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The Design, Implementation, and Evaluation of a Pointing Device For a Wearable Computer

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U.S. Air Force special tactics operators at times use small wearable computers (SWCs) for mission objectives. The primary pointing device of a SWC is either a touchpad or trackpoint, which is embedded into the chassis of the SWC. In situations where the user cannot directly interact with these pointing devices, the utility of the SWC is decreased. We developed a pointing device called the *G3* that can be used for SWCs used by operators. The device utilizes gyroscopic sensors attached to the user's index finger to move the computer cursor according to the angular velocity of his finger. We showed that, as measured by Fitts' law, the overall performance and accuracy of the *G3* was better than that of the touchpad and trackpoint. These findings suggest that the *G3* can adequately be used with SWCs. Additionally, we investigated the *G3*'s utility as a control device for operating micro remotely piloted aircrafts

BACKGROUND

United States Air Force special tactics operators are dismounted soldiers who make copious use of technology for assistance in performing their duties. Small wearable computers (SWC) have recently been incorporated into their equipment portfolio and are actively being used in field operations. Operators can view the screen of the SWC on a head-mounted display (HMD) while concomitantly observing potential threats in their immediate environment (Snyder, 2010). Operators currently rely on traditional pointing devices to control the functionality of SWCs, in particular, a touchpad or a trackpoint. To effectively operate either of these pointing devices, which are embedded into the chassis of SWCs, operators must wear their SWCs on their chests as depicted in Fig. 1.

Due to the requirements of their missions, operators find themselves in situations in which they need to utilize their SWCs but cannot physically interact with the pointing devices embedded into the chassis of their SWCs. For instance, the pointing devices are inaccessible when operators are prone, holding a weapon, or in other positions/situations that prevent them from reaching their chests (see the right side of Fig. 1). An external pointing device can overcome this limitation by allowing operators to control their SWCs without reaching the pointing devices embedded into their chassis.

Given the necessity of dismounted operators to have uninhibited access to their SWCs, the objective of this paper was to design, implement, and evaluate a pointing device customized for SWCs that meets the needs of the specialized community of operators. The overall performance and accuracy of the pointing device were compared to that of the touchpad and trackpoint currently integrated into SWCs. As recommended by the ISO 9241-9 standard for the evaluation of non-keyboard input devices (ISO, 2002), we used Fitts' law to evaluate and compare pointing devices.

Figure 1: U.S. Air Force operators using a SWC on their chest. (left) an operator utilizing the SWC with an HMD, and (right) an operator using the SWC while carrying additional equipment.

Additionally, we investigated a use case scenario in which our pointing device would be used by dismounted operators as a controller for micro remotely piloted aircrafts (mRPAs). Operators use mRPAs to survey areas of interest by flying over them to acquire visual information with the cameras embedded in these vehicles. In addition to the vehicle itself, the operator must carry a control station, which includes a handheld controller and communication equipment. Since operators typically carry over 100 pounds of equipment, they benefit from light-weight and multipurpose devices that can replace heavier and larger equipment. Thus, we adapted our pointing device to replace the handheld controller. A preliminary demonstration showed that the precision of our device is statistically the same as that of the handheld controller.

RELATED WORK

Although many pointing devices have been developed for SWCs, few have taken into account the stringent requirements of dismounted operators. Zucco, Thomas, and Grimmer (2006) evaluate four pointing devices for wearable computers: a trackball and trackpoint adapted to operate as a hand-held devices, a touchpad mounted to the users wrist, and a hand-held mouse based on gyroscopic sensors manufactured by *Gyration*. Similarly, Oakley, Sunwoo, and Cho (2008) implemented and evaluated a pointing device based on an inertial sensor pack. They evaluated the pointing device in three locations: on the wrist, the back of the hand, and hand-held. Although these devices may be usable for many SWCs, they are not usable for operators because their form factor precludes the use of at least one hand for anything else or was too combersome.

PROTOTYPE DESIGN AND IMPLEMENTATION

Since a hand-held device would hinder an operator's use of other equipment, our pointing device was required to be incorporated into his attire. We decided to mount our device into a tactical glove because operators must wear tactical gloves during the majority of their missions to protect their hands from abrasions and burns. Consequently, operators can utilize our pointing device without carrying any additional equipment. Moreover, this allows operators to manipulate our pointing device with their fingers and hands, which usually have a high level of dexterity.

The proof-of-concept prototype shown in Fig. 2 is called the *G3*. The *G3* uses a 3-axis gyroscopic sensor, which measures angular velocity about three orthogonal axes, to detect the finger motion of the user and move the cursor accordingly. We implemented the *G3* using a gyroscopic sensor since they require a small footprint because they are available as integrated circuits. These integrated circuits are sourceless, consume low power, and have a low profile, making them ideal for devices that require a small form factor.

Although a gyroscope is incapable of detecting translation (i.e., non-rotational motion), it is able to precisely detect changes in orientation with a fast response time, unlike an accelerometer (*InvenSense Corporate FAQ*, n.d.). We implemented the *G3* using gyroscopic sensors instead of accelerometers primarily because of this fast response time. Consequently, the user must rotate the sensor placed on the index finger of the tactical glove to move the cursor rather than simply translating it.

The *G3* contains three main components:

Figure 2: The *G3*.

- a gyroscopic sensor, placed on the tip of the index finger, detects the user's wrist and index finger motion by measuring angular velocity. Moving the sensor across the air proportionally moves the cursor in the same direction. This mechanism attempts to emulate pointing with the finger;
- two buttons are attached to the side of the glove's index finger in such a way that the user's thumb can press them. One button, referred to as the trigger, ensures that the user only moves the computer's cursor when desired. The user must press and hold the trigger to enable cursor motion. Pressing the other button performs left-clicks;
- a microcontroller, placed on the back of the glove, connects the buttons and sensor with a computer through a standard Universal Serial Bus port.

A digital low pass filter is used on the output of the gyroscopic sensor to provide smooth cursor motion. Moreover, angular velocities smaller than a predetermined threshold were neglected to mitigate the effects of hand jitter and ensure users can keep the cursor steady. The horizontal displacement of the cursor is proportional to the gyroscopic sensor's horizontal angular velocity, and the vertical displacement of the cursor is proportional to the sensors vertical angular velocity. A right-handed *G3* currently requires users to position their right-hand palm towards the left, similar to holding a pistol, to properly align the sensor and match the cursor's direction of motion with their hands.

EXPERIMENTAL DESIGN AND RESULTS

An experimental task modeled by Fitts' law was used to evaluate and compare the *G3* with the touchpad and trackpoint of General Dynamics's operational SWC, the *MR-1 GD2000*. The hypothesis of this experiment is that the *G3* will perform as well as the touchpad and trackpoint on a Fitts' task.

Evaluation of Performance and Accuracy

We evaluate and compare pointing devices using a mathematical model called *Fitts' law* that relates movement time, distance, and accuracy for rapid aimed movements. Fitts' law is used to compare pointing devices by measuring the movement time of several movement tasks and determining how each device affects both speed and accuracy. Fitts' law is used to calculate the *throughput* of a movement task, which objectively quantifies its speed and accuracy and is independent of the speed-accuracy tradeoff (MacKenzie & Isokoski, 2008). The significance of throughput has been academically and industrially recognized (Soukoreff & MacKenzie, 2004). This study follows the recommendations for comparing and evaluating pointing devices of Soukoreff and MacKenzie (2004), which support and supplement the methods described in the ISO 9241-9 standard (ISO, 2002).

Participants. Twelve paid participants composed of seven men and five women took part in the study. Their ages were between 22 and 29 years (M = 23.75). Right-handed participants were selected because the *G3* was implemented using a right-handed tactical glove only. Note that these participants were not trained dismounted soldiers.

Apparatus. The experiment was conducted on a *MR-1 GD2000* with a 5.6" screen and the resolution set to 800 × 600 pixels. The experiment used MacKenzie's *FittsTaskTwo* software (MacKenzie, 2009) to present participants with the experimental task. Furthermore, this software also measured and recorded movement time and distance for each trial. The touchpad and trackpoint, which are embedded into the chassis of the *MR-1*, and the *G3* were evaluated in this experiment. The touchpad, and trackpoint were utilized with default sensitivity (i.e., 50%). The *G3* was calibrated similarly.

Task. We employed the *multidirectional tapping task* that is described in the ISO 9241-9 standard (ISO, 2002). Nine circular targets were arranged in a circular pattern as shown in Fig. 3. Each circular pattern generated a sequence of eight trials. Participants were asked to click inside the circular targets sequentially in ther order depicted by the numbers in Fig. 3. The next target in which a participant should click was always highlighted. Clicking outside a circular target resulted in an error for the current trial and participants were notified with a beep. If an error occurred before the end of a sequence, the next target was highlighted and participants immediately continued with the next trial.

Procedure. Participants wore the SWC on a tactical vest and took part in a 60-minute training session, which explained and demonstrated the multidirectional tapping task as well as the equipment used in the experiment. They were instructed to select the highlighted target as quickly and as accurately as possible. Participants were required to reach asymptotic performance with each pointing device before beginning the experimental task. It is important to note that due to the novelty and lack of experience with *G3* as compared to the other pointing devices, all participants had to complete more trials with *G3* to reach asymptotic performance.

A within-subjects design was employed with three conditions corresponding to the three pointing devices evalu-

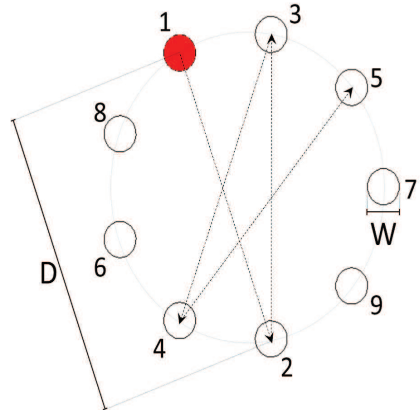

Figure 3: Illustration of the multidirectional mapping task. Each participant was asked to click on the circular targets in the order shown by the numbers 1-9. The shaded circle (labeled 1 here) represents the next target.

ated (touchpad, trackpoint, and *G3*). The order in which devices were presented to participants was counterbalanced using a Latin square. Data were collected in a series of sessions, with each session lasting approximately 30 minutes. No participants completed the experiment in a single session. Each participant typically completed one or two sessions a day until the completion of all three conditions. Combining each distance (128, 256, 384, and 512 pixels) with each width (35 and 45 pixels) generated eight distinct circular patterns. Each participant completed the experimental task four times with each of these eight patterns. This generated 32 sequences constituting 256 trials for each device (768 trials in total).

The distance and width values were chosen to obtain targets that fit inside the limited resolution and size of the *MR-1*. Trials in which the movement time or distance was greater than three standard deviations from the average of the movement times and distances for each sequence were considered outliers and were removed from the data. Soukoreff and MacKenzie (2004) note that these trials are often caused by an accidental double-click on the target or by a mid-trial pause, which violates the requirement of Fitts' law that movements are rapid.

Results

Throughput. The average throughput for each pointing device is given in Fig. 4. Data from Fig. 4 were tested for statistical significance by means of a three (device) within-subjects analysis of variance (ANOVA). A main effect was found for device, $F(1.74, 19.17) = 49.96$, $p < 0.05$. Post-hoc tests revealed that the throughput of the *G3* ($M = 3.13, SD = 0.22$) significantly differed from the throughput of the touchpad ($M = 2.46, SD = 0.15$) and trackpoint ($M = 1.49, SD = 0.07$), which were significantly different from each other. In this and all subsequent ANOVAs, Box's Epsilon was used to correct for violations of the sphericity assumption (Maxwell & Delaney, 2004).

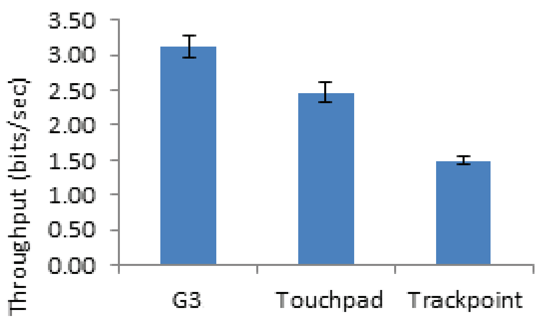

Figure 4: Mean and standard error for the throughput scores for each of the experimental conditions.

In addition to the *G3*, touchpad, and trackpoint, participants also completed the task with a mouse to verify that the throughputs obtained with our methodology fall in the range of values reported in other studies that are compliant with the ISO 9241-9 standard (ISO, 2002). The throughput of the mouse was found to be 4.741 bits per second, which belongs to the expected range of 3.7–4.9 given by Soukoreff and MacKenzie (2004). This result suggests that the methodology used in this study was valid since it produced data consistent with other studies.

Movement time. Another ANOVA was performed on the movement time data and revealed a statistical significant difference between the pointing devices, $F(1.60, 17.61) = 66.98$, $p < 0.05$. Post-hoc tests showed that movement time was fastest for the *G3* ($M = 1024.43, SD = 54.90$), which was significantly faster than the touchpad ($M = 1329.13, SD = 85.93$) and trackpoint ($M = 1997.64, SD = 98.28$), which were also significantly different from each other.

Error rate. A third ANOVA performed on the error rate data found a statistically significant main effect for pointing device, $F(1.31, 14.46) = 36.31$, $p < 0.05$. Post-hoc tests found that the *G3* produced the most error ($M = 15.51, SD = 1.12$), which was greater than that of the trackpoint ($M = 11.05, SD = 1.44$) and touchpad ($M = 3.29, SD = 0.77$), which were also significantly different from each other.

USE CASE OF THE G3

The *G3* was found to be a quick and accurate pointing device. Thus, a use case demonstration was developed to test its ability as a control device for mRPAs. The *G3* was configured to replace the bulky handheld controller currently used by operators to pilot mRPAs (shown in Fig. 5), thus demonstrating the ability of the *G3* to have multiple functions. We compared the ability to fly a simulated mRPA through a series of waypoint in an operational training simulator. The ability of the handheld controller was compared to that of the modified *G3*.

In this use case, participants navigated a simulated mRPA with real-world flight physics through a series of waypoints using both a handheld controller and the *G3*. The precision of the path of the simulated mRPA using each device was quantified using the *root mean square deviation* (*RMSD*) between the path of the mRPA and the ideal path between every pair of adjacent waypoints in the path. We assumed that the ideal path between two waypoints is the line segment between them. The path between the starting position of the mRPA and the first waypoint was neglected and, as a result, data collection began once the vehicle crossed the first waypoint.

Figure 5: An mRPA handheld controller.

Methods

Participants. Six paid participants composed of four men and two women took part in the study. Their ages were between 21 and 26 years ($M = 23$). Right-handed participants were selected because the *G3* was implemented using a right-handed tactical glove. Note that these participants were not trained mRPA operators.

Apparatus. The experiment was conducted on an Air Force certified mRPA trainer. The trainer consists of a field deployable Operator Control Unit (OCU) and a virtual sensor payload emulator. The OCU connects to a joystick, which manipulates the mRPA flight signals. For this experiment, we connected the *G3* to the OCU in place of the joystick with minimum effort. This study tested the effects of the *G3* as an alternative input device to the OCU.

Task. Twenty-nine waypoints were placed at a height of 133 meters in a figure-eight path. The separation between adjacent waypoints was placed such that the travel time between them is between 15 and 45 seconds. The waypoints were rendered as red cubes in a 3D virtual environment as shown in Fig. 6

Procedure. Participants took part in a 10-minute training session. They were told that their task was to fly through the waypoints displayed on the screen using a simulated mRPA. Then, they were given training trials in which they flew the simulated mRPA through a series of waypoints using both the operational joystick and *G3*.

A within-subject design was employed with two conditions (joystick and *G3*). The order in which devices were presented to participants was counterbalanced using a Latin Square.

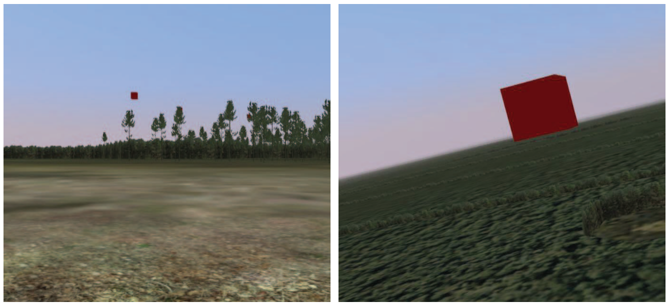

Figure 6: Waypoints rendered in the 3D virtual environment. (left) the simulated mRPA taking off, and (right) the simulated mRPA approaches a waypoint while flying.

Results

The average *RMSD* for the handheld controller and the *G3* are 8.70 and 8.73 meters, respectively. The standard deviation of the *RMSD* are 2.37 and 3.58 for the controller and *G3*, respectively. The experimental results were tested for statistical significance by means of a paired sample t-test. A statistically significant main effect was not found for control device, $t(5) = 0.185$, $p > 0.05$, thus there were no differences in the RMSD between the two type of control devices.

DISCUSSION

The objective of this effort was to develop a prototype for a pointing device for SWCs used by dismounted special tactics operators in the U.S. Air Force and to compare the device against the touchpad and trackpoint, which are embedded into the chassis of SWCs. The *G3* was found to have a greater throughput and faster movement time than the touchpad and trackpoint. Additionally, the data show that there were more errors made with the *G3*. This result shows the classic speed-accuracy tradeoff. Since participants were instructed to complete the task with rapid movements, these results are not surprising, in particular because finger and hand motions allow users to move the cursor very quickly. Since the throughput is a measure that encompasses both speed and accuracy, the results show that the overall performance of the *G3* is better than that of the touchpad and trackpoint. In particular, the *G3* serves as an adequate pointing device in situations where the pointing devices embedded into the chassis of the SWC are inaccessible. Additionally, use of the *G3* coupled with a HMD frees operators from wearing the SWCs on their chests and allows them to utilize their SWCs while stowed in their backpacks. Thus, their chests can hold additional equipment such as ammunition or medical kits.

The additional study was an operational use case for the utility of the *G3* as a control device for mRPA. Participants performed equally well with the *G3* as they did with the handheld controller in flying the mRPA through a series of waypoints. These results suggest that the *G3* can effectively replace the handheld controller. Moreover, the amount of equipment that a dismounted operator has to carry is reduced. Since operators must wear tactical gloves during their missions, the *G3* adds a very small amount of weight and size to the equipment the operator must carry. On the other hand, the mRPA controller is large enough to be held with two hands and serves no purpose other than as a mRPA controller.

The next iteration of the *G3* is currently in the work to address some issues found in this study. One such issue is that the *G3* currently requires users to position their right-hand palm towards the left to properly align the sensor and match the cursor's direction of motion with their hands. The placement of multiple sensors in the tactical glove will be investigated to eliminate this constraint, produce gesture-based inputs, and add capabilities for the controlling other equipment used by dismounted operators.

Although the above issues with the *G3* should be addressed in future work, it is a promising device for SWCs used by dismounted operators because its form factor has the potential to allow operators to access their SWCs in ways that are not possible with the touchpad or trackpoint. This is the first step towards providing the operator with an intuitive, fully accessible, common control interface that literally establishes control at their fingertips.

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