Spatial Orientation Aware Smartphones for Tele-operated Robot Control in Military Environments: A Usability Experiment

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We report an experiment conducted to assess the usability of a smartphone-based controller for use by dismounted troops using unmanned ground vehicles for reconnaissance and surveillance. A virtual joystick controller is compared to a specially designed tilt-based controller intended to limit the device's touch interface while providing intuitive control. Participants drove a small tracked robot on an indoor course using both controller options where metrics regarding performance, mental workload, and user satisfaction represented various measures of controller usability. Results indicate that the tilt controller is preferred by users and performs equally as well, if not better, on most performance metrics. These results support the development of a smartphone-based control option for military robotics, with a focus on gestural input methods which overcome deficiencies of current touch-based systems, namely lack of physical feedback, high attention demands, and unreliability in field environments.

INTRODUCTION

The U.S. military is in the midst of arming soldiers with a new type of technology already ubiquitous in civilian life–the smartphone. Recent tests at White Sands and Fort Bliss training areas proved encouraging, putting 300 phones from multiple manufacturers through their paces (Milian, 2011). While there are still unanswered questions regarding screen glare, ruggedization, and battery life, the Army, at least, is clearly committed to continuing development towards a standardized military smartphone and operating system.

Initially, these smartphones will connect to the secure military network via Rifleman Radio to provide GPS data, map overlays, and other situational awareness tools (Gould, 2012); however, industry developers are anxious to expand applications to logistics, maintenance, and more. Our intent is to provide an option for smartphone-based robot control to meet the needs of dismounted troops using small, portable unmanned ground vehicles (UGVs) for reconnaissance and surveillance. This research specifically tests suitability of an *orientation-based, spatially aware* smartphone controller. By exploiting onboard micro-electromechanical sensors, such as accelerometers and gyroscopes, we hope to use proprioceptive device inputs (tilt and rotation) to overcome common user complaints regarding touchscreens in field environments.

Orientation Aware Control

Spatial orientation refers to an object's three-dimensional pose with respect to its inertial frame (gravity). Smartphones are orientation aware thanks to their accelerometers and gyroscopes, measuring linear motion and rotation respectively. By accessing the phone's knowledge of its orientation, applications can then use that information to respond to custom gestures, recognize orientation changes, and monitor dynamic motion. This can improve the user experience by providing a more physical mode of feedback, removing clutter from the display, and mapping to mental models more intuitive to operators.

Unmanned Ground Vehicles in the Military

Robots are taking over a larger part of the workload from U.S. soldiers, with ground vehicles becoming an important part of the Army and Marine Corps' missions. They are generally cheaper, easier to deploy and maintain, and more mobile than their aerial counterparts, requiring limited specialized training to operate. Thanks to these factors, the number of robots in combat is rising consistently. A 2011 report estimated a 1:50 robot to soldier ratio in Afghanistan, expected to increase to 1:30 by the end of 2013 (Zakaria, 2011). While their growing use is no doubt saving lives, the soldier-robot interaction experience is still vastly under-researched.

Neither of the two most popular ground robots (Talon and PackBot) are defense programs of record; they are purchased "off the shelf," outside the military's official acquisition scheme (Magnuson, 2012). As such, the robots currently deployed by the military are a hodgepodge of different platforms, controllers, batteries, and communication protocols. The side effects of this, then, are a logistics system unprepared to support the hardware, questions about both mechanical and network reliability, and no proven measure of system usability. This lack of user-centric design is not unique to the military's problem, as researchers like Adams (2002) and Nguyen & Bott (2000) have noted systemic issues with a lack of user involvement in the design process. In the case of military robotics over the past ten years, the operational need to ship robots overseas paired with limited access to military users has resulted in a product that soldiers had no ability to shape.

Current Operator Control Units (OCUs) (Figure 1). For many years, robot control has been achieved via laptop-based systems originally designed for desktop use then rudimentarily converted for field operations. Robots have since gotten smaller, users have become more mobile, and yet the laptop OCU remains--a cumbersome control option. Various versions exist, whether they be worn around the user's neck or carried in a backpack with a tethered handheld component. Aside from their size, many of these systems are inherently complicated for dismounted users, whose demands require more simplicity.

Several companies have recently unveiled updated controller options which, while drastic improvements over previous designs, are hardly revolutionary. Recon Robotics (2012) currently deploys their Throwbot XT with a simple handheld device weighing 1.6 pounds, where both video feedback and joystick are housed; iRobot (2012) has upgraded to a small, two pound handheld controller with 5" LED screen for their FirstLook robot; and Applied Research Associates (2011) uses something similar for their Pointman robot. Aside from decreases in size and weight, none of these dramatically alter the landscape for user control. On the whole there remains a lack of significant progress on "field-able" operator control technologies that eschew the standard single-mode, tactile joystick.

(a) Laptop-based Controller

(b) Recon Robotics Controller

(c) iRobot FirstLook Controller

(d) ARA Pointman Controller

Figure 1. Operator Control Unit (OCU) Examples

Touchscreens in the Military. Touchscreen devices, such as smartphones, play host to one of the most promising new controller platforms since the advent of modern video games. Their unique combination of processor power, size, and high-resolution displays makes them inherently adaptable—one of the military's doctrinal requirements for robotics systems (Department of Defense, 2009)! Unfortunately, touchscreens remain a tough sell given their disadvantages when compared to traditional tactile controls: 1) lack of physical feedback; 2) difficulty operating when hands are dirty or gloved; 3) fragile; 4) small screens limit size/resolution of remote viewing.

While valid, none of these deficiencies are insurmountable. Some can be addressed through small changes to the hardware, while others may be managed via chosen control mode. By limiting the touches necessary to operate in field environments, *orientation-based control* offers an intuitive interface to address nearly all of the disadvantages of current OCUs.

Related Work

The Army Research Laboratory (ARL) has done significant work with smartphone-based controllers through a series of scalability experiments started in 2008. Redden (2011) summarizes the results of the complete series, while a usability study by Pettitt (2011) is most relevant to our own.

In Pettitt's technical report, the authors describe an experiment comparing an Android-based (smartphone) virtual joystick controller to an XBox 360 joystick (whose haptic, vibratory feedback was not active) for remotely operating a PackBot Explorer robot on two courses–indoor and out. Users were asked to drive the robot using each controller after a brief training period. Results overwhelmingly favored the XBox 360 controller, reaching significance *($p < 0.001$)* in mean time to complete the courses, mean number of off course errors, and mean number of driving errors. Additionally, users reported a higher total workload score with the Android controller, specifically on the mental, effort, and frustration scales. Finally, participants rated their own performance with the XBox 360 controller superior to that with the Android with 26 of 30 participants preferring the former (Pettitt, 2011). While most users appreciated the Android's light weight, small size, ease of use, and one-handed operation, many complained about the lack of proprioceptive feedback and sensitivity of a rather small virtual joystick.

Current Study

Our study expands upon ARL's work by comparing a second smartphone-based controller option designed to overcome many of the user-perceived deficiencies of Pettitt's controller. Adopting orientation aware, tilt-based controls helps to limit the user's touch interface while providing inherently physical feedback to the user via device orientation. Our study closely mimics the experiment design of Pettitt (2011) and began by comparing ARL's version of virtual joystick control to our own orientation aware controller. The goal was to ascertain whether the design characteristics of the orientation aware controller provide a suitable, more satisfying smartphone-based control option.

Twenty-five participants were recruited to help answer the question "Can smartphone accelerometers be implemented in tele-operated control of ground robots such that their advantages (performance, usability, size/weight) overcome suspected deficiencies, including negative user perception?" We hypothesized that over time, and after reasonable training, users would be able to perform surveillance and reconnaissance tasks to a reasonable standard and **equally as well** with tilt inputs as with a virtual joystick.

METHOD

Apparatus

Trials took place in a large lab space staged as an indoor "obstacle" course through which users drove their robot (see Figures 2 and 3). A modified Kyosho Blizzard SR RTR tracked vehicle, pictured in Figure 4, was developed as the robot platform, chosen for its maneuverability and similarities to the PackBot used by ARL.

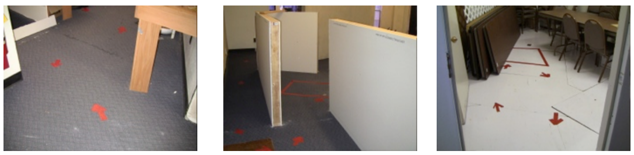

Figure 2. Pictures of Course

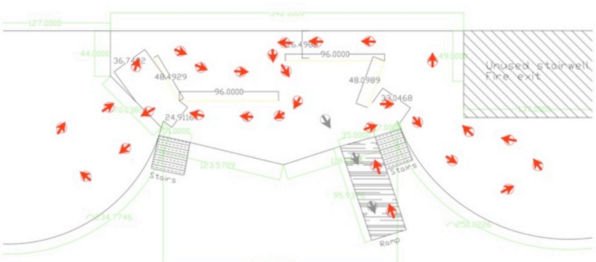

Figure 3. Course Layout

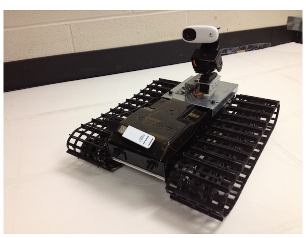

Figure 4. Modified Kyosho Blizzard

Figure 5. iPhone Controller Devices

Controller applications were hosted on both a 4th generation iPod Touch and an iPhone 4; each was ruggedized by an Otterbox Defender case to make their size, weight, and shape as comparable as possible while protecting them from damage (see Figure 5).

Joystick Controller (Figure 6). The joystick controller was presented in portrait mode, using the upper half of the screen for video feedback from the robot's onboard camera. A small virtual joystick on the bottom half of the screen was used to drive the robot. When the joystick was stationary in its center position, the robot did not move. As users touched and dragged the joystick from center, the robot reacted accordingly. Distance from joystick center affected the robot's speed, and position around the top 180º of the joystick's radius determined vehicle heading. When the joystick was dragged backwards, the robot reversed. The screen configuration and controls echo those used in Pettitt (2011). Controller sensitivity was fixed and vehicle throttle was scaled to 40%.

Tilt-based Controller (Figure 7). The tilt-based controller was designed to work as a steering wheel and was scaled in the same manner as the joystick controller. Tilting forward and back set robot speed and direction (reverse), while rotation left and right controlled heading. Magnitude of input movements linearly mapped to the magnitude of the robot's corresponding actions i.e. rotating far left resulted in a hard left turn; tilting just slightly forward resulted in slow forward motion. The controller display remained level to the horizon at all times, to appear as if the image floated inside the screen (much like an airplane's altimeter display). This served as visual feedback indicating degree of rotation and reassured users that controls were active and responding accordingly.

The only necessary touch interface, and one that can be replaced by a physical button (volume button) in user settings, is presented as a thumbprint in the lower right corner of the display. It acts as a deadman switch; users must maintain contact with it to activate controls. The lack of other buttons combined with the controller's landscape orientation serve to maximize the area devoted to video feedback of the robot's camera feed.

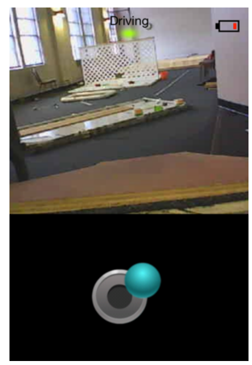

Figure 6. Virtual Joystick Controller

Figure 7. Tilt-based Controller

Participants

Participants were recruited primarily from the undergraduate and graduate engineering populations at our university. They ranged in age from 18 to 51, with a median age of 26. The subject population consisted of 21 men and four women, recruited to mimic the military gender split (approximately 85% male and 15% female). While 4 participants reported military experience, none were exposed to unmanned systems during their service. Only one individual reported being left-handed. Participants were monetarily compensated for their time, approximately one and a half hours. No previous experience with either smartphones or robots was necessary to participate, although 76% reported good or excellent proficiency with mobile devices, with 22 respondents reporting at least 12 hours of weekly use.

PROCEDURES

We used a one-factor repeated measures (within-subject) design with two levels of the independent variable, controller type, counter-balanced for order and learning effects. Participants were presented with two controllers--virtual joystick and orientation aware.

All experiments began by having participants walk through the course (Figures 2 and 3), where path points (red arrows) were identified and obstacles surveyed. Each user then received formal video training on their randomly assigned controller before being granted up to 15 minutes for hands-on practice.

Official timed trials commenced on each controller immediately following training using that same controller. Participants remained seated at the user workstation, located just below the test course and positioned to ensure that all driving was conducted via tele-presence. Users were video-taped at their workstation to capture facial expressions, movements, and verbal statements, while the robot was filmed by cameras overlooking the course for redundancy.

Runs began with the robot at the bottom of an eight-foot ramp leading up to the course, while participants awaited the signal to begin. Users were instructed to complete the course as quickly and as accurately (hitting all of the marked path points) as possible while minimizing collisions. Performance data was collected while users maneuvered their robot through the course and was halted when the robot reached the start/finish point at the base of the ramp.

Users then transitioned to post-iteration data collection, filling out the NASA TLX (NASA, 1988) via desktop application and completing a web-based questionnaire regarding controller features and system usability. Following this, the next controller option (if applicable) was prepared for the participant. He/she trained with the new controller in the same manner previously described, executed a timed trial, and finished with the same post-iteration TLX and questionnaire. Once both timed trials were complete, users indicated their preferred controller (of the two presented) in a final post-experiment questionnaire.

Measures

The dependent variables (DVs) used for statistical analysis were a combination of performance results, formal measures of workload and usability (Hart, 1988; NASA, 1988; Brooke, 1996), and informal measures of user satisfaction collected via survey. Where possible, survey questions were modeled after ARL's published post-iteration questionnaires (Pettitt, 2011). Performance data included practice time **(ptime)**, the amount of time actually used by each subject of the 15 minutes granted for hands-on practice, collected as a quantifiable indicator of ease of use. Trial time **(ttime)**, major errors **(majerror)**, minor errors **(minerror)**, and path points **(pathpts)** were collected real-time by the experimenter during the robot's traversal of the course. Major/minor errors were differentiated as instances from which a driver *could* (minor), or *could not* (major), self-recover. Path points, recorded as a measure of driving accuracy, represented the total number (of 32 possible) run over by the robot.

Mental workload was assessed using the results of the NASA TLX **(tlx)**. All other measures were derived from user surveys. The System Usability Scale (**sus**) was incorporated into these surveys as a generic, quick, simple, and widely accepted measure of usability for industrial systems (Brooke, 1996). Comprised of ten questions on a five-point Likert scale, overall usability totals to a number between 0 and 100; 100 being most usable. Additionally, users rated their performance at a number of specific driving tasks on a scale ranging from extremely difficult (1) to extremely easy (5) (see Table 1).

Table 1: Questions Asked to Measure User Rated Driving Abilities

Rate your ability to complete each of the following maneuver tasks for the surveyed controller:		
1)	*Move in the correct direction*	**move**
2)	*Avoid obstacles*	**obstacles**
3)	*Maintain control when driving at slowest speeds.*	**slow**
4)	*Maintain control when driving at medium speeds.*	**med**
5)	*Maintain control when driving at fastest speeds.*	**hi**
6)	*Overall ability to perform driving tasks.*	**maneuver**

RESULTS

Analysis of variance (ANOVA), with controller and subject as factors, was used to identify the effects of the independent variable on each of the 13 dependent variables. Means and standard deviations for each measure were also examined. Table 2 depicts the p values for four performance variables, plus workload and usability (**sus**); those below the critical value of 0.05 are highlighted. Figure 8 shows the relevant survey results (from Table 1) in graph form.

Table 2: *F*-Statistics for Dependent Variables

		ttime	majerror	minerror	pathpts	tlx	sus
Joystick Controller	*mean*	305.88	0.28	5.64	28.6	55.31	64.9
	std. dev.	69.4	0.61	2.6	2.02	14.78	16.9
Tilt Controller	*mean*	339.56	0.4	4.16	28.28	53.89	68.7
	std. dev.	100.34	0.76	2.75	2.67	20.09	17.08
	p (< 0.05)	***0.046***	0.417	***0.049***	0.55	0.695	0.258
	F	4.41	0.68	4.29	0.36	0.16	1.34

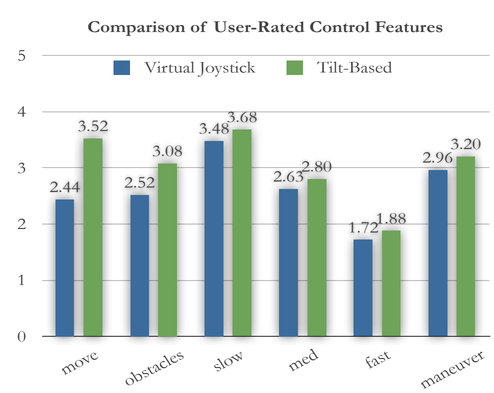

Figure 8. Comparison of User-Rated Control Features

ANOVA shows a significant effect due to controller type on four dependent variables: trial time, minor errors, move, and obstacles. Trial time favored the joystick controller, which matches observations made during experiment trials. We noted that joystick runs were generally faster than those with tilt controls (in fact, significantly so). It appeared to be a result of the small virtual joystick limiting travel between center and bezel. Users struggled to find the joystick "sweet spot," with most running at top speed, or close to it, for the duration of their runs. Similar problems were noted in Pettitt's (2011) ARL study. Participants seemingly adapted to these conditions by driving in short bursts, noticeably increasing the frequency of collisions/minor errors as a result ($\textbf{minerror}_{joy} = 5.64$ vs. $\textbf{minerror}_{tilt} = 4.16$).

Post-experiment questionnaires indicated a clear preference for tilt controls, with 64% of users favoring them over the joystick option. Comments indicate that users found the tilt controls more intuitive, with several users praising its interface as more "natural, smoother, consistent, and familiar."

Correlation among all 13 DVs was tested using Spearman's correlation coefficient. Spearman's was used to accommodate the ordinal, discontinuous nature of our chosen variables. Two noteworthy correlations exist: **sus-maneuver** ($\rho=0.7147$) and **sus-slow** ($\rho=0.6009$), indicating how heavily those measures play in to a user's perspective of ease of use.

The answer to the question regarding overall driving ability, **maneuver**, was expected to affect usability; the role of **slow**, on the other hand, is less obvious. It is much more strongly correlated to usability than answers to either of the other speed questions ($\rho_{med} = 0.4284$, ρ_{hi} = non-significant), implying that users relied on their ability to control the robot at *slow* speeds to, at least partially, inform their overall impressions regarding usability. Given users' documented struggles to achieve the slowest speeds using the joystick controller, it is not entirely surprising that tilt controls achieved better average scores on all user-rated metrics (driving ability, workload, and usability). The System Usability Scale, our formal measure of usability is, as expected, negatively correlated with the NASA TLX workload score ($\rho = -0.622$). It was anticipated that more usable systems would rank lower in terms of mental workload, and that appears to be supported by our results.

DISCUSSION

This research aimed to identify a smartphone-based control option for tele-operated ground robots that limited touchscreen requirements without adversely affecting user performance and satisfaction. A usability study with 25 participants shows that, in fact, spatial orientation aware controllers are intuitive and feasible and out-perform virtual joysticks in a number of areas, including user satisfaction. Tilt-based controls appear to overcome a number of issues inhibiting touchscreens in field environments; they limit (or eliminate) the touch interface, provide an intuitive control mapping (steering wheel), reduce mental workload, and are hosted on adaptable systems significantly smaller than current OCUs. As the military expands smartphone use, applications in robotics should absolutely be considered, as proven here.

A second and third phase of this study have already been conducted, investigating the use of tilt controls for other robot degrees of freedom (e.g. camera pan/tilt) and customizable control (Walker, 2013). Future work with spatially aware controllers will expand this experiment even further, examining tilt-based controls alongside the XBox 360 interface used by ARL (Pettitt, 2011). Experiments will be moved to more realistic *field* environments, preferably using military operators and a ruggedized robotic platform; the goal being to provide further evidence of our controller's suitability in reconnaissance and surveillance operations, while collecting formal feedback from the "designed-for" audience.

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