately landing on and pitching over the dummy.

On slopes with slippery surfaces such as wet grass, ZTMs can lose drive traction leading to out-of-control downhill rearward motion with potential for contact with a trip hazard such as a culvert, berm, or tree stump. This second test maneuver can lead to quasi-lateral rollover events. Figure 15 shows how this type of rollover event can be replicated using the ZTM ATD. The vehicle started uphill of the trip hazard (top photo of Figure 15) and the ATD was programmed to drive the vehicle rearward onto the trip hazard. The bottom photo of Figure 15 shows the test dummy starting to move away from the mower as the quasi-lateral rollover event progresses.

The ZTM ATV is a reliable tool that can be used to generate repeatable test maneuvers including ones that result in tip over events. The images in Figures 14 and 15 are exemplar runs conducted without a ROPS. These same maneuvers could be repeated with a ROPS to study the effectiveness of ROPS for mitigating injuries to drivers.


Figure 14: ZTM Rearward Pitch-over Maneuver


Figure 15: ZTM Quasi-Lateral Rollover Maneuver

6. Conclusion

This paper covered the designs and use of automated test drivers (ATDs) for several different style off-road vehicles. The use cases highlighted in the paper involved full scale maneuvers without a human operator, driving vehicles in scenarios that are unsafe for human drivers. Full-scale vehicle tests presented include rollovers, pitchovers, and crashes involving ROVs, ATVs, and ZTMs.

The mechanical actuators used to control steering, throttle, and braking differ for the different ATDs. However, they use similar control strategies, network architecture, and electronics. A brief overview of the basic control strategies for all the ATDs was presented in the background section of the paper.

The tests featured here used unmanned ATDs in path-following (full autonomous) mode. However, the ATDs can be used in remote control (joystick driving) mode, thus not requiring a GPS for path following control.

The ATD features and hazardous test types presented in these examples could be extended for different styles of vehicles, including both on-road and off-road commercial and military vehicles.

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