# Interactive Dirt: Increasing Mobile Work Performance with a Wearable Projector-Camera System

**Daniel C. McFarlane and Steven M. Wilder**
Lockheed Martin Advanced Technology Laboratories
3 Executive Campus, Cherry Hill, NJ 08002
{daniel.c.mcfarlane, steven.m.wilder}@lmco.com

**ABSTRACT**
Mobile teamwork requires people to maintain good situational awareness (SA) about their real world environments. Current mobile devices are highly portable, but their user interfaces (UIs) require too deep of focus of attention to allow their users to use them and simultaneously maintain SA. As a result, some mobile practitioners have little or no access to useful computer-based interactive services. Inspired by existing projector-camera systems, this paper studies the feasibility of developing a wearable projector-camera system that enables users to access human-computer interaction (HCI) services without negatively affecting their SA. A functional prototype of the "Interactive Dirt" system was developed using inexpensive commercial off-the-shelf technologies. A field experiment was conducted as a formative evaluation to test the utility of the prototype under extreme mobile teamwork requirements for SA—military stability and support operations (SASO). Results show strong potential to increase performance of mobile teams.

**Author Keywords**
Projector-camera system, mobile computing, wearable user interface, situational impairment.

**ACM Classification Keywords**
H5.m. Information interfaces and presentation (e.g., HCI): Miscellaneous.

**General Terms**
Design, Experimentation, Human Factors, Measurement, Performance, Security.

## INTRODUCTION

The quality and usability of user-interfaces (UI) are not static, but dependent on the context of use. For example, a particular web site may be useable for a person working in an office with a 19 inch monitor and no distractions. However, this person's ability to use this website through a cellphone display while crossing a busy street on foot is greatly diminished. These negative contextual effects on performance are called situational impairments [1]. Mobile work has several negative contextual influences, including the need to deal with: dynamically changing conditions; poor visibility and/or audibility; inconvenient work surfaces; social responsibilities; physical locomotion, like walking; navigation; reading signs; the need to operate physical devices, like opening doors; and the need to talk with other people, like airline ticket counter representatives. Outdoor mobile work has the additional challenges of: weather; poor visibility because of too much or too little sunlight; and significant physical dangers.

Mobile work contexts can cause situational impairments to HCI use, but HCI use in mobile contexts can also cause situational impairments that affect a person's primary activities. For example, many governments have traffic safety laws that ban the use of cellphones while driving because mobile devices cause situational impairment in people's driving performance. Poor design for mobile HCI, not only degrades its usability, but can cause people to fail at critical real-world tasks.

This paper focuses on an extreme example of mobile work context that requires HCI design beyond the current state-of-the-art—military stability and support operations (SASO). This mobile teamwork involves foot soldiers providing safety and support to friendly local civilians while suppressing threatening adversaries. SASO operations are sometimes conducted in response to natural disasters or political upheavals. This is stressful dangerous work; in addition to coordinating with other members of their teams and/or local civilians, foot soldiers must maintain continual best-possible SA and remain fully unencumbered so they can react quickly to unpredictable emerging threats. These mobile team workers move around on foot, largely in outdoor conditions, with their hands, arms, eyes, ears, face, head, and voice fully engaged in their actual context.

Several applied research and development projects have shown the potential value of technologies to aid dismounted infantry operations. Different UI solutions previously tried for supporting foot soldiers include: laptop computers worn on the users' chests, hand-held devices (PDA); see-through visor displays; spoken-language understanding technologies; 3D spatial audio; and small displays with buttons mounted on rifles. These UI attempts, and many others, have shown unsatisfactory support for safety and/or portability requirements.

Previous work shows that UI design to support mobile teamwork must consider users' requirement to achieve and maintain SA of their surroundings, especially outdoors. A UI design that causes significant situational impairment will break the usability of the device/application for supporting mobile teamwork. A new mobile UI solution that reduced situational impairment would be highly useful for several kinds of mobile workers, especially for outdoor work. Examples include: law enforcement, construction workers, site inspectors, fire fighters, cargo handlers, transportation workers, life guards, search and rescue, foot soldiers, and people tending small children in public spaces.

## BACKGROUND

Current mobile workers can often be found standing still on a sidewalk or other public place while others go around. Like a stationary rock in a moving river of water, they stare down at a hand-held device, and hammer on tiny buttons with their thumbs, totally engrossed in whatever is happening in that virtual microcosm. Advances in technology for miniaturization make this possible, giving mobile workers access to their virtual computer environment from anywhere, albeit through an awkward peephole. Having ubiquitous computer access can be very useful for communicating, scheduling, remote monitoring, and accessing information and geographically-relevant services. However, there are situations and jobs where it is too risky for users to “tune out” to what is happening in the immediate real world.

Some work contexts include dynamic, potentially dangerous situations, and/or job responsibilities that require maximum vigilance. For example, warehouse workers need to maintain continuous SA about nearby forklift activity to avoid accidents. Whether it is worthwhile for mobile workers to “tune out,” and incur some temporary situational impairment depends on: (1) how long the impairment will last; (2) to what degree it will degrade the person's abilities; (3) the type of impairment (perception, cognition, and/or motor) relative to the capabilities required to manage threats and responsibilities; and (4) the timing of the impairment to the specific work activities being done. For example, normal eye blinking impairs 100% of visual perception for about 300-400 milliseconds. This duration and type of impairment is not problematic except in rare situations where human performance in an event requires fully-reliable visual perception, like when trying to hit a baseball. Perry et al. [2] observed that mobile workers adopt strategies to deal with limited access to resources. In another example, car drivers who use cellphones are often aware that dialing a number temporarily impairs their driving performance and causes a safety problem. They adopt strategies to minimize the impact of this situational impairment when dialing: (1) single-button speed dial; (2) holding the phone up in their normal field of view to not fully lose visual awareness; (3) voice activated dialing; and (4) waiting to place a call until stopped at a red light.

From our experience working with military subject-matter experts (SME), we assert that mobile SASO teams have intermittent times where they could find strategic ways to tolerate brief, low-impact, partial situational impairments to access collaborative computer-based aids. Unfortunately, no existing UI solution can deliver this type of ultra-quick, light-weight limited-modality interaction, with instant accessibility anywhere at anytime.

### Can Mobile Hand-Held Devices Be Improved So Their Use Causes Less Situational Impairment for Mobile Teams?

It is possible to use cellphone cameras to detect hand movement of the phone, and then allow people to control the UI, including writing text, by moving the device in space [3]. This study and several other insightful works have made significant progress in reducing situational impairment effects for use of hand-held devices. However, one or both of the user’s hands remains fully impaired and the tiny screens permit relatively slow information presentation and requires extremely focused visual attention.

### What Other UI Approaches Can Reduce Situational Impairment for Mobile Teams?

Machine vision based HCI keeps users from having to physically manipulate manual controls. The *Magic Board* includes a projector-camera system that watches a person using a normal whiteboard, allowing the person to select and copy images from a whiteboard with finger pointing [4]. Commercial companies have introduced projector-camera systems into public spaces for interactive advertising. Two examples are Reactrix™ and EyeClick™. These systems mount in the ceiling and project a large display on the floor. When people move over the projection, the system detects where they occlude the image and causes the advertisements to move as an interactive game. Combining projection with vision-based UI has shown utility for enabling collaborative work. A UI approach for mobile HCI support, based on a projector-camera approach, might enable the minimal situational impairment of users that is required by SASO workers.

### What is the Potential for a Mobile Projector-Camera System UI Approach to Cause Reduced Situational Impairment for Mobile Teams?

Cao et al. [5] explored novel collaboration techniques for two co-located mobile teammates using hand-held devices with built-in miniaturized projectors. This innovative work is based on an observation that the consumer electronics marketplace will soon release mobile hand-held projector-phones. The study asks “How could people use these devices to increase collaboration performance?” Their results show several useful types of novel interaction based on spatial movement of the hand-held devices (captured with an environmentally installed camera-vision system) combined with button presses. Interaction design follows a "flashlight" metaphor where HCI is driven by a users' movement of the projector. This work has highest relevancy for low situational impairment requirements for SASO teams. However, some issues make it unsuitable. The camera-vision-based spatial tracking system is fixed in the environment and not part of the mobile device. This means none of the interaction techniques will work in a mobile work setting. Each user has one hand fully encumbered holding and moving the device. All experiments were conducted in a low-light office setting with projection on a flat wall. It's uncertain what issues may impact generalization of these findings to a mobile workplace.

Inexpensive commercially available projector phones will soon be a reality. Others besides Cao et al. have explored the use of projector phones. Projector phone displays have shown advantages over hand-held displays especially for collaborative tasks [6, 7]. A flashlight metaphor enables novel interaction techniques including: (1) a *peek technique* where a larger virtual image stays stationary and the hand-held projector reveals portions of it through movement; (2) a *clutching technique* where motion of the hand-held projector is used to move the larger virtual image on the wall; and (3) a *layer-switching technique* where the view switches back and forth from an image navigation screen for selecting several images, and an image viewing screen (all within the flashlight-plus-peek metaphor) [8].

Early pioneering research on movable projection UIs includes: IBM T.J. Watson Research Center and Mitsubishi Electric Research Laboratories (MERL). The *Everywhere Display* project explored the use of a steerable projector-camera system mounted on the ceiling that could be steered to project on different surfaces within view [9, 10]. Interaction was supported through machine vision recognition of the users' finger pointing so the display was used as a touch screen. Problems with projection are identified and discussed, including: brightness and contrast, oblique projection distortion, focus, resolution, and obstruction and glare. MERL created a bulky prototype "handheld" projector to facilitate research [11, 12]. They experimented with a novel interaction technique that uses one concept from the steady-cam capability for video cameras. The projector shows the computer image but only with part of the area that the projector is capable of displaying—about one quarter of the potential display size. As the user moves the hand-held projector, the visible image appears to stay stationary. The user's hand movements are mapped to a cursor on the display that drives the interaction. The *FlowMouse* technology shows the potential for a camera-vision system to allow a user to control HCI through relative hand movements [13]. This is analogous to normal mouse control of HCI. The *PlayAnywhere* project evaluated this relative control to direct control of a projector-camera system [14].

In the *Wear Ur World* project at the MIT Media Lab, Pranav Mistry, Patty Maes, and Liyan Chang investigate gestural interaction with a wearable projector-camera prototype [15]. This work shows the potential utility of this technology for low-cost augmented reality applications. The *Map Torchlight* project showed that a hand-held projector-camera system could be used to dynamically augment paper-based maps with personalized information [16]. It enabled a significant improvement in speed of locating things on maps compared to *magic lens* solutions (hand-held computers used as pucks over paper maps for displaying details) because it reduces the time and effort needed to switch the user's eyes between the paper map and a separate screen. An experiment by Hang et al. [17] predicted the potential utility of projector phones (miniature projectors embedded in cellphones) to augment the large paper-based maps. They found the projection of personalized information allowed people to find things more quickly.

The *Brainy Hand* project developed an extremely lightweight ear-worn camera hand gesture system [18]. It enables people to control a computer with unfettered single hand gestures and receive computer responses in audio through an earphone. The authors speculate about the potential added benefits of including a miniaturized projector on the ear-worn device that would project simple interfaces onto the palm of user's other hand.

### Summary

Previous work shows useful progress toward more lightweight interaction to reduced situational impairment for mobile teams, but no existing UI solution meets all SASO requirements.

- *Portability*: Hand-held UIs have good portability but impair use of hands, eyes, and attention for maintaining SA in real-world environments.
- *Unencumbered interaction*: Vision-based HCI is useful for unencumbered interaction, but does not solve the display problem for mobile computing.
- *Minimal demand on eyes*: Large projection displays do not require a change of eye focus, but projection on varied real-world surfaces is still an open research topic.
- *Team collaboration*: projector-camera systems can produce large interactive displays that support multi-person collaboration. Portability has been a problem.

## APPROACH

A formative evaluation was conducted to explore the technical feasibility, usability, and validity for a wearable projector-camera system. A prototype system was constructed and used in field-testing with former military SMEs in both urban and forest conditions for SASO operations. Results focus on identification of potential application and problems that require future work. The objective of the experiment was not to evaluate the readiness of the prototype for productization but to construct a provisional research platform to elicit useful formative information.

### Hypothesis

A wearable projector-camera system can enable sufficiently lightweight interaction to allow SASO mobile teams to use HCI services to improve work performance without negatively impacting SA.

## FIELD EXPERIMENT

Semi-structured expert review methods were used for predictive evaluation in this formative study [19]. These research methods have demonstrated effectiveness in identifying opportunities and problems for application of novel UI technologies. Experts were paired to minimize the effects of bias and to enable them to simulate collaboration. Previous work has shown that paired SMEs with expertise in both the application domain and usability evaluation are able to deliver comprehensive and detailed predictive usability information under certain conditions. Careful selection of highly qualified SMEs and realistic field use conditions enables the collection of useful information with very few participants.

### Apparatus

Inexpensive newly released off-the-shelf products were used to construct the Interactive Dirt feasibility prototype: (1) a miniature projector (Dell M109S); (2) an infrared (IR) camera (Nintendo® Wii™ Remote); and (3) a pocket-PC computer (Sony Vaio® UX380N running Windows Vista®). The camera and computer communicate via Bluetooth. The computer and projector communicate through a normal display cable (Figure 1). Open software from a Carnegie Mellon University project by Johnny Chung Lee was used to convert the Wii™ remote's output into mouse click and drag actions [20].


**Figure 1. The prototype with interaction equipment: (a) projector, (b) camera, (c) computer, (d) laser, (e) replacement camera with band-pass filter for laser interaction, (f) IR LED on telescopic metal pointer, (g) IR spotlight, and (h) Glint Tape patch.**

The projector is mounted on a piece of sheet metal to maintain space under the projector for heat ventilation. The projector (and its sheet metal base) and camera are fastened in alignment. The sheet metal base is backed with Velcro for easy positioning on the wearer. Figure 2 shows the projector-camera system worn on the upper right shoulder of one of the participants in the field experiment. The computer and battery are housed in an ordinary military pouch worn on the waist. This Interactive Dirt prototype is a research platform for formative evaluation, not an early product version; so many product details are not solved. For example, a video cable from the projector to the computer hung down the wearer's back. Powering the projector with battery power was not the focus of this project. A first step solution powered the projector with a lightweight portable electric generator and a long cable. The second step investigated battery power.

**Figure 2. The Interactive Dirt prototype projector-camera system being worn on a participant's upper right shoulder, and he is looking at the projected image on the ground outside in a forested area (December 17, 2008). The mobile computer is worn in a pouch at the waist (not visible in this picture).**

The literature does not give clear generalizable guidance about which type of interaction approach is best for mobile interaction with a projector-camera system. Five approaches were tried for Interactive Dirt. These approaches were selected as a set of easily-constructed alternatives intended to gather formative feedback that can be used to inform a viable design approach:

1. Pointing sticks with button-controlled, back-pointing IR emitters on the ends. The sticks are metal telescopic presentation pointers (49.75 inches when extended). A single IR LED on the tip is powered by an AA battery in the handle.
2. A powerful IR spotlight pointing down in line with the projector, and reflective tape on the end of a pointing stick. The 6W 940nM IR illuminator had 48 LEDs and delivered a 60° beam. It mounted with Velcro on the projector (not shown in Figure 2). Glint Tape was used for reflection because it reflects IR but not visible light.

3. The same IR spotlight as in #2, but with the reflective tape on soldiers’ index finger tips.
4. The same IR spotlight as in #2, but with the reflective tape on the soldiers’ boot tips.
5. Visible-light, eye-safe laser pointers with a matching band-pass filter on the camera.

Participants wore full military gear. This helped identify potential projector occlusion problems and obtain accurate wearability results and exploring different use cases. Gear included: standard battle dress uniforms (BDUs—military camouflage coat and pants); body armor (bullet-proof vest) and helmet; knee and elbow protectors; boots; gloves; and high-fidelity simulated M4 rifles. Figure 2 shows that the armored vest comes standard with several green Velcro patches in the shoulder and upper chest areas. These were useful for affixing the Interactive Dirt prototype in different ways.

The Lockheed Martin proprietary DisOPS software was used in the Interactive Dirt field experiment. DisOPS is a multi-user collaborative map-based aid with Global Positioning System technology for maintaining SA. This includes awareness of the positions of all members of a mobile distributed team. It also facilitates collaborative planning and plan monitoring. Its services have proven useful in several military and security field events, including supporting the U.S. Park Police during the United States Presidential Inauguration, January 20, 2009. The product normally includes a ruggedized hand-held computer. For the Interactive Dirt experiment, however, only the software was used and participants interacted with DisOPS using the projector-camera system UI.

Figure 3 shows the DisOPS interface. It supports collaborative drawing of lines and selection and placement of icons on a map-based display using tool trays and pull-down menus. This interface was designed for stylus-based interaction on a hand-held computer (the DisOPS product), and its utility is not the focus of this study. It was selected for inclusion in the Interactive Dirt prototype because it supports collaborative use of a map-based display for SASO teams.


**Figure 3. The DisOPS user interface supports collaborative drawing of lines and selection and placement of icons on a map-based display.**

### Participants
Two skilled SMEs participated in this field experiment. Both are former infantry with extensive real-world dismounted infantry operations experience. They also have wide-ranging experience as consultant evaluators for several military research and development projects. They provided expert perspectives into mobile teamwork needs for dismounted infantry operations, including SASO. Participants had combined 22.5 years of military experience (one Army, and one Marine Corp) and combined 42 years of experience using computers. Both SME participants had prior training and extensive use of DisOPS and had already validated the use of the DisOPS HCI services for supporting SASO work in numerous field exercises.

### Methods
A one-day, eight-hour field experiment was conducted on December 17, 2008, during daylight hours, in New Jersey, USA. The evaluation had three sequential stages: introduction, urban operations evaluation, and outdoors evaluation. The introduction was conducted in a normal office environment meeting room and included: informed consent to participate; an entrance questionnaire; an appearance release agreement; an introductory briefing that described and demonstrated the Interactive Dirt prototype, and the different interaction approaches. The goals of the evaluation were discussed. The SMEs discussed potential concepts of use (CONOPS) for Interactive Dirt, and tutored the investigative team on dismounted military operations. After the introduction (~1.75 hrs), the venue moved to a large warehouse to simulate urban operations conditions. After testing the prototype there (~3 hrs), the venue moved to an undeveloped outdoor forested area with a small lake. Testing concluded at sundown.

The evaluation was conducted as a series of semi-structured interviews in expert review interleaved with collaborative field trials of the prototype under different conditions of use, and methods of interaction. There was one Interactive Dirt prototype, and this was worn by one of the two SMEs. There were two sets of the five interaction methods (IR emitter sticks, reflective tape sticks, reflective tape on finger, and laser pointer). SMEs performed a series of trials—some required multi-user collaboration, and others required a single user.

### Validate Assertions
The entrance questionnaire included seven questions intended to assess the validity of assertions made in this research. SMEs marked each question on a scale from 0 equals “Disagree” to 10 equals “Agree.” Table 1 shows the questions and the responses for the two SMEs. Each SME had similar responses. They confirm that dismounted infantry have critical safety concerns, and are often busy using their hands, hearing, speaking, and vision. Soldiers frequently need to collaborate with others. SMEs were neutral about the potential use of weapons as a platform for delivery of HCI.

| Question | Ans |
|---|---|
| (A) In general, dismounted infantry have unusual requirements for safe and effective use of computer-based services during operations | 10, 8.5 |
| (B) Dismounted infantry often do not have both hands available to operate a computer | 9, 10 |
| (C) Dismounted infantry often do not have their hearing/listening cognitive resources available to listen to computer-generated audio | 8, 6.5 |
| (D) Dismounted infantry often do not have their speaking resources available to control a computer with spoken language | 7, 8 |
| (E) Dismounted infantry often do not have their visual/seeing resources available dedicate to close-up "heads-down" viewing of computer-based results, i.e., a small hand-held display | 7, 8 |
| (F) Dismounted infantry do not want general computer services delivered to them through a display interface mounted on their rifle. This would be perceived as a negative encumbrance | 5, 5 |
| (G) Dismounted infantry frequently need to collaborate with others | 10, 8 |

**Table 1. Entrance Questionnaire to Validate Assertions**

Beyond the questionnaire, SMEs explained that teams of soldiers have an existing strategy that enables one of them to use a hand-held computer. If the HCI service is extremely valuable and is worth risking situational impairment and the team has access to a mobile hand-held UI, then a team leader decides when to allow access. The team coordinates who will access the UI, and how the others will provide security for the distracted UI user. Very few HCI services merit the extreme coordination required to access a traditional mobile UI under debilitating situational impairment.

## RESULTS

[Note, for all quotes: "E" is experimenter, "P1" is participant #1, and "P2" is participant #2.]

### Where to Wear?

An iterative series of semi-structured usability trials were conducted to determine the best place to wear the Interactive Dirt projector-camera system. This investigative process is similar to that used by Holleis et al. [21] to determine the best position to embed input controls into clothing. The Interactive Dirt device however had different requirements for wearing because users do not touch the device.

Figure 4 shows the different locations investigated. Through trial of the prototype in different positions, SMEs revealed their evaluation criteria: (1) problems with occlusion of the projector by gear, arms, legs, and/or weapon; (2) interference with movements; (3) ability to support several types of normal stances or patterns of movement; (4) ability to keep the projected image sufficiently stationary to permit interaction; and (5) minimal risk of breaking the device.

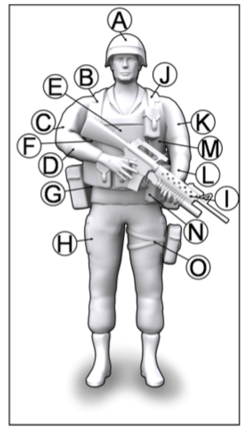


**Figure 4. Options for placement of the Interactive Dirt projector-camera system. SMEs eventually selected B.**

G, H, O, and N were in the way and were totally occluded when kneeling or crouching. A did not allow a steady image. E, K, L, and J were partially occluded by the weapon. F and M were on the side of the chest in the hollow of the arm. Before actual testing, the SMEs thought F and M (especially F) would be good. SMEs discussed how the wearer could rest their arm on the device, and how the projection would shine out between the chest and arm just below their armpit. In the actual trial, however, there were occlusion problems with the wearer's lower arm and rifle. Except for I, this left B, C and D. Before testing, the SMEs also talked about the merits of C and D. These positions are not occluded and afforded rapid positioning of the display. In trials, however, SMEs found that they wanted to use their dominant arm to interact with the display. Interaction movements inadvertently moved the display. This made collaboration very difficult. SMEs also explained that placement at C, D, K, or L would carry a high risk of damage to the projector because of the soldier's arms. B was the one body location that did not have any problems. It had no occlusion problems, did not interfere with movement, supported all stances and movements, could hold a steady image for collaboration, and did not expose the device to risk of breakage. This was judged to be completely satisfactory. Location B had the added advantage of being nearest to the wearer's line of sight. This minimized perceived image distortion for the wearer when projecting on uneven surfaces. A left-handed soldier would hold his or her rifle the opposite way, so J would be recommended.

SMEs were interested in speculation about the utility of mounting the device on the rifle (I) as a potential replacement for the existing tactical light and laser sight system. Future exploration of this option is warranted. "(P1) I'd still like to see it mounted on the weapon in a way that you could control where it points for the projection, as well as it's also acting as a tactical light."

**Use Cases or "Concepts of Operation"**

SMEs were asked to describe/demonstrate some common situations soldiers might be involved in, and how a projector-camera system might be used those situations. Through a diverse series of discussions and trials, valid use cases were identified. Teams of soldiers occasionally gather together for huddles to collaboratively plan, re-plan, or evaluate the progress of a plan (Figure 5). A shared interactive projection would be useful for collaborative discussion, and ensure that everyone accurately understood their responsibilities and how to coordinate. "(P1) So as a collaborative tool, with the RTO (radio/telephone operator) beaming the mission plan in front of people like we are right now, on the ground, and then the squad leaders, and platoon commander, platoon sergeant collaboratively planning out an operation."

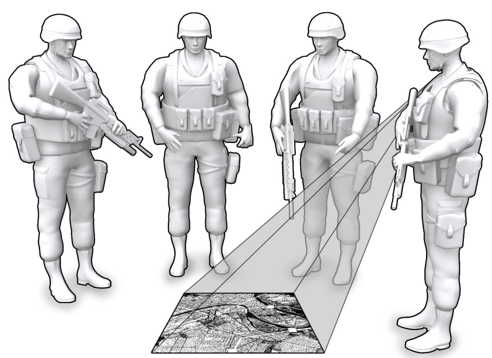

**Figure 5. Interactive Dirt supporting a huddle for collaborative re-planning.**

While moving, each soldier is continually trying to acquire temporary cover from objects in their environment—places affording less exposure to potential hostile attack. Within a place of relative cover, such as behind a tree or kneeling next to a parked car, a soldier could have a second or two when they could tolerate lightweight situational impairment to check a projected display for status. Useful information could include locations of other teammates, objectives, plans, or intelligence about threats. Figure 6 show the use case for operations in urban or forest environments. These single-use quick check situations have much higher demands for reducing the amount of impairment imposed by the UI.

"(P1) When an individual is on the move and they beam it onto something that they're taking cover behind: a vehicle, a tree, a wall. I wouldn't expect them to have to interact with it while they're also trying to maintain some security."

"(E) So it's just a quick look?"

"(P1) Just a quick look. See where my other men are. Blue force tracking, or other information that's just become available, maybe a message from the platoon commander of

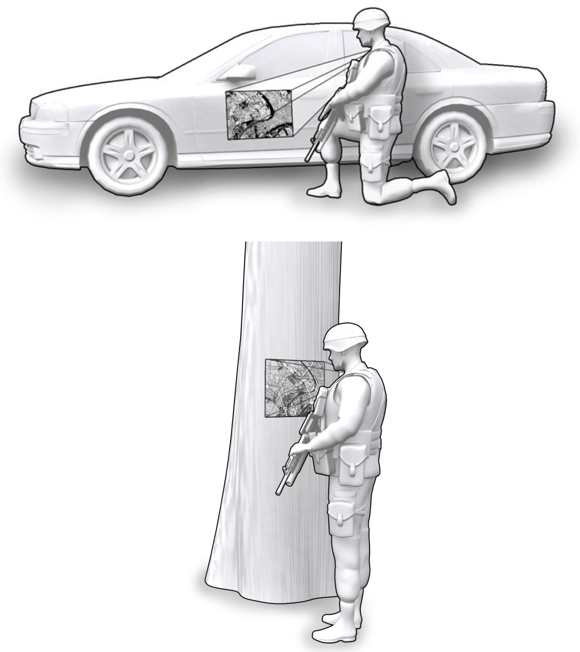

**Figure 6. Interactive Dirt supports a quick check on status during a moment of relative protection behind a parked car (urban operations) or behind a tree (outdoor operations in a forest).**

a course-correction. And he has stopped, maintained security, he's asked his RTO to unfold it. He's saying 'we've come across something, we've got new intel, so we're changing our route slightly, let me send out the new route to everyone,' bing, it beeps somehow, and they can pop it up on something right quick and say, 'Oh, my route's changed. OK, we need to shift.'"

"(E) You could take a quick check without taking your hands off the weapon?"

"(P1) Correct."

"(P2) [confirm with a nod.]"

"(P1) You just press a button and on a surface near you see the new route."

A third use case was identified, but was out of scope for consideration in this experiment. This is the case where a soldier needs to talk to local civilians. Figure 7 illustrates this situation. Interactive Dirt could enable non-combatants to express themselves through the use of a collaborative display, even without a common language. SASO work requires frequent and meaningful coordination with local civilians. This might be one of Interactive Dirt's most useful applications. "(P2) Because you could sit down and you can brief indigenous guys without having to give them any gear, that costs a lot of money. You can brief them, they can see everything, they can understand it, and then it's gone, and there's nothing left behind that can be compromised."

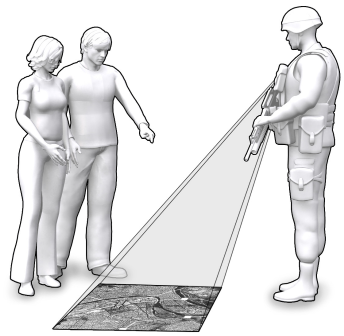

**Figure 7. Interactive Dirt supporting a discussion between a soldier and local civilians.**

### Usability of Different Surfaces

The field experiment investigated the unique challenges presented by surfaces for projection faced by dismounted infantry. Our first series of tests involved projecting on different surfaces inside a warehouse to test Interactive Dirt's abilities in an urban setting. Surfaces tested include: brown concrete floors, cinderblock walls, and metal panels on machinery. Indoor lighting was good for projection, and all surfaces were equally useful as a surface for projection. Trials of interactive projection were also tried on parked cars (hoods and sides) outdoors in partial shade. Car surfaces were the best outdoor surfaces examined and supported legible interaction even in partial afternoon sunlight.

Field operations in an outdoor forest environment present two challenges not in the indoor urban environment: the lack of uniform surfaces for projection; and brighter ambient lighting. This outdoor phase of testing was done in the afternoon (2-5p.m. EDT) on a partially overcast day, in December, in New Jersey, USA. Visibility would be worse in sunnier conditions. Many different surfaces were tried with varying degrees of success. The overall result was that the brightness of our projector (50 lumens) was unsatisfactory for these outdoor conditions (with the exception of the cars surface trials).

Most horizontal surfaces did not reflect enough light to allow legibility of the display or meaningful interaction. These included: fallen leaves, sand, dirt, rocks, moss, lake bottom below shallow water, and muddy water. The brightness was the main problem. Most mildly uneven surfaces would have been usable with a much brighter projector. The horizontal surface of sand bags was better and almost usable. Highly uneven surfaces, like gravel and bushes, failed to show anything useful and would probably not be usable even with bright projection.

Mildly uneven vertical surfaces were significantly better. No large rocks were available, but several types of tree trunks were tried. About half were somewhat usable. Although the bark was uneven, the pattern and the coloring of the bark were regular enough to render the projection almost legible in the late afternoon sunlight. Also, vertical surfaces allowed the wearer to get closer than ground projection and this increased the brightness of the image. Once the sun started to set, we found that the trunks of trees were excellent surfaces for projection and meaningful interaction was possible. The best surfaces in the forest were man-made. The clothing of a fellow soldier provided relatively even surfaces with good reflectance. The major problem with this surface is that it renders the soldier who is providing it incapable of interacting with the display. The SME projecting also experimented with holding out his right arm and projecting onto his lower arm or hand. The brightness was relatively good; however the projector could not focus this close in.

Existing work shows the potential feasibility of increasing the visibility of projected images on natural real-world surfaces [22-24]. A camera is used to capture the characteristics of the surface (color, texture, shape, etc.), and the image is computationally distorted before projection to inversely match this specific surface. Most existing work has focused on fixed projection installations; however doing this for mobile projection is a promising future research topic [25].

### Usability of Alternative Interaction Techniques

In laboratory conditions, all five techniques functioned and showed promise (laser pointer, IR emitting stick, IR reflection from a spotlight from tape on a stick, boot, or finger). However, in field trial conditions only the IR emitting stick had sufficient reliability to be usable (Figure 8). This method of interacting with the display was extremely reliable and intuitive. It supported reliable interaction with a single user or with two concurrent users. There were some slight issues with the field-of-view of the camera. Some of the buttons near the corners of the projected image were out of line-of-sight of the camera. Occasionally, the camera and the projector would become slightly unaligned, causing the pointer to be offset from where the actual IR emitter was located.

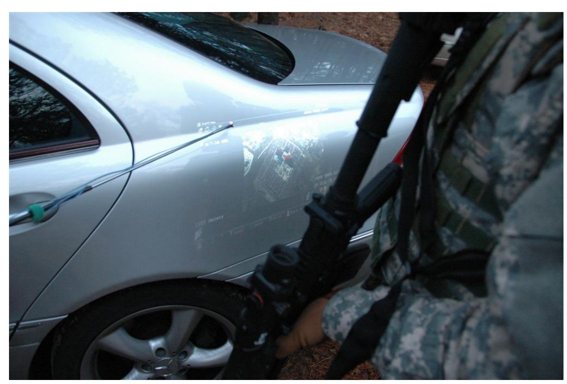

**Figure 8. Two SMEs collaborating on an Interactive Dirt display projected on a car.**

When asked about how useful this IR pointer would be in actual use, the experts said that the largest drawback would be the ruggedness of the metal stick. In most situations, equipment is under high amounts of stress and is likely to break. The other issue is that this pointer must be retrieved and stored, which increases the amount of impairment required to use the system. SMEs mentioned that rifles in the field have a powerful near IR laser targeting device attached to them. The simulation M4 weapons used in this study did not have functional IR lasers, so trials of this idea were not possible. Furthermore, rifle mounted near IR lasers are not eye-safe.

"(E) And your favorite way, like we talked about: finger reflection, stick point reflection, toe reflection, the IR [LED] stick, laser pointer, hand-held or on the weapon?"

"(P2) Laser would be the best!"

"(E) Laser on the weapon?"

"(P2) Yea, the laser would definitely be the best."

"(P1) Agreed."

### Light and Sound Discipline

SMEs said mobile teams of foot soldiers exercise extreme caution in drawing attention to themselves, because of the risk of being spotted by enemies. Their practice of minimizing the lights and sounds they use is called "light and sound discipline." Light discipline is mainly for night-time operations. As an anecdote, our SMEs were trained in this discipline so when they collaborated over the display they would talk in very low voices. The investigators had to stand very close to hear what they were saying.

Sound and light discipline have important design impacts on the interaction techniques and use cases for Interactive Dirt. For example, the SMEs were strongly opposed to the interaction techniques based on an IR spotlight. They said that IR light, although less risky than visible light, could be potentially seen by well-equipped enemies. A bright spotlight could draw attention from a wide area. Nighttime use of a projector is visible from farther away on vertical surfaces than horizontal surfaces. Also, the projector needs far less brightness to be usable in low-light conditions. SMEs also discussed the potential for a low-brightness IR projected image. Further study of this issue is indicated. "(P1) My main concern still is light discipline."

## CONCLUSION

Results of expert review predict that it is possible to develop a wearable projector-camera system that allows SASO mobile teams to use HCI services to improve work performance without negatively impacting SA. The Interactive Dirt prototype demonstrated the potential for reduced situational impairment while using a computer for mobile SASO teams. It successfully supported realistic mobile team collaboration and single-use projection on several different organic surfaces in urban conditions and some outdoor conditions. A comprehensive set of high-level technical and usability problems were identified, and four valid use cases were identified. An exit interview with the paired expert reviewers asked whether the projector-camera system approach was worth pursuing given the set of problems they had identified. Both SMEs responded emphatically "yes!" They predicted that the projector-camera system approach will become extremely valuable for SASO operations. They said this approach has more promise than any other existing alternative approach—it may not replace all hand-held UIs, but it could become the dominant UI solution for this type of work and receive widespread-fielded use by foot soldiers to improve their performance and security.

Multiple aspects of wearable projector-camera systems for mobile SASO teams require future work. (1) Visibility of the image in outdoor daylight conditions. The use of laser-based displays seems promising ([16] makes the same suggestion). Radiometric compensation also seems promising [22-25]. (2) An interaction technique that does not require users to hold a separate input device. Camera vision approaches for hand gestures seem promising [13, 18]. SMEs also suggested the potential utility of using laser pointers mounted on users' weapons. (3) Methods for night use that avoid conflict with users' policy of light discipline. This is a non-issue for daylight use, but a highest priority future research question for nighttime use. An IR laser-based display may have utility. (4) Improved miniaturization and battery power issues. This is an important issue, however, the growing swell of consumer electronics investment in the emerging projector phone business promises to engage a large community of talent to solve many of these issues in the near future.

With the exception of the question about the potential use of laser pointers mounted in rifles to interact with the display, all other predicted use/utility for Interactive Dirt should generalize to many other types of more main-stream mobile teamwork. This is especially true for situations where continual SA is important for personal safety. Examples include: pedestrian navigation, information access on the go, and multitasking while performing critical vigilance tasks. The predicted benefits of mobile projector-camera systems include: instant any-time hands-free access to computer-based information with minimal situational impairment; instant computer-supported collaboration with co-located people and/or autonomous systems without the need for others to have any devices; potential augmented reality capabilities with the added benefits of instant readiness, and hands-free viewing; and a large interactive display that is always available regardless of the circumstances.

Three additional future research topics are indicated: SMEs said that the inclusion of dual-use capabilities (like games or use of the projector as a flash light) would increase the potential adoption of this technology by SASO teams; development of a predictive model of situational impairment would be very useful general tool for design of mobile UIs; and an exploration of different applications for mobile projector-camera systems might reveal surprising uses. For example, there may be utility to enable underwater workers to communicate or to control underwater autonomous systems.


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