# Gravity-Referenced Attitude Display for Teleoperation of Mobile Robots

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Attitude control refers to controlling the pitch and roll of a mobile robot. As environments grow more complex and cues to a robot's pose sparser it becomes easy for a teleoperator using an egocentric (camera) display to lose situational awareness. Reported difficulties with teleoperated robots frequently involve rollovers and sometimes even failure to realize that a robot has rolled over. Attitude information has conventionally been displayed separate from the camera view using an artificial horizon graphic or individual indicators for pitch and roll. Information from separate attitude displays may be difficult to integrate with an ongoing navigation task and lead to errors. In this paper we report an experiment in which a simulated robot is maneuvered over rough exterior and interior terrains to compare a gravity-referenced view with a separated attitude indication. Results show shorter task times and better path choices for users of the gravity-referenced view.

## INTRODUCTION

Control over attitude, the pitch or roll of a robot is crucial to its successful operation. If the degree of roll is too great the robot may *roll over* onto its side or top. Conversely, if limits on pitch are exceeded it may *flip over* around its longitudinal axis, although due to geometry this is a less likely event. While it may be easy to see from the outside when a robot is approaching these limits it is surprisingly difficult when trying to teleoperate a robot from an onboard camera. McGovern (1991) reported on the cumulative experience in testing a variety of remotely controlled land vehicles at Sandia National Laboratories. All of the reported accidents for camera teleoperated vehicles were roll-overs with 60% of these involving loss of control on hills. All but one involved off-road operation. McGovern reports: "As the roll-over occurs, the operators express surprise. In debriefing, it appears that the operator had no indication that the vehicle was approaching a dangerous condition." For remotely controlled vehicles within the operator's line of sight, by contrast, there were no reported roll-overs.

Roll-overs continue to plague teleoperators. One of the key findings reported by Casper (2002) in describing the experiences of robotic rescue researchers at the World Trade Center involved the difficulties in determining robot state from video alone. A full 54% of the time spent on two of the eight drops was reported to have been wasted trying to determine the state of the robot. While this includes both hidden obstructions (a pipe caught in a tread) as well as a difficult to detect to roll-over, Casper concludes that equipment certifiers should "Create a specification for minimal competency of a USAR rated robot. Never allow a robot without proprioceptive sensors (sensors that provide measurements of movements relative to an internal frame of reference)…to be rated [for use]."

To be effective this proprioceptive information must be provided in a cognitively efficient manner. We hypothesize that the lack of context for robot attitude in camera supplied video creates an illusion of flatness under certain conditions. As a consequence the teleoperator will be unlikely to attend or integrate separately displayed attitude information when engaged in her control task. The reported experiment compares a display in which attitude information is separated from the camera view with one in which attitude and camera view are integrated through presenting the camera view in a gravity referenced orientation.

### The Fixed Camera Illusion

A display designer has three basic options for conveying an entity's location, orientation and the world around it:

**Egocentric**- The world and its symbology are presented from an inside-out perspective. The view through the windshield of a car or a forward-looking camera on a robot provide egocentric views.

**Exocentric**- The world and the entity are presented from an outside-in perspective. Remotely operated vehicles such as slot cars or radio-controlled planes rely on exocentric views.

**Mixed perspective**- The controller's point of view moves with the entity but includes information about its orientation as well as the surrounding scene. Artificial horizon displays with an icon depicting the plane's orientation or tethered displays used in video games and virtual environments are examples of mixed views.

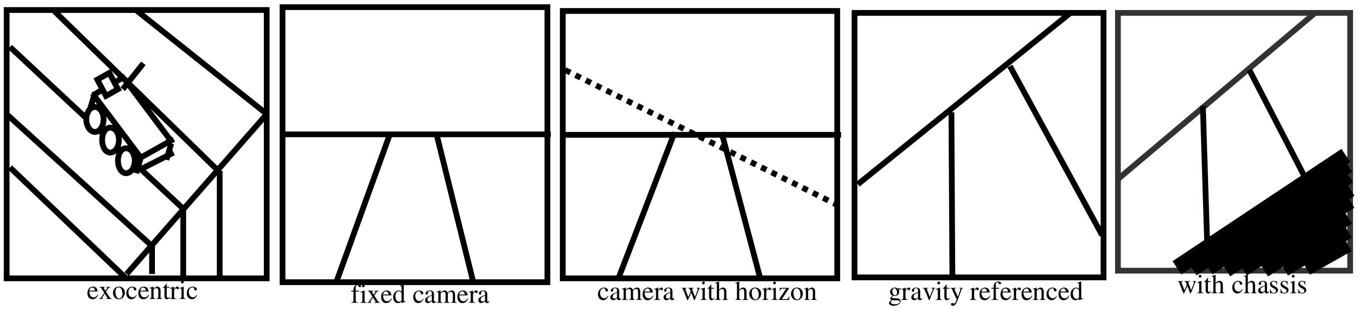


Figure 1. Five views of a robot on a slope

In most cases choice of viewpoint is at least partially determined by the application. Aircraft displays or camera-guided robots for example, are inherently egocentric because the sensors they depend upon are anchored to the vehicle. It is more difficult to convey situation awareness through egocentric displays because they require inferring the entity's orientation from the viewed scene. Where there is a clear basis for this inference such as an easily identifiable horizon or proprioceptive cues orienting the viewer to gravity and acceleration, situation awareness can be quite good. As cues become more ambiguous the quality of situation awareness decreases although the viewer may retain an illusion of certainty much as with the dominant interpretation of an ambiguous figure. This simultaneous loss of situation awareness and failure to recognize that loss can lead to inappropriate control actions.

Attitude related loss of situation awareness has been most widely studied in the context of aviation. During instrumented flight a pilot must rely on displayed attitude, usually an artificial horizon presented on the instrument panel or projected through a heads up display (HUD) to control the aircraft. An artificial horizon display conveys attitude through an egocentric view in which the horizon is presented as a line across the display. The angle that line is rotated from the horizontal conveys the amount of roll while the area of the bottom semicircle representing the ground conveys the pitch.

Attitude display and artificial horizon instruments in particular have been implicated in the *graveyard spiral* (Roscoe 1999), which occurs when outside visual reference is lost and a pilot makes a "reversed" response to the artificial horizon rolling the plane into a spiral dive. The effect seems rooted in the egocentric viewpoint. When the plane rolls to the right the horizon appears tilted to the left and vice versa. Any attempt to make a compatible correction (confuse the horizon line with the plane's orientation) only acts to exacerbate the situation.

The problem of attitude display for robotic teleoperation is further complicated by the presence rather than the absence of outside visual reference. The robot's camera returns an image that is normal to the robot's frame. If the robot is sitting perpendicular to a slope, the camera image will appear flat. If the robot is facing up or down a slope it will also seem flat. Conversely, a horizontal area may appear sloped to a robot viewing it from an inclined position. These camera-linked illusions of flatness are likely to be the source of the roll-overs by surprised operators reported by McGovern and the difficulties in determining whether a robot has actually rolled-over that Casper reports.

Figure 1 illustrates a variety of possible approaches to conveying robot attitude. The exocentric view on the left shows the robot on a slope. The second frame shows the scene as it might appear from an egocentric robot-mounted camera. The third frame shows the fixed camera view with an artificial horizon line added. In the fourth frame the camera's view is rotated to gravity referenced vertical. In the final frame part of the robot's chassis is brought within view to produce a mixed viewpoint in which the robot's pose is conveyed by its chassis while the scene is presented through an egocentric gravity referenced view (GRV).

Robot attitude has most often been displayed on instruments separate from the camera view either on an artificial horizon or on separate roll and tilt indicators (Fong and Thorpe 2001). As the camera view with the horizon line shown in Figure 1 demonstrates, conflict between actual and artificial horizons may be difficult to resolve making conventional HUD attitude presentations best suited for flat office or road environments (Fong and Thorpe 2001). For uneven terrain the gravity-referenced view seems likely to offer the most intuitive integration of scene and robot pose. There are actually two closely related issues involving gravity reference and attitude: 1) accuracy in estimating current attitude and 2) accuracy in predicting changes in attitude associated with traversing terrain.

The first issue was addressed by Heath-Pastore (1994) who conducted an experiment using pre-recorded video and audio clips taken from either a fixed (no attitude indication) or gravity referenced camera mounted on a vehicle driven over rough terrain. The participant's task was to adjust the tilt and roll of a gimbaled control to reflect the vehicle's attitude. Adjustments for roll were found to be very accurate for subjects using the gravity referenced camera but poor for other conditions and measures. A GRV camera might also be expected to improve awareness of the surrounding terrain because surfaces that appeared horizontal would be normal to gravity while those that appeared slanted would depart from the normal. The reported experiment compares a GRV display integrating attitude with scene information with a fixed camera display equipped with a separate attitude indicator. The participants were not asked to estimate attitude directly as in Heath-Pastore (1994) but instead navigated through irregular terrain. The dependent measures reflected their ability to avoid rollovers and sharply slanted surfaces.

Experiments were conducting using a high fidelity mobile robot teleoperation simulation (Lewis, Sycara, and Nourbakhsh 2003) developed using the Unreal game engine (Lewis and Jacobson 2002). A simulation of the NIST Urban Search and Rescue arenas was modified to accommodate gravity-referenced views and large interior and exterior environments were constructed for use in the experiment.

## METHOD

### Experimental Task

The experiment used a between groups design comparing two forms of attitude display for teleoperating a simulated USAR robot. The forms of display were: separated attitude indicator with fixed camera and gravity referenced roll with fixed tilt camera. To evaluate the effects of attitude display in teleoperating the robot, subjects are asked to travel between five beacons in specified sequences for an indoor and an outdoor environment. The outdoor environment (Figure 2) contained mountains, ravines, and other sloping planar features to challenge the fixed camera illusion of flatness. The indoor environment (Figure 3) had rubble-covered, difficult to distinguish walls, ceilings, and slanted floors to obscure references commonly used for orientation. Both terrains were very rough causing the robot to rollover if it went too fast over too steep a grade. To drive the robot safely the subject needed to keep it on as flat ground as possible and to slow down when the robot could not avoid steep grades. Demographic information, a continuous log of the robot's location, attitude and control input and a posttest survey were collected to help identify the effect of the attitude display on teleoperator's remote perception, control behaviors and strategy

### Performance Measures

The following indices used to explicitly or implicitly measure the situation perception and control are described in this paper.

*Confidence Level (CL)*: A subjective rating on a five point scale (0-4) of the participants' confidence in their awareness of pitch angle, roll angle, dangerousness of slopes, and likelihood of rollover.

*Time*: The time required to visit the sequence of beacons. With better situation awareness, less time should be needed because participants could choose either more direct paths or flatter paths that allowed them to go faster. The environments were designed in such a way that there were unique "best paths" between the beacons

Figure 2. Gravity Referenced View (note the indication of roll provided by the tilt of the robot's body)

*Rollovers (TRO)*: The amount of time a robot has spent rolled over or recovering from a rollover. Participants were instructed to avoid rolling over. Good performance on this measure required good estimates of current and predicted attitudes.

An indication used to investigate control behavior and strategy was:

*Time spent backing*: The percentage of time used to move the robot backward indicating a poor choice of path or prediction of terrain..

### Experimental Simulation

The simulation was based on a simulator developed to model the NIST USAR arenas (Lewis, Sycara, and Nourbakhsh 2003). The simulated robot.

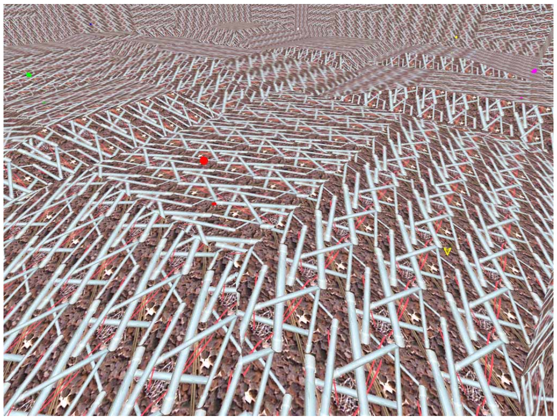

Figure 3. Rubble filled interior environment

was a four-wheeled ground vehicle. Realistic dynamics including the potential to roll-over were modeled using the Karma Physics engine

The environments built for the experiment include an indoor environment, an outdoor environment and a training environment. Five spheres of different colors were added into the environments to provide beacons the participants must try to reach. The indoor environment was an artificial environment constructed from planes with different slopes. The floor, ceiling and walls were constructed in the same way to simulate a confusing environment similar to a mine or collapsed building where attitude cues are very limited. The outdoor environment was a simulated desert region filled with hills, ravines, and obstacles but with some cues for attitude awareness. The training environment was a simplified combination of indoor and outdoor environments.

The camera view was achieved by attaching a viewpoint to the simulation corresponding to a fixed camera or a gravity referenced camera mounted on a ground vehicle. For fixed camera**,** horizontal (roll) and vertical (pitch) linear scales were overlaid on the bottom left corner of the screen to indicate the roll angle and pitch angle.

### Procedure

26 participants divided into equal groups took part in the experiment. One group controlled simulated robots with a fixed camera and separate attitude indicator. The other group controlled simulated robots with a GRV display. Demographic information was collected at the start of the experiment. The participant was then allowed 10 minutes of practice in the training environment. After the practice session the participant was randomly assigned to either the indoor or outdoor environment. Upon completion in that environment the participant repeated the task in the other environment. Participants were allowed up to 20 minutes in the outdoor and 30 minutes in the indoor environments.

In each session, the participant followed instructions displayed on the screen to move the robot from the current beacon to the next designated beacon. After each session, the subject was given the posttest questionnaire.

### Situational Awareness and Confidence Level

The average confidence levels for judging robot pose varied little between indication (pitch, roll, dangerous, or rollover) or group (fixed camera, GRV). As shown in Figure 4 only the perception of likelihood of rollover seemed to favor the GRV although this difference failed to reach significance.

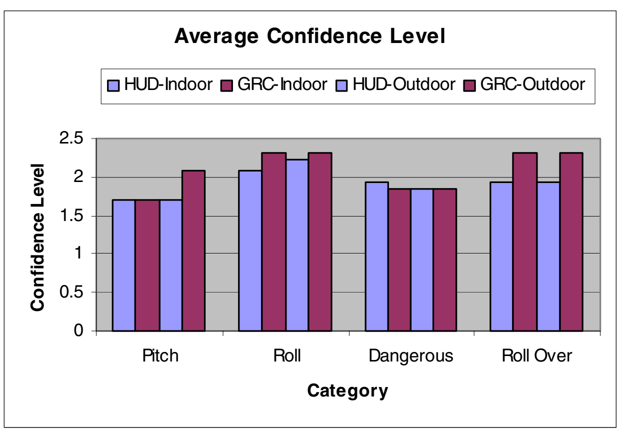


Figure 4. Confidence Levels

### Time to Completion

The time taken to complete the circuit of beacons reflects several aspects of the perception and control tasks. To complete the traversal in a short time the participant must select relatively direct and flat routes to reduce the time spent in traversal while avoiding costly delays associated with rollovers. As shown in Figure 5, participants in the GRV condition were significantly faster, $F_{1,24}$=7.031, p = .014, than those using a fixed camera with a separated attitude display.

### Strategy and Time Spent Backing

Another measure of situational awareness and ability to control the robot is the degree to which participants were able to plan and choose successful paths through rough terrain. One measure of this capability is the percentage of time that is spent backing-up the robot to recover from unsuccessful path choices. On this measure, as well, participants using the GRV display showed superior performance, $F_{1,24}$=6.11, p=.021, with significantly less time spent backing up and choosing new routes (Figure 6).

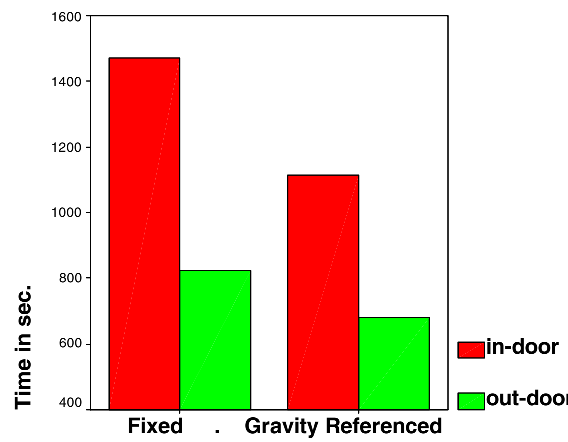


Figure 5. Task Times

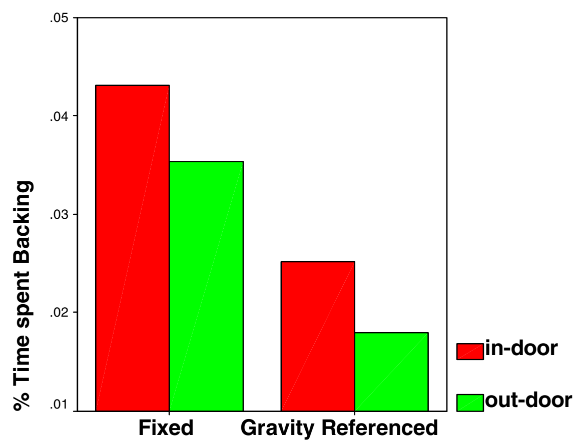


Figure 6. Percent Time Spent Backing

**Maintaining Stability**

The extremity of roll was also lower for participants using the gravity-referenced view as found by a repeated measures ANOVA for roll normalized for task time, $F_{1,24}=6.35$, $p=.019$.

## CONCLUSIONS

In the introduction we hypothesized that a gravity-referenced view would provide the most usable integration of attitude and scene information for teleoperation over uneven terrains. The results of our experiment bear this out.

1) A mixed viewpoint gravity-referenced view can make operators more situationally aware of a vehicle's attitude.

A mixed viewpoint gravity-referenced view indicates roll angle through the slope of the robot's body that forms an integral part of the navigational view. When attitude information is made available on a separated display it is more difficult for the operator to incorporate this information in navigation and planning. Our results not only replicate Heath-Pastore's (1994) finding that gravity-referenced views can lead to better estimation of roll but demonstrate that this improvement in situational awareness extends to prediction and choice of safer more efficient paths through irregular and difficult to navigate terrains. While our experiment cannot distinguish the contributions of the mixed viewpoint from the gravity-referenced view inclusion of the chassis within the camera view seems desirable and easily accomplished.

2) There appears to be a relationship between the awareness of roll angle and perception of pitch angle.

Although the gravity-referenced view used in this experiment was referenced only to roll, participants using it had similar levels of confidence in the judgments of pitch to those in the fixed camera condition who had explicit indication. Indirect measures of pitch perception such as rollovers suggest that GRV users were not appreciably handicapped by this lack of indication. Whether a better integrated indication such as a HUD pitch ladder could improve performance further would require more experimentation.

3) The conditions favoring gravity-referenced views are relatively uncommon and may limit the use of the technique to domains such as urban search and rescue or military applications in which confusing environments and stressful operation are expected.

In an initial pilot study we found several off the shelf environments, which appeared to meet our requirements, were insufficiently confusing to show clear differences between the displays. Where there are sufficient cues such as a horizon or perpendicular walls, neither explicit attitude displays nor gravity-referenced views are needed for situational awareness. In naturalistic observations such as McGovern's (1991) survey of accidents, mishaps due to loss of situational awareness are relatively infrequent although operationally significant.

We consider gravity-referenced views to be only one of a growing number of techniques needed to make human interaction with mobile robots easier and more fruitful. Robots should probably be equipped with safeguards to prevent them from falling into holes, exploration and mapping utilities to keep us from getting lost, camera control and perceptual routines to scan the environment, and a host of other assists that will continue to take us further from direct teleoperation and toward cooperative exploration.

## ACKNOWLEDGEMENTS

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