THE DIFFICULTY OF REMOTELY NEGOTIATING CORNERS

Robert Pastel, Jacob Champlin, Matthew Harper, Nathan Paul, and William Helton
Michigan Technological University
Houghton, Michigan

Martin Schedlbauer and Jesse Heines
University of Massachusetts Lowell
Lowell, Massachusetts

Remote navigation, popular in computer games and prevalent in areas such as clinical medicine and teleoperations of robots and drones, uses human-computer interfaces for control. Usability studies of remote navigation interfaces require good metrics for evaluating interfaces, assessing users' capabilities, and determining the difficulty of the navigational task. We studied the time proficient users took to navigate virtual hovercrafts through virtual hallways with corners of various widths and discovered that the time to negotiate corners is inversely proportional to corner width. We derive and evaluate two models for the index of difficulty for negotiating corners. Both models fit the data well, with r^2 greater than 0.85 for the mean time to negotiate corners verses corner width.

INTRODUCTION

Exploration is a pleasurable human activity. Much of the excitement of playing video games is in navigating and exploring new virtual worlds by maneuvering an avatar through hallways and avoiding dangerous obstacles. But if these maneuvers become too difficult, such as when navigating very narrow hallways, the activity becomes tedious and loses it appeal for the player. Understanding players' capabilities is important for designing pleasurable and exciting games.

Navigating corners is not only a concern of game designers, but is also important in settings such as modern clinical medicine and the teleoperation of robots. Remote and microscopic surgeries require the surgeon to maneuver probes equipped with video cameras while observing the surroundings on a monitor in real time. Some procedures require the surgeon to maneuver the probe around corners, such as in colonoscopy. A complete colonoscopy reaching the cecum requires the surgeon to maneuver the probe through three corners (WebMD, 2007). Currently, the technique for maneuvering probes is crude; manually pushing the probe and using the colon walls to guide the probe. Some techniques use variable stiffness colonoscopes (Shumaker, Zaman, & Katon, 2002). More genteel procedures will require sophisticated remote navigational techniques (Dario, *et al.*,1999). To ensure safe and successful medical procedures, interface designers will need to understand the limits of surgeons' capabilities to remotely guide self-propelled probes.

Remote navigation of drones and rovers also requires operators to navigate through corners. These remotely operated vehicles are currently being used in military and security operations and for the exploration of space and underwater. Although there is a great deal of interest in the development of completely autonomous vehicles (DARPA, 2006), reality lags far behind this dream. For the foreseeable future, real time navigation of robots in time-critical environments will require manual control by a human operator. The U.S. military's Talon and SWORDS (Special Weapons Observation Reconnaissance Detection Systems) robots are examples of remotely operated vehicles requiring a human operator for navigation (BBC, 2005). These robots are designed to enter areas deemed too dangerous for humans, and this often entails navigating the robots through tight passageways and through corners. Actual exploration still requires human control, and the design of these controls requires understanding pilots' capabilities.

This paper explores the difficulties of remotely navigating a vehicle by measuring the time for participants to maneuver a virtual hovercraft through virtual hallway corners. Tests were implemented by modifying a popular first-person shooter computer game (Unreal Torment). Because navigating the straight sections of the hallways can easily be automated, we record only the time for the participants to negotiate the corner regions. Also, because we want to understand proficient users' limitations, we analyze only experienced game players, self reported, using conventional game controls, keyboard and mouse at least once a week.

FIRST EXPERIMENT: LEARNING

Our first experiment determines the amount of learning involved in remotely navigating hovercrafts through hallways with corners in the Unreal Torment game engine, and the difference in difficulty for horizontal and vertical maneuvers. Length measures are complicated in a 3D game engine; the game engine, Unreal Engine 2.5, uses a unique unit for length, which are called "unreal units" (uu) as measured in the level editor, Unreal Editor 3.0. Nine male experienced computer game players (average age 21 years), who self reported playing first-person computer games at least once a week, maneuvered the hovercraft through six hallways; three widths (w = 512 uu, 1024 uu, 1536 uu), and two directions (horizontal to the left and vertical up) in six sequential sessions. The participants used the standard computer game controls to maneuver the hovercraft: keyboard keys W and S for controlling horizontal acceleration, and keys A and D for strafing (side to side motion). The computer mouse controlled the viewing perspective and yawing of the hovercraft simultaneously, and the right mouse button controlled the vertical acceleration. The hovercraft dimensions are height, 208 uu, width, 192 uu, and length, 320 uu. Each participant maneuvered the six hallways in a different random sequence for each session. Participants viewed the hallways and craft in tracking third person perspective on 17" 1280x1024 flat screen monitors.

Figure 1 shows the third-person perspective as the craft enters the narrowest hallway turning to the left.

Figure 1: Hovercraft entering corner turning left.

Time to negotiate a corner is defined as the time difference between the craft's nose projecting into the cubic region of the corner and the craft's nose exiting that region. The craft's maximum velocities are 250 uu/sec in both the horizontal and vertical directions, and the craft's acceleration is 250 uu/sec^2 horizontally and 65 uu/sec^2 vertically. The hallways had equal entrance and exit hall lengths, at least 3 times longer than the hallway width. The entrance and exit halls allow the participant room to orientate the craft before entering the corner and to ensure that the entire craft exited the corner before completing the task. The craft would explode if it touched any wall of the hallway, and the participant had to repeat the maneuver. Only successful trails were analyzed in the ANOVA and linear regressions.

The hallway width [$F(2, 300) = 22$, $p < 0.001$] and corner direction [$F(1, 300) = 34$, $p < 0.001$] were significant factors on the time to negotiate the corner. Session was not statistically significant [$F(5, 300) = 1.5$, $p = 0.17$]. All the interaction terms were not significant and had p-values greater than 0.5. We still investigated learning by non-linear least-square fit of BN^{α}, the power law of practice (Newell and Rosenbloom, 1981), for the mean time in the two directions (horizontal and vertical), where N is the session, and B and α are the estimated model parameters. Figure 2 shows the estimated curves for both corner directions. The exponent for corners turning up was significant [$t(4) = -3.9$, $p = 0.017$], $\alpha = -0.16$, but not significant for corners turning left [$t(4) = -2.1$, $p = 0.10$], $\alpha = -0.11$.

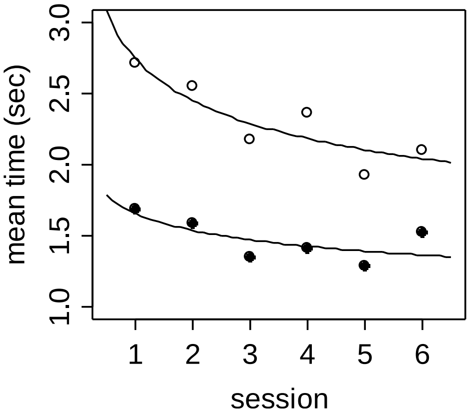

Figure 2: Mean time to negotiate a corner versus session for corners turning up (empty circles) and corners turning left (filled circles). Curves are exponential regressions for the respective corner direction.

Corners turning up consistently took longer to negotiate than corners turning left for all sessions. We believe that negotiating corners turning up took longer because the viewing angle in the vertical is less than in the horizontal. Turning up is also a more complex task requiring the pilot to release the forward acceleration key, W, possibly braking (pressing the S key), and finally pressing and holding the right mouse button to accelerate up. Negotiating corners turning left only requires yawing left, which is combined with changing the perspective into a single mouse motion, moving the mouse to the left. We assume that the participants were skilled at negotiating corners turning left as this is a typical maneuver in most first-person shooter games and is a simpler maneuver than turning up.

The hallway width [$F(2, 288) = 35$, $p < 0.001$] and session [$F(5, 288) = 3.5$, $p = 0.004$] were significant factors on the number of errors made. Corner direction was not significant [$F(1, 288) = 1.8$, $p = 0.18$]. All the interaction terms were not significant and had p-values greater than 0.35. The total number of failures was 293. 71% of the failures are made on the narrowest hallway, $w = 512$ uu. The wider hallways, $w = 1024$ uu and 1536 uu, made up 16% and 13% of the failures, respectively. Recall that the length of the hovercraft was 320 uu; thus, the narrowest hallway was the most difficult.

Figure 3 shows the mean time for each corner width and direction. Corners turning up consistently take longer to negotiate than corners turning left for all widths. The curves are linear regressions of all the corner negotiation times on the reciprocal hallway width, $1/w$, so they appear as curves plotted against w. The regression slopes are 611 sec•uu for turning left [$F(1, 160) = 20$, $p < 0.001$] and 724 sec•uu for turning up [$F(1, 160) = 12$, $p < 0.001$]. Because the time to negotiate corners is inversely proportional to corner width, we do not believe that the negotiation time is limited by acceleration. However, the difference in the regression slopes between vertical and horizontal turning could be due to the difference in horizontal and vertical acceleration or the difference in difficulty between turning left and turning up**.** There is a large variation between trials; a repeated measure analysis determined that the variation between participants was 618 sec•uu in the regression slope for turning left (≈100% of the fixed effect slope) and 498 sec•uu in the slope for turning up (≈ 70% of the fixed effect slope).

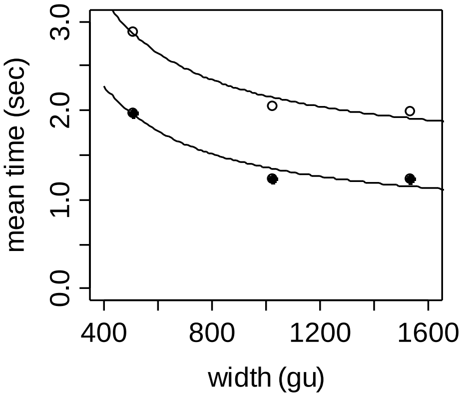

Figure 3: Mean time to negotiate corners versus width for corners turning up (empty circles) and corners turning left (filled circles). Curves are inverse corner width regressions.

CORNER NEGOTIATION MODELS

The primary result of the first experiment is that narrower corners take longer to negotiate than wider corners. This result is manifested despite the fact that wider corners may have longer negotiation path lengths than shorter corners. In other words, the time to negotiate corners is not dominated by the craft's acceleration; the participants have sufficient acceleration to traverse the corner at their preferred velocity. The observed corner negotiation times must be due to user limitations.

A fundamental model for movement times is Fitts' Law. Using information theory, Fitts (Fitts, 1954; Mackenzie, 1992) derived an index of difficulty for target acquisition,

$$ID_F = \log_2(A/W + 1)$$

where A is the movement amplitude and W is the target size. The movement time, MT, is modeled by linear regression on ID_F. Because both A and W are approximately proportional to the corner width, any formulation of MT for negotiating a corner using Fitts' Law is independent of corner width. Even Looser's generalization of Fitts' Law (Looser *et al.*, 2005) for selecting targets by angle results in corner negotiation times that are independent of corner width. Accot and Zhai (Accot and Zhai, 1997) derived the steering law, which models the MT to draw lines through constrained paths, from Fitts' Law. But the steering law, also results in corner negotiation times independent of corner width for paths near the center of the hallway. We cannot use Fitts' Law or any model derived from Fitts' Law because the amplitude and accuracy in corner negotiation are approximately proportional to each other.

Without an established theory, we can derive an index of difficulty for negotiating a corner, ID_C, by considering limiting cases. From the first experiment we believe that the difficulty negotiating a corner is inversely proportional to the corner width, $ID_C \sim 1/w$. Our intuition is that the difficulty negotiating corners should increase as the craft size approaches the corner's width. In the limit where the craft size is equal to the corner width, negotiating the corner becomes nearly impossible, so $ID_C \sim 1/(w - p)$, where p is the craft size. An index of difficulty should be non-dimensional. Consider when the craft becomes infinitesimal, negotiating the corner is easy and the task reduces to a steering task. So an index of difficulty for negotiating a corner could be

$$ID_C = p/(w - p)$$

An alternative form for the corner negotiation index of difficulty can be derived from information theory. We assume that the primary task of negotiating a corner is recognizing when the craft is sufficiently centered in the corner that the craft can exit the corner unimpeded, without hitting the walls of the corner. In this case, the gain in information is the difference in the logarithms of the uncertainties before and after the craft is ascertained to be sufficiently centered (Brillouin, 1962).

$$\begin{aligned} ID_C &= \log_2(w) - \log_2(w - p) \\ &= \log_2(w/(w - p)) \\ &= \log_2(p/(w - p) + 1) \end{aligned}$$

The final form shows the similarity of the two models, and also suggests a comparison with Fitts' law, $A = p$ and $W = w - p$. The forms of ID_C and ID_F are similar because they both derive from information theory although they may represent different cognitive processes.

SECOND EXPERIMENT: MORE WIDTHS

In the second experiment we observe more hallway widths, attempting to better assert the usefulness of the ID_C and possibly discriminate between the forms for ID_C. Again, we observe experienced computer gamers negotiating corners turning left. We studied only turning left because we assume minimum learning is required from the participants.

Ten experienced male computer gamers (average age 21 years) maneuvered the hovercraft through six width hallways (w = 512 uu, 556 uu, 680 uu, 1024 uu, 1536 uu, 3072 uu) with corners turning left in random order for two sequential sessions. All other experimental parameters were the same as for the first experiment. Again the participants used standard computer game controls, keyboard and mouse, in the tracking third-person perspective. Observed times began when the craft's nose entered the cubic corner region and ended when it exited.

Figure 4 shows mean time for negotiating the six corner widths, and the two linear regression models, using repeated measure analysis, transformed back to widths, so they appear as curves plotted against corner width, w. Using the largest dimension of the hovercraft, length, for the craft size, p = 320 uu, the intercept, a, and slope, b, for the model $ID_C = p/(w-p)$ were a =1.09 sec and b = 0.633 sec/bit, and for the model $ID_C = \log_2(w/(w-p))$ were a = 0.9756 sec and b = 0.787 sec/bit. All coefficients were significant ($p < 0.001$, $df = 118$). The between participants variation was approximately the same for the two models, 30% of the fixed effect value for the interception, and 50% for the slope. Also, the estimation for residual variance was the same for the two models, 0.543. R-square for the linear regression on the mean times for the six widths were 0.853 for $ID_C = p/(w-p)$ and 0.863 for $ID_C = \log_2(w/(w-p))$. Both models fit the data well. We cannot discriminate between the two models.

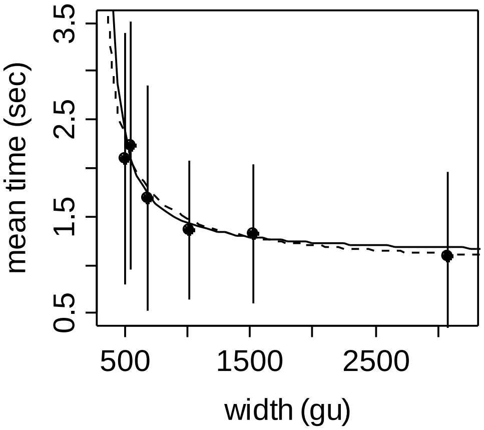

Figure 4: Mean time to negotiate corners versus width and regressions. Solid line is for $ID_C = p/(w-p)$ and dashed line is for $ID_C = \log_2(w/(w-p))$. Vertical lines are standard deviations.

Participants failed to negotiate 124 corners. Table 1 shows the number of failures per hallway width. Except for w = 1536 uu, the number of failures was inversely proportional to hallway width. 70% of the failures on w = 1536 uu were due to two participants; these same participants performed well at the other hallway widths.

Width(uu)	512	556	680	1024	1536	3072
Failures	40	32	25	7	18	2

Table 1. Number of failures per hallway width.

CONCLUSIONS

These experiments do not explore all the possible effects on corner negotiation times, such as corner angle (the angle between the entrance and exit leg of the hallway), visibility of corner, field of view, and different craft controls. Pastel (2006) studied MT for moving a cursor using a mouse through constrained paths with various corner angles. Corner negotiation times did not appear in these experiments because the probe size was small, a single pixel, and $p/w\text{-}p = 0.05$, making the effect of corner negotiation proposed in the current study negligible. We have tried to make the corner as visible as possible by adding a large yellow arrow to the corner's far wall texture (see Figure 1). The models for corner negotiation only attempt to describe the effects of easily observable parameters of corner negotiation, corner width and craft size.

We propose negotiating corners as a fundamental remote navigational task, and we have demonstrated, using proficient game players, that the task can be modeled using either the index of difficulty $ID_C = p/(w\text{-}p)$ or $ID_C = \log_2(w/(w\text{-}p))$, where w is the corner width and p is the craft size. The models are too similar to distinguish. The index of difficulty $ID_C = p/(w\text{-}p)$ is derived considering the limiting case performance, while $ID_C = \log_2(w/(w\text{-}p))$ is derived using information theory. We believe that the task is general and frequently occurs in conjunction with other navigational tasks such as Fitts target acquisitions and constrained steering tasks. Due to the close connection with Fitts tasks, we prefer the information theory formation of the index of difficulty. Because remote navigation is becoming more prevalent at all length scales, from microscopic surgery to semi-autonomous robotic vehicles, we believe that navigating corners is a useful metric for evaluating interaction techniques and devices.

In the future, we plan to generalize the task to 3D remote navigation, and alternative perspectives and control devices such as joysticks. We are also interested in exploring the role individual differences plays in this task. We are, for example, interested in whether users' emotional state may impact their ability to navigate robots through corners.

ACKNOWLEDGEMENTS

The authors especially thank Chair Linda Ott for providing both encouragement and support for the experiments. The authors also thank all the experts, computer science students, who participated in the experiments.

REFERENCES

Accot, J., and Zhai, S., (1997). Beyond Fitts' Law: Models for Trajectory-Based HCI Tasks*, Proceedings of CHI 97 Conference on Human Factors en Computing Systems*, 295-304.

Brillouin, L., (1962). *Science and Information Theory*, second edition, Academic Press Inc., New York, NY, 1962.

BBC News, (2005). US plans 'robot troops' for Iraq, January 23, 2005, at: http://news.bbc.co.uk/2/hi/americas/4199935.stm

DARPA, (2006), DARPA Grand Challenge, downloaded January 6, 2006, at: http://www.darpa.mil/grandchallenge/overview.asp

Dario, P., Carrozza, M., and Pietrabissa, A., (1999). Development and In Vitro Testing of a Miniature Robotic System for Computer-Assisted Colonoscopy, *Computer Aided Surgery*, 4, 1-14.

Fitts, P.M., (1954). The Information Capacity of the Human Motor System in Controlling the Amplitude of Movement, *Quarterly Journal of Psychology*, 47, 381-391.

Looser, J., Cockburn, A. and Savage, J., (2005). On the Validity of Using First-Person Shooters for Fitts' Law Studies, *Proceedings of. People and Computers XIX* (Volume 2): *British Computer Society Conference on Human Computer Interaction,* 33-36.

MacKenzie, S. and Buxton, W., (1992). Extending Fitts' Law to Two-dimensional Tasks, *Proceedings of CHI 92 Conference on Human Factors en Computing Systems*, 219-223.

Newell, A. and Rosenbloom, P., (1981). Mechanisms of Skill Acquisition and the power law of practice, *Cognitive Skills and their Acquisition*, Anderson, J. (editor), Erlbaum, Hillsdale, NJ, 1-55.

Pastel, R. (2006). Measuring the Difficulty of Steering Through Corners, *Proceedings of CHI 06 Conference on Human Factors in Computing Systems*, 1087-1096.

Shumaker, D., Zaman, R., and Katon, M. (2002). Use of a Variable-Stiffness Colonoscope Allows Completion of Colonoscopy after Failure with the Standard Adult Colonoscope, Endoscopy, v. 34, 711-714. http://www.thieme-connect.com/ejournals/abstract/endoscopy/doi/10.1055/s-2002-33442

WebMD (2007), Colorectal Cancer Health Center, Colonoscopy, download May 5, 2007 at http://www.webmd.com/colorectal-cancer/Colonoscopy-16695, See photo link.